

前言

近两年随着新冠疫情的爆发与蔓延，全球经济增速持续放缓，环境和资源压力叠加以及能源供应紧张等不确定性风险不断加大。习近平总书记在党的十八大会议上提出了新发展的理念，坚持生态优先、推动经济社会全面绿色转型、实现高质量发展已经成为未来中国经济社会发展的长期目标。

碳达峰和碳中和战略目标既定，必将给中国经济和社会发展带来广泛而深刻的系统性变革，也将孕育出巨大的发展机遇。数字经济为传统产业高质量发展赋能，大数据、云计算、人工智能、物联网等数字技术的广泛应用将系统提升能源、资源的利用效率。数字经济强大引擎的加入，将有力助推经济发展和社会治理进入全面智能化、集约化时代，构建起更加高效、清洁和可持续的现代能源体系，为顺利实现双碳目标、建设生态文明的“美丽中国”做出突出贡献。

本次经济管理学院研究生学术论坛以“双碳目标与数字经济背景下的理论创新与政策前沿”为主题，引导研究生积极关注经济社会发展的现实而重要的问题，努力探索解决之道，在双碳背景下肩负起时代赋予的责任和使命。截止收稿日期共收到投稿 154 篇，每篇论文由 3 为专家匿名评审打分，最终遴选出 77 篇优秀论文汇编成《中国矿业大学经济管理学院第十六届研究生学术论坛优秀论文集》，以供广大师生交流探讨。

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绿色基金助力企业环境信息披露质量提升了吗？ ——机构投资者参与公司治理视角

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摘要：基于 2011-2020 年沪深 A 股上市公司的非平衡面板数据，本文探究了中国的绿色基金能否促进企业提高环境信息披露质量。研究发现：绿色基金对企业环境信息披露质量总体具有正向影响，但具体来看，其能够促进企业披露定量类环境信息，对企业披露定性类环境信息并无显著影响；进一步地，绿色基金对环境信息披露质量的提升作用可以通过提高企业环境责任表现间接实现；此外，异质性分析表明，绿色基金对企业环境信息披露质量的影响因企业的行业性质、产权性质而存在差异。本文结论可以为推动企业积极披露环境信息与缓解环境信息不对称、进一步发展和完善绿色基金市场提供依据，对促进我国绿色金融体系完善发展具有参考价值。

关键词：绿色基金；企业环境责任；环境信息披露质量

Do green funds promote the quality of corporate environmental information disclosure?—A consideration of institutional investors' participation in corporate governance

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Abstract: Based on unbalanced panel data of A-share listed companies in Shanghai and Shenzhen from 2011 to 2020, this paper examines whether green funds in China can promote enterprises to improve quality of environmental information disclosure. This paper finds that green funds have a positive impact on the quality of corporate environmental information disclosure. Green funds can promote corporate disclosure of quantitative environmental information, but have no significant impact on the disclosure of qualitative environmental information. Further research shows that green funds can indirectly improve environmental information disclosure quality by improving corporate environmental responsibility performance. Heterogeneity analysis shows that the impact of green funds on the quality of corporate environmental information disclosure varies with the industry attributes and corporate property rights. This study provides evidence for promoting enterprises to actively disclose environmental information and alleviate environmental information asymmetry, and has important value for promoting the improvement and development of China's green fund market and green financial system.

Keywords: green funds; corporate environmental responsibility; quality of environmental information disclosure

一、引言

2020 年 9 月，中国政府向世界承诺碳排放力争在 2030 年前达到峰值，于 2060 年前实现碳中和（简称“双碳目标”）。在碳中和背景下，“十四五”规划和 2035 年远景目标纲要明确提出大力发展绿色金融以助力“双碳目标”的实现。2021 年，在政策的引导下，中国已经初步形成了支持绿色金融发展的

政策体系和市场环境^①。但是，中国的绿色金融发展存在着一些结构性问题：目前以绿色信贷为代表的间接融资占比过大，而以绿色基金和绿色债券为代表的直接融资占比较小，尤其是绿色基金，这种结构性失衡与绿色资金需求并不匹配。作为绿色金融体系的重要组成部分，绿色基金越来越受到中国政府的重视。绿色基金^②是一种主要投资于环境友好

^① 2021 年 9 月 25 日，中国人民银行副行长陈雨露在 2021 中国金融学会绿色金融专业委员会年会上的讲话。

^② 在中国，绿色基金具体分为绿色证券投资基金、绿色股权基金、排放权基金、绿色担保基金等。本文研究的对象

公司的基金，其投资决策同时考虑金融因素和环境因素，以实现双重投资目标（金融目标和环境目标）(Munoz et al., 2014^[1])。近年来，中国的绿色金融政策和绿色金融实践极大地促进了绿色投资理念的传播，中国金融市场出现了大量具有绿色投资理念的投资者，由此衍生出大量的绿色投资需求。不同于机构投资者，个体投资者可能因资金规模限制而无法充分分散非系统性风险以及因信息不对称而不能准确识别绿色企业而放弃进行绿色投资，这不利于充分调动社会资本支持绿色发展。而绿色基金因其信息优势和较大的资产规模，可以在一定程度上解决上述问题，满足投资者的绿色投资需求(Jin and Han, 2018^[2])，进而充当个体投资者绿色投资的重要工具。

目前，关于绿色基金的研究主要关注绿色基金的投资绩效以及绿色基金的“业绩-资金流量”关系。就前者而言，一个基本问题是绿色投资实践是否给绿色基金带来超额收益或额外成本。虽然存在着不同观点，但是大量实证研究表明绿色基金的投资业绩与传统基金并无显著差异(Ibikunle and Steffen, 2017^[3]; Soler-Dominguez et al., 2021^[4])，这意味着绿色投资没有额外成本或额外收益，来自中国的证据也支持这一结论(Marti-Ballester, 2021^[5])。就后者而言，相关研究通过考察绿色基金业绩与资金流量的关系，试图探究投资者对绿色投资的认可度，但尚未形成一致结论。唐亚晖等(2019)^[6]发现投资者对绿色基金业绩敏感，因此得出基金市场投资者不存在绿色偏好。危平和舒浩(2018)^[7]、邹小芄等(2019)^[8]的研究结果表明投资者对绿色基金业绩不敏感，基金市场投资者认可绿色投资。

作为机构股东，绿色基金可以对被投资企业的绿色行为产生影响，但已有研究相对较少。姜广省等(2021)^[9]发现以绿色基金为代表的绿色投资者能够促进企业增加绿色支出、实施绿色行动，促进企业积极参与绿色治理。此外，绿色基金作为企业环境信息使用者，还可能促进企业提高环境信息披露质量，抑制企业“漂绿”行为。环境信息披露是各

社会主体了解上市公司环境责任履行状况的重要途径，当前我国上市公司存在着环保声明与实际行动不一致的“漂绿”行为(黄溶冰和赵谦, 2018^[10])。它们倾向于披露环境政策、环保愿景等描述性信息，而回避披露污染排放、法律诉讼等不利信息(王霞等, 2013^[11])，这使得企业环境信息披露水平较高，但披露质量相对较低(李哲等, 2021^[12])。已有研究表明机构投资者在促进企业环境信息披露、缓解信息不对称方面发挥着重要作用。绿色基金作为关注环境因素的机构投资者，具有不可忽视的异质性，其能否促进企业提高环境信息披露质量、有效发挥监督作用尚未得到证实。

鉴于此，本文基于中国基金市场现状，试图探究绿色基金能否促进企业提高环境信息披露质量，并梳理绿色基金提高企业环境信息披露质量的潜在机制。与既有研究相比，本文的推进性在于：（1）回答了绿色基金能否促进企业提高环境信息披露质量这一问题，并就其对不同类型（定性类与定量类）的环境信息披露质量作用的差异进行了分析，一定程度上填补了研究空白；（2）诠释了绿色基金如何促进企业提高环境信息披露质量，对促进我国上市公司提高环境信息披露质量、抑制“漂绿”行为具有重要参考价值；（3）本文的研究结果对进一步促进绿色基金市场的完善发展和绿色金融政策的制定提供了依据。

二、文献综述与研究假设

1、绿色基金参与企业环境信息披露治理的途径

发声（“用手投票”）和退出威胁（“用脚投票”）被认为是机构投资者参与企业环境治理的两种主要途径(McCahery et al., 2016^[14]; Dyck et al., 2019^[15])，同时也是其参与企业环境信息披露治理的主要途径。“用手投票”是股东通过提案以及投票表决权表达诉求，进而影响企业的环境信息披露质量。此外，股东也可以通过“用脚投票”参与治理，由于羊群效应的存在，机构投资者的股票抛售行为可能引发其他投资者跟风抛售，并向市场传递企业经营不佳的信号，可能导致企业股价大幅下跌(吴晓晖等，

为绿色证券投资基金，以下简称绿色基金。

2019^[16])。如果机构投资者对企业的决策不满,他们可以宣布出售股份以威胁企业做出改变。作为企业股东,绿色基金可以通过上述渠道参与环境信息披露治理,影响企业的环境信息披露。

“用手投票”和“用脚投票”等途径的有效性取决于机构投资者的持股比例,对于持有企业大量股份的大股东来说该途径能够发挥作用(Azar et al., 2021^[17]),但是对于体量相对较小且投资具有分散化特点的绿色基金来说,上述途径的作用相对有限(Dam and Scholtens, 2015^[18])。对此, Yan et al. (2021)^[19]指出绿色基金参与企业环境治理的另一种途径:规范和文化传播途径。绿色投资不仅仅为环境友好企业提供资金,更重要的是它成为在市场领域传播环境逻辑的文化规范和价值的工具。绿色基金可能会带动企业内部的利益相关者,并在社会压力的共同作用下,直接或间接说服企业管理者,影响企业的环境决策,促进企业的环境保护实践(Alda, 2019^[20])。征集委托代理权和提交股东提案等方式可以有效联合利益相关者(姜广省等, 2021),增强绿色投资者的话语权。规范和文化传播途径意味着绿色基金的存在可能会对企业的信息披露产生较大的影响,即使其仅持有企业很少的股份。

2、绿色基金与企业环境信息披露质量

绿色基金为提升企业价值从而获得更高的投资收益而促进企业提高环境信息披露质量。第一、高质量的环境信息披露能够传递企业履行环境责任信号,获得供应商、客户、金融机构、投资者和政府等利益相关者的支持(Meng et al., 2014^[21]),形成绿色竞争优势(包括环境奖励、再融资便利、可交易许可证和绿色信贷等),从而提高企业的财务绩效(温素彬和周鑒鑒, 2017^[22])。第二、环境信息披露质量的改善有利于树立和维持良好的企业形象和声誉(Dhaliwal et al., 2012^[23]),可以在一定程度上减轻投资者面对企业负面事件的反应、降低企业股价崩盘风险(宋献中等, 2017^[24]),即“声誉保险效应”,从而降低机构投资者的投资风险。第三、环境信息披露质量的提高可以降低股权融资成本(李力等, 2019^[25])、增加预期现金流量(Clarkson et al.,

2013^[26]),从而提升企业价值(Plumlee et al., 2015^[27]; 唐勇军等, 2021^[28]),并由此给机构股东带来更高的投资收益。因此,受经济利益驱使,绿色基金可能会促进企业提高环境信息披露质量。

环境因素已经成为机构投资者进行投资决策的重要因素(Nofsinger et al., 2019^[29]),企业的环境信息披露可以在一定程度上反映企业的环境责任状况,成为机构投资者进行投资决策的参考依据。由于与被投资企业之间不存在业务关系,以基金为代表的压力抵制型投资者一方面较难获得公司内部信息,具有更强的促进企业披露环境信息、降低信息不对称的动机;另一方面,压力抵制型投资者具有较强的独立性,有利于发挥对被投资企业环境信息披露的监督作用(全晶晶, 2022^[30])。Pucheta-Martinez and Lopez-Zamora (2018)^[31]发现压力抵制型机构投资者在促进企业环境信息披露方面具有积极作用,来自中国的实证研究也支持该结论(王垒等, 2019)。绿色基金作为绿色投资的践行者,具有更强的环境责任意识,为获得更加真实、准确的企业环境信息,其具有更强的促进企业提高环境信息披露质量的动机。综上,本文提出假设 1:

H1: 绿色基金对企业的环境信息披露质量具有正向影响。

就环境信息披露类型而言,定量类环境信息更为客观、可靠和准确;而定描述性环境信息较为空泛,常被企业用于应对外部压力(吕明晗等, 2018^[32])。因此,环境信息定量披露因其可信性和准确性,可以反映企业真实的环境责任状况,代表企业进行实质性环境信息披露;环境信息定性披露具有模糊的特点且很难验证,被视为企业“掩饰”真实环境状况的表现,成为企业“漂绿”的手段。朱炜等(2019)^[33]的实证研究表明环境表现差的企业更倾向于披露定性环境信息,环境表现好的企业更倾向于披露定量环境信息,并印证了上述观点。绿色基金对企业环境信息披露的监督作用可能表现为促进企业环境信息披露方式由定性披露向定量披露转变。据此,本文提出以下假设:

H2: 绿色基金对企业的环境信息定量披露具有

正向影响；

H3: 绿色基金对企业的环境信息定性披露具有负向影响。

三、模型设定与变量选择

1、样本选择与数据来源

本文选取沪深 A 股上市公司作为初始样本, 研究区间为 2011-2020 年。并对初始样本进行以下处理: (1) 剔除存在缺失值的样本; (2) 剔除金融企业、ST 和*ST 公司; (3) 为消除异常值的影响, 对主要连续变量进行上下 1% 的 winsorize 缩尾处理。经上述处理后, 最终获得 19755 个样本。本文所使用的公司经营特征、股权结构、公司治理数据来自 CSMAR 数据库, 环境信息披露数据来自上市公司年报、社会责任报告、环境报告和可持续发展报告。参考已有研究, 本文将基金名称、投资策略和招募说明书中含有“环保”“绿色”“新能源”“低碳”“可持续发展”“生态”等关键词的基金作为绿色基金, 共得到 80 只样本基金。然后, 剔除成立年限小于 1 年、数据不全和被动指数型基金, 最终筛选出 42 只绿色基金。绿色基金筛选过程中所使用的基金信息来自天天基金网, 绿色基金持股数据来自 CSMAR 数据库。

2、模型设定

为从不同维度检验绿色基金对企业环境信息披露质量的影响, 本文构建以下双向固定效应模型, 如式(1)-(3)所示。

$$EID_{i,t} = \alpha + \beta GF_{i,t} + \gamma control_{i,t} + individual_i + year_t + \varepsilon_{i,t} \quad (1)$$

$$EID_qual_{i,t} = \alpha + \beta GF_{i,t} + \gamma control_{i,t} + individual_i + year_t + \varepsilon_{i,t} \quad (2)$$

$$EID_quan_{i,t} = \alpha + \beta GF_{i,t} + \gamma control_{i,t} + individual_i + year_t + \varepsilon_{i,t} \quad (3)$$

其中, EID 表示企业环境信息披露质量, EID_qual 表示定性披露, EID_quan 表示定量披露, 解释变量 GF 表示绿色基金持股, $control$ 表示控制变量, $individual$ 表示个体固定效应, $year$ 表示时间固定效应, ε 为随机扰动项。

3、变量说明

(1) 被解释变量。借鉴李志斌(2014)^[34]、姚海博等(2018)^[35]的做法, 本文采用“内容分析法”测量企业环境信息披露质量(EID), 对企业在年报、社会责任报告、环境报告和可持续发展报告中披露的环境信息进行评分, 具体规则为: 企业披露量化类环境信息计 2 分, 披露文字描述性环境信息计 1 分, 未披露计 0 分。最后将企业当年披露的环境信息得分加总并除以最高得分作为企业当年的环境信息披露质量得分。并参照朱炜(2019)的做法, 分别以定性披露和定量披露评价环境信息披露质量。定性披露(EID_qual)定义为企业当年披露的描述性环境信息数量并除以最大值; 定量披露(EID_quan)定义为企业当年披露的量化类环境信息数量并除以最大值。

(2) 解释变量。为探究绿色基金能否影响其投资的企业, 本文选取绿色基金持股(GF)作为解释变量, 该变量为虚拟变量, 若报告期内企业被绿色基金持股, 取值为 1, 否则为 0。绿色基金为上文所选 42 只基金, 具体见上文。

(3) 控制变量。参考已有研究, 本文选取企业层面的经营特征、股权结构、公司治理特征作为控制变量, 主要包括: 企业规模($size$)、盈利能力(roa)、财务杠杆($leverage$)、成长性($growth$)、经营活动现金流量($cash$)、产权性质(soe)、机构所有权比例(io)、股权集中度($Fshare$)、董事会规模($board$)和企业年龄(age)。具体变量定义见表 1。

表 1 相关变量说明

变量名称	变量符号	变量说明
被解释变量		
环境信息披露质量	<i>EID</i>	由企业报告期内披露的描述性和量化类环境信息数量计算而来，具体见上文
环境信息定性披露	<i>EID_qual</i>	企业报告期内披露的描述性环境信息数量并除以最大值
环境信息定量披露	<i>EID_quan</i>	企业报告期内披露的量化类环境信息数量并除以最大值
解释变量		
绿色基金持股	<i>GF</i>	虚拟变量，若报告期内企业被绿色基金持股，取值为 1；否则为 0
控制变量		
股权集中度	<i>Fshare</i>	企业第一大股东持股比例
企业规模	<i>size</i>	企业年末总资产的自然对数
盈利能力	<i>roa</i>	净利润/总资产
财务杠杆	<i>leverage</i>	总负债/总资产
成长性	<i>growth</i>	营业收入增长率
产权性质	<i>soe</i>	国有性质企业为 1，否则为 0
经营活动现金流量	<i>cash</i>	经营活动产生的现金流/总资产
企业年龄	<i>age</i>	企业成立年限
机构所有权比例	<i>io</i>	除绿色基金之外机构投资者持股比例
董事会规模	<i>board</i>	董事会人数
固定效应		
个体	<i>individual</i>	企业层面的固定效应
时间	<i>year</i>	时间层面的固定效应

表 2 各变量描述性统计

变量	均值	标准差	最小值	最大值	样本数量
<i>EID</i>	0.1277	0.1849	0.0000	1.0000	19755
<i>EID_quan</i>	0.0643	0.1476	0.0000	1.0000	19755
<i>EID_qual</i>	0.1642	0.2253	0.0000	1.0000	19755
<i>GF</i>	0.2267	0.4187	0.0000	1.0000	19755
<i>size</i>	22.2621	1.2985	20.0656	26.2969	19755
<i>roa</i>	0.0459	0.0537	-0.1659	0.2129	19755
<i>growth</i>	0.1696	0.3651	-0.4896	2.1956	19755
<i>soe</i>	0.3582	0.4795	0.0000	1.0000	19755
<i>cash</i>	0.0485	0.0663	-0.1462	0.2353	19755
<i>io</i>	43.7324	24.9018	0.2805	90.6550	19755
<i>Fshare</i>	23.0107	18.0302	0.3659	69.9425	19755
<i>board</i>	8.5922	1.7358	0.0000	18.0000	19755
<i>leverage</i>	0.4158	0.1986	0.0539	0.8508	19755
<i>age</i>	17.2305	5.6905	1.0000	61.0000	19755

四、实证结果及分析

1、描述性统计

表 2 列示了相关变量描述性统计的结果。可以看出，绿色基金持股(*GF*)的均值为 0.2267，意味着

42 只绿色基金的投资范围涵盖大约 22.67%的样本企业，说明绿色基金的投资范围广泛以及投资组合较为分散。环境信息披露质量(*EID*)的均值为 0.1277，且定量披露(*EID_quan*)的均值为 0.0643，表明样本

企业的环境信息披露质量普遍较低。

2、基准回归结果及分析

表 3 列示了基准模型估计结果。第(1)(2)列汇报了绿色基金持股(*GF*)对企业环境信息披露质量(*EID*)的回归结果，无论是否加入控制变量，绿色基金持股对环境信息披露质量的回归系数均在 1%的显著性水平为正，表明绿色基金对被投资企业的环境信息披露质量具有正向影响，绿色基金持股导致企业环境信息披露质量提高 0.78%，假设 1 得到验证。第(3)(4)列汇报了绿色基金持股(*GF*)对企业环境信息定量披露(*EID_quan*)的回归结果，无论是否加

入控制变量，绿色基金持股对企业环境信息定量披露的回归系数均在 1%的显著性水平为正，表明绿色基金对被投资企业的环境信息定量披露具有正向影响，绿色基金持股导致企业环境信息定量披露提高 0.96%，假设 2 得到验证。第(5)(6)列汇报了绿色基金持股(*GF*)对企业环境信息定性披露(*EID_qual*)的回归结果，无论是否加入控制变量，绿色基金持股对企业环境信息定量披露的回归系数均为负数，但是均未达到 10%的显著性水平，因此绿色基金对被投资企业的环境信息定性披露不具有显著影响，假设 3 不成立。

表 3 基准模型估计结果

变量	<i>EID</i>		<i>EID_quan</i>		<i>EID_qual</i>	
	(1)	(2)	(3)	(4)	(5)	(6)
<i>GF</i>	0.0087*** (3.26)	0.0078*** (2.93)	0.0102*** (4.11)	0.0096*** (3.84)	-0.0030 (-0.82)	-0.0037 (-1.04)
<i>control</i>	<i>no</i>	<i>yes</i>	<i>no</i>	<i>yes</i>	<i>no</i>	<i>yes</i>
<i>individual</i>	<i>yes</i>	<i>yes</i>	<i>yes</i>	<i>yes</i>	<i>yes</i>	<i>yes</i>
<i>year</i>	<i>yes</i>	<i>yes</i>	<i>yes</i>	<i>yes</i>	<i>yes</i>	<i>yes</i>
<i>N</i>	19755	19755	19755	19755	19755	19755
<i>Adj R²</i>	0.1115	0.1140	0.0656	0.0678	0.0525	0.0540

注：***、**、*分别表示在 1%、5%、10%的水平上显著，括号内为使用聚类稳健标准误计算的 t 值，下表同。

上述基准模型的回归结果表明，中国的绿色基金可以促进企业披露量化类环境信息，提高企业环境信息披露质量，并在一定程度上促进企业进行实质性披露、缓解环境信息不对称。同时，在当前阶段我国的绿色基金尚不能有效减少企业披露定性类环境信息，绿色基金对企业“漂绿”行为的抑制作用相对有限，须进一步疏通绿色基金股东参与企业环境信息披露治理的机制。

3、稳健性检验

为验证结果的可靠性，本文进行了以下检验：

- (1) 本文将报告期内企业股东中绿色基金个数（绿色基金数量）作为解释变量对基准模型进行再估计；
- (2) 对 2015-2020 年的样本数据进行重新估计；
- (3) 以工业企业样本数据对基准模型进行重新估计；
- (4) 为缓解双向因果及遗漏变量等内生性问题，本文采用两阶段最小二乘法(2SLS)进行工具变量回归，参

考谢德仁等(2016)^[36]的工具变量构建策略，选取了两个工具变量：一是当年同行业的其他企业绿色基金持股(*GF*)的平均值*IndavGF*，二是当年企业同省份的其他企业绿色基金持股(*GF*)的平均值*ProavGF*，后续检验表明上述工具变量不存在弱工具变量、识别不足问题且满足排他性要求。上述检验结果与基准模型结果并无实质差异，表明基准回归结果具有稳健性。受篇幅限制，相关结果不再展示。

五、机制分析与异质性分析

1、机制分析

前文提到绿色基金可以通过参与企业环境信息披露治理直接影响企业的环境信息披露质量，此外，绿色基金还可能通过其他机制间接影响企业的环境信息披露质量。绿色基金可以促进企业积极履行环境责任，提高企业的环境责任表现，姜广省等

(2021)的研究证实了绿色基金的上述作用。环境信息披露是反映企业环境责任状况的重要方式,环境责任表现的提高有利于企业提高环境信息披露质量(沈洪涛等, 2014^[37]; 朱炜等, 2019)。根据信号传递理论, 为避免利益相关者的逆向选择, 环境表现良好的企业为使自己区别于环境表现较差的企业, 更倾向于披露可核实的环境信息, 提高信息披露的可信度和准确性, 向市场传递“绿色”或环境友好信号, 以获得投资者的青睐, 环境责任表现对环境信息披露质量具有正向影响(Clarkson et al., 2008^[38])。因此, 绿色基金可能通过提高企业环境责任表现间接提高环境信息披露质量。

为验证绿色基金是否通过影响企业环境责任表现进一步影响环境信息披露质量, 本文参考Baron and Kenny(1986)^[39]提出的逐步检验法检验中介效应。根据中介效应检验流程(温忠麟和叶宝娟, 2014^[40]), 依次检验各方程主要变量的回归系数。

对于企业环境责任表现(CER), 参考姬新龙(2021)^[41]的做法, 选取CSMAR数据库中的上市公司环境管理披露数据来衡量企业环境责任表现, 共包括8项指标, 分别为环境理念、环境目标、环保管理制度、环保专项行动、环保教育与培训、环境

事件应急机制、环保荣誉或奖励、“三同时”制度, 以上指标均为虚拟变量, 若公司符合某一项取值为1, 不符合或未披露则为0, 将以上8项分数求和并除以8作为企业当年环境责任表现。

表4列示了中介效应模型的估计结果。从表4可以看出, 解释变量(GF)对被解释变量(EID)的系数 a_1 为0.0078, 显著大于0, 说明绿色基金可以提高企业的环境信息披露质量; 解释变量(GF)对中介变量(CER)的系数 b_1 为0.0061, 显著大于0, 说明绿色基金能够提高企业环境责任表现; 解释变量(GF)和中介变量(CER)对被解释变量(EID)的系数 c_1 和 c_2 分别为0.0057和0.3457, 均显著大于0。以上结果表明, 企业环境责任在绿色基金持股与企业环境信息披露质量之间存在部分中介效应。此外, 以环境信息定量披露(EID_quan)为被解释变量的中介效应检验同样得到企业环境责任在绿色基金持股与企业环境信息定量披露之间存在部分中介效应。上述结果表明, 绿色基金不仅可以通过积极参与企业环境信息披露治理促进企业披露更多的量化类环境信息, 直接提高企业的环境信息披露质量, 而且还能通过促进企业积极履行环境责任间接提高企业的环境信息披露质量。

表4 中介效应模型检验结果

变量	(1)		(2)			
	EID	CER	EID	EID_quan	CER	EID_quan
GF	0.0078***	0.0061**	0.0057**	0.0096***	0.0061**	0.0083***
	(2.93)	(2.00)	(2.38)	(3.84)	(2.00)	(3.48)
CER			0.3457***			0.2225***
			(32.19)			(19.51)
control	yes	yes	yes	yes	yes	yes
individual	yes	yes	yes	yes	yes	yes
year	yes	yes	yes	yes	yes	yes
N	19755	19755	19755	19755	19755	19755
Adj R ²	0.1140	0.1169	0.2681	0.0678	0.1169	0.1494

2、异质性分析

(1) 基于产权性质的分析。考虑到企业产权性质不同, 绿色基金对其环境信息披露质量的影响可

能有所差异, 因此本文将样本企业分为国有组别和非国有组别, 并对上述两组样本分别进行回归, 回归结果如表5所示。在国有企业样本中, 绿色基金

持股(*GF*)对环境信息披露质量(*EID*)和环境信息定量披露(*EID_quan*)的系数分别为 0.0111 和 0.0143, 且均在至少 5%的水平上显著; 而非国有企业样本中, 上述系数分别为 0.0062 和 0.0071, 均小于国有企业样本。上述结果表明, 无论是环境信息披露质量还是环境信息定量披露, 绿色基金对国有企业的作用更大, 对非国有企业的作用相对较小。

近年来, 我国政府一直在致力于推动环境保护与绿色发展, 由于与政府具有天然的产权联系, 国有企业更有可能积极响应政府的政策, 积极履行环境责任。因此, 绿色基金通过沟通等方式更容易说服国企管理层积极履行环境责任以及提高环境信息披露质量, 这体现了国有企业在履行环境责任、推动绿色发展上的积极作用, 与近年来我国政府积极推动环境治理和绿色发展的政策意图具有一致性。

表 5 基于产权性质的异质性分析

国有性质	是	否	是	否
变量	<i>EID</i>		<i>EID_quan</i>	
<i>GF</i>	0.0111** (2.22)	0.0062** (2.04)	0.0143*** (2.93)	0.0071** (2.51)
<i>control</i>	yes	yes	yes	yes
<i>individual</i>	yes	yes	yes	yes
<i>year</i>	yes	yes	yes	yes
<i>N</i>	7076	12679	7076	12679
<i>Adj R²</i>	0.0973	0.1353	0.0576	0.0858

(2) 基于行业性质的分析。同样地, 考虑到绿色基金对企业的影响可能因行业性质的不同而表现出差异, 本文进一步探究绿色基金对重污染企业与非重污染企业的影响是否存在差异。参考黎文靖和路晓燕(2015)^[42]的做法区分重污染企业与非重污染企业, 并对重污染企业 and 非重污染企业分别进行回归, 估计结果如表 6 所示。

表 6 基于产权性质的异质性分析

重污染企业	是	否	是	否	是	否
变量	<i>EID</i>	<i>EID_quan</i>	<i>EID_qual</i>			
<i>GF</i>	0.0056 (0.94)	0.0065** (2.44)	0.0117* (1.93)	0.0061*** (2.68)	-0.0154** (-1.99)	0.0018 (0.47)
<i>control</i>	yes	yes	yes	yes	yes	yes
<i>individual</i>	yes	yes	yes	yes	yes	yes
<i>year</i>	yes	yes	yes	yes	yes	yes
<i>N</i>	6483	13272	6483	13272	6483	13272
<i>Adj R²</i>	0.1803	0.0873	0.1266	0.0404	0.0591	0.0583

从表 6 可以看出, 非重污染企业的绿色基金持股(*GF*)对企业环境信息披露质量(*EID*)的系数为 0.0065 (显著性水平为 5%), 大于重污染企业的 0.0056。重污染企业绿色基金持股(*GF*)对环境信息定量披露(*EID_quan*)的系数为 0.0117 (显著性水平为 10%), 大于非重污染企业的 0.0061 (显著性水平为 1%)。重污染企业绿色基金持股(*GF*)对环境信息定量披露(*EID_qual*)的系数为-0.0154, 在 5%的显著性水平上为负, 而非重污染企业的上述回归系数为 0.0018。以上结果表明, 对环境信息披露质量(*EID*)

而言, 绿色基金持股(*GF*)对非重污染企业的正向影响更大, 说明绿色基金更能促进非重污染企业提高环境信息披露质量。具体而言, 绿色基金持股(*GF*)可以促进重污染企业披露更多量化类环境信息, 且减少重污染企业披露描述性环境信息, 表明绿色基金可以抑制重污染企业的“漂绿”行为, 促进其实质性披露环境信息; 绿色基金促进非重污染企业提高环境信息披露质量, 主要是通过促进其披露描述性环境信息、提高环境信息披露水平所致。

六、结论与启示

本文通过研究发现：绿色基金能够促进企业提高企业环境信息披露质量、促进企业披露定量类环境信息，但对企业披露定性类环境信息无显著影响；除直接效应外，绿色基金可以通过提高企业的环境责任表现间接提高环境信息披露质量；相比非国有企业，绿色基金更能促进国有企业提高环境信息披露质量；相比非重污染企业，绿色基金更能促进重污染企业披露实质性环境信息，抑制其“漂绿”行为。总之，绿色基金可以通过参与公司治理提高企业的环境信息披露质量，对促进企业进行实质性披露环境信息以及缓解环境信息不对称、进而在一定程度上抑制企业“漂绿”行为具有积极作用。

基于上述结论，本文得出如下启示：（1）基金管理人应采取成熟的运作模式，借鉴国外成熟的绿色基金，参与被投资企业的环境决策，积极进行投后沟通与管理，建立与利益相关方关于绿色议题的沟通机制，采取多渠道促进企业积极履行环境责任以及提高环境信息披露质量，充分发挥绿色作用；此外，应积极披露绿色信息，制定绿色信息披露标准并定期发布绿色投资评估报告，以使公众了解基金的“绿色性”。（2）政府应进一步推动绿色基金的发展，促进绿色基金数量增加、规模扩大，进而增强绿色基金的影响力与决策话语权，从而更好地发挥绿色作用。具体而言：推动绿色基金法律法规建设，从法律层面上对绿色基金进行定义、制定统一的绿色基金标准，同时明确绿色基金的运作模式、监管机制以及各责任主体的法律责任，规范引导绿色基金发展；进一步扶持绿色基金，可采取税收优惠政策，减轻绿色基金税负，以鼓励绿色基金的设立，从而增加绿色基金数量；建立健全绿色基金评价体系，尤其是环境效益评价体系，科学合理地对基金“绿色性”进行评价，避免基金“漂绿”行为。

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经济政策不确定性下能源与股票市场的网络系统性风险测度

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摘要： 全球经济作为不可拆分的整体，不同类型、地区的市场存在不同程度的系统性风险。能源市场与金融市场作为与国家及个体息息相关的重要市场，其在全球经济环境中的系统性风险贡献或暴露程度测度研究十分重要。本文以原油、天然气代表能源市场，以全球主要经济体的特征股指代表金融市场，共选取 17 个市场进行双向、交叉条件风险价值研究。为研究低频经济政策不确定性信息对市场极端风险预测的贡献，本文利用分位数回归模型及混频数据处理模型构建 QR-MV-GARCH-MIDAS 模型，进行 VaR、CoVaR、 ΔCoVaR 的预测分析。为直观展示贡献或暴露 ΔCoVaR 对各市场的影响幅度，创建 ΔCoVaR -Ratio 百分比指标，便于形成网络状系统性风险冲击图。研究结果表明，经济政策不确定性指数可有效提升原油市场间风险预测精度；原油、天然气与股票市场间存在不同程度的风险溢出关系，股票市场间的网络系统性风险较能源市场更加活跃，以美国股票市场最为显著，中国上证指数表现的风险贡献与暴露程度均相对较小；能源市场中 WTI 期货与天然气期货市场对现货市场具有显著系统性风险贡献。该研究可为国家战略投资与风险管控、能源安全与储备等方面提供系统性风险预警信息。

关键词： 网络系统性风险，经济政策不确定性， ΔCoVaR -Ratio 指标，市场风险预测

Network Systematic Risk Measures for Energy and Equity Markets under Economic Policy Uncertainty

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Abstract: The global economy is an indivisible whole. There are different degrees of system risk between different types and regions of markets. It is significant to research the contribution- or exposure-system risk of energy and financial markets in the global economy, as closely related to countries and individuals. In this article, 17 markets are chosen from crude oil markets, nature gas markets and characteristic stock indices of major global economies, to represent energy markets and financial markets respectively, for bidirectional and crossed risk analysis. To get the influence of Global Economic Policy Uncertainty (GEPU) involved in the extreme risk forecasting, the modeling idea of Quantile Regression and Mixed Data Sampling is adopted; and the new QR-MV-GARCH-MIDAS model is created to forecast the VaR, CoVaR and ΔCoVaR . To reduce the dimension of the contribution- or exposure- ΔCoVaR to each market, the ΔCoVaR -Ratio% indicator is designed to visualize the network systemic risk map. The results show that, GEPU index can effectively improve the risk forecasting accuracy of crude oil markets. Crude oil, natural gas and stock markets have different levels of risk spillover. The network systemic risk relationships between stock markets, with U.S. S&P500 index as the most dynamic and China's SSEC index under least shock, are more active than that among energy markets. The WTI futures and natural gas futures markets have significant systemic risk contribution to the spot markets. The study is capable of offering systemic risk warning information for national strategic investment and control, energy security and reserves.

Key Words: Network system risk, GEPU, ΔCoVaR -Ratio, market risk forecasting

一、引言和文献综述

能源市场与股票市场作为全球经济活动中活跃板块,其价格波动、风险传导具有较广泛的影响,因此其系统性风险监测与防控也尤为重要。能源市场,以原油与天然气市场为代表,其供应量与价格波动影响着相关国家与地区的能源安全与经济成本,影响投资者决策,从而波及资本活跃的股票市场出现价格波动甚至是应激风险。反向,股票,作为国家或地区金融风险的风向标,也给能源市场带来不同程度的冲击。同时,这两类市场均存在于全球宏观经济、政治、公共安全与卫生等市场环境因素(后简称“宏观因素”)的影响下,因此其风险预测过程不可排除宏观因素而独立完成。

以原油市场与股票市场为例,在宏观因素与跨市场风险传导影响下,原油市场的价格走势可谓一波三折。1997-2000年的亚洲金融危机与复苏时期,原油价格走势呈V型反转;2008-2014年金融危机与复苏,再次出现V型反转;2018年至今的贸易摩擦、COVID-19疫情、价格战的混合效应,出现史诗级暴跌,2020年4月20日,美国西得克萨斯轻质原油(WTI)期货收盘-37.63美元/桶。美股也在2020年3月期间出现4次熔断,美国股市的这段震动对部分国家地区的股票市场也带来紧张情绪与价格波动,系统性风险特征显著。

因此,以考虑宏观因素影响为前提,分析测度极端风险状态下能源与股票市场的相互风险溢出关系、理清不同能源与股票市场间辐射状或网络状系统性风险测度研究变得更加迫切。本文旨在探索更具理论与实证依据的方法、更精确的风险预判结果,为国家战略投资与管控、能源与外汇储备等方面提供系统性风险预警信息。

现有的系统性金融风险的研究方法以CoVaR方法最受欢迎,SES/MES方法及SRISK方法等也从不同角度度量系统性风险。Adrian和Brunnermeier(2016)^[1]提出的“条件风险价值”(Conditional Value at Risk, CoVaR)指标及 ΔCoVaR 指标,是在VaR的基础上改进为当系统或其他机构处于风险状态时,自身的风险价值及变化,由于其

灵活的设计捕获了财务回报之间的非线性尾部依赖结构。Girardi和Ergun(2013)^[2]应用多元GARCH模型估计了CoVaR模型,度量了美国银行、保险、证券和非借贷类金融部门的系统性风险贡献,结果显示银行部门对金融系统的风险贡献更大。近期研究还有Michele和Alberto(2020)^[3];Tiwari等(2021)^[4]。除CoVaR方法外,Acharya等(2010)^[5]提出了“系统性预期短缺”(Systemic Expected Shortfall, SES)方法与“边际预期不足”(Marginal Expected Shortfall, MES)方法。范小云等(2011)^[6]使用MES和SES方法度量了美国次贷危机期间以及危机前后,中国金融机构对金融系统的边际风险贡献程度。赵进文等(2013)^[7]比较了MES模型和CoVaR模型这两种方法,并针对我国14家上市银行进行实证分析。SES可以作为特定时点金融机构风险暴露的一种度量。为更好同质比较系统性风险大小,Brownlees和Engel(2017)^[8]基于流动性不足理论提出的SRISK指标,侧重于测量重要性个体机构对于整体风险的贡献。Brownlees等(2020)^[9]对8次金融恐慌期间进行CoVaR和SRISK的表现,发现CoVaR和SRISK满足了系统重要性金融机构(SIFI)排名的挑战,且在危机爆发前半年协助甄别处于危机时期的系统性机构。

更多的系统性风险实证研究关注市场内机构间的风险传染效应,如Acharya等(2012)^[10]、宫晓莉等(2020)^[11],但在各能源市场与金融市场的系统性风险研究方面,更关注以市场为单位的不同地区、类型市场间风险的冲击与传染。已有各有侧重的诸多研究,如Turhan等(2014)^[12]揭示在2008年全球金融危机之后,原油、股票和债券市场之间的正相关性几乎是瞬时上升的。Li和Wei(2018)^[13]的研究结果表明金融危机加剧了原油市场与中国股票市场的依赖关系金融危机。Yuan和Yang(2020)^[14]探索金融市场与碳市场间的风险溢出关系。相关研究还有Tiwari(2020)^[15],Salisu和Gupta(2021)^[16],Liu等(2021)^[17],Riza等(2020)^[18],Zhang(2017)^[19],Petrella等(2019)^[20],Tiana和Ji(2022)^[21]。现有的市场间风险溢出关系尚有

可改进优化之处,如 Yang 等 (2021) [22] 的研究仅基于 GARCH 族以 VaR 为基础建立联结网络来衡量上行和下行风险溢出,并不能体现 CoVaR 方法的条件风险水平。且现有研究中少有考虑宏观因素对多市场风险溢出或依赖关系研究的共同影响。

能源与金融市场面临的宏观因素很多,涉及经济政策、地缘政治、汇率波动等。经济政策不确定性作为有关经济状态与政策导向的指向性指标,已在诸多研究中应用。如, Fang 等 (2018) [23] 研究了受 EPU 影响的原油和美国股市的长期时变相关性,发现 EPU 对石油库存的长期相关性有显著的正向影响。Ma 等 (2019) [24] 的研究表明 EPU 对原油收益率波动有显著的正向影响,并分别研究了不同国家地区 EPU 指数的影响效果。Liang 等 (2020) [25] 的研究结果表明 GEPV 和美国股市波动率指数 (EMV) 对原油市场波动具有显著的预测能力。

本文旨在考虑经济政策不确定性下研究主要能源与金融市场间的风险溢出关系与系统性风险测度。能源市场主要包含原油、天然气、煤炭、电力、碳市场等,其中原油与天然气市场尤为活跃,碳市场在近年兴起,仍在起步与成长阶段。金融市场以股票市场最为活跃,且有较广泛的行业代表性。以原油、天然气、股票市场为代表的系统性风险研究有利于跨市场投资者择选市场进行风险规避。

本文剩余部分结构安排如下:第二节介绍 QR-MV-GARCH-MIDAS-CoVaR 模型构建过程;第三节描述具体研究对象与所用数据;第四节分析实证结果;第五节总结。

二、模型介绍

本文构建的 QR-MV-GARCH-MIDAS-CoVaR 模型,以 GARCH-MIDAS 模型、多变量 CAViaR 模型、CoVaR 方法融合而成。为清晰阐述本文模型的构建原理,本节先从时间序列 GARCH 模型

与混频数据处理的 MIDAS 模型结合、分位数回归模型的加入、向量自回归结构的叠加,逐步阐述模型构建过程;再结合现有的 CoVaR、 ΔCoVaR 方法及设计的 ΔCoVaR -Ratio 指标,分段介绍理论模型构建过程。

1、QR-MV-GARCH-MIDAS 模型构建过程

(1) 以 GARCH-MIDAS 模型为理论基础

Engle 等 (2013) [26] 得出一种方法,将波动率描述为长期成分和短期成分的组合,并使其参与自回归过程,应用于以收益率为代表的时间序列数据:

$$r_{it} = \mu + \sqrt{\tau_t g_{it}} \epsilon_{it} \quad (1)$$

公式中, τ_t 代表第 t 月波动率的长期成分, g_{it}

是第 t 月、第 i 天的波动率短期成分,这里令:

$$\begin{aligned} \tau_t^{\frac{1}{2}} &= \exp(m + \theta \sum_{k=1}^K \varphi_k(\omega) X_{t-k}), \quad (2) \\ g_{it}^{\frac{1}{2}} &= \alpha + \beta \frac{|r_{i-1,t} - \mu|}{\tau_t^{\frac{1}{2}}} + \gamma g_{i-1,t}^{\frac{1}{2}}. \quad (3) \end{aligned}$$

其中, $\varphi_k(\omega)$ 是简化的 Beta 权重函数,公式为:

$$\varphi_k(\omega) = \frac{\left(1 - \frac{k}{K}\right)^{\omega-1}}{\sum_{j=1}^K \left(1 - \frac{j}{K}\right)^{\omega-1}}. \quad (4)$$

该模型对混频信息的处理方法在本文后续模型演变中具有指导意义。

(2) 从 CAViaR 到 QR-GARCH-MIDAS 模型

早期的 GARCH-MIDAS 模型建立在均值-方差框架下,需要对残差的分布进行假设,无疑会增加假设偏误的几率。在研究极端风险时,分位数回归方法可以避免对时间序列的整体建模。于是,当设定分位数水平为 $\xi\%$, 公式 (1) 可改写成分位数回归表达式:

$$Q_{\xi}(r_{it} | \Psi_{i-1}) - \mu = \sqrt{\tau_t g_{it}} F_{\xi}^{-1}(\epsilon_{it}). \quad (5)$$

Engle 和 Manganeli (2004) [28] 直接用分位数回归方法对风险价值进行建模,并采用自回归过程来

³ r_{it} 是第 t 月、第 i 天的收益率, $i = 1, \dots, n_t$, n_t 为第 t 月最大天数, $t = 1, \dots, T$, T 为样本月份总数; ϵ_{it} 是独立同分布 (i.i.d.) 且服从均值为 0、方差为 1 的未知分布 $F(\epsilon_{it})$ 。 μ 为收益率的均值。

⁴ $\exp()$ 指数式结构是为了确保 τ_t 为正; X_t 是第 t 月的外生变量; K 为 X 可参与预测 r_{it} 的最大滞后月数,可固定或使用优化算法提前算出。

⁵ 公式参考 Zakoian (1994) [27]; $r_{i-1,t}$ 代表上一天的收

益率, $r_{n_{t-1},t-1}$ 表示上个月最后一天的收益率。为简化后方公式,在月首日 ($i = 1$) 用 $r_{i-1,t}$ 替代表示 $r_{n_{t-1},t-1}$ 。

⁶ Ψ_{i-1} 是第 $i-1$ 天的信息集。 $F_{\xi}^{-1}(\epsilon_{it})$ 是 ϵ_{it} 在 ξ 分位水平的分位数; 由于假定 ϵ_{it} 独立同分布, 当 ξ 固定时可简化为常数值 $F_{\xi}^{-1}(\epsilon)$ 。根据市场收益率的分布特征, 通常假定参数 μ 为 0。 K 在后方模型中均需提前固定或优化求解。

描述分位数随时间的演变。这个条件自回归风险价值（CAViaR）模型的对称绝对值方程为：

$$f_t(\beta) = \beta_1 + \beta_2 f_{t-1}(\beta) + \beta_3 |y_{t-1}|。^7 (6)$$

因此 Xu 等（2021）^[29]在上述模型基础上推导出单一因变量分位数框架下的 GARCH-MIDAS 模型，简称 QR-GARCH-MIDAS 模型，公式如下：

$$Q_\xi(r_{it}|\psi_{i-1}) = c * \exp\left(\theta \sum_{k=1}^K \phi_k(w) X_{t-k}\right) + \exp\left(\theta \sum_{k=1}^K \phi_k(w) \Delta X_{t-k}\right) * [a * Q_\xi(r_{i-1,t}|\psi_{i-2}) + b * |r_{i-1,t}|]。^8 (7)$$

（3）吸收向量自回归模型结构

在分位数回归框架下，White 等（2015）^[30]建立了一个多变量、多分位模型——MVMQ-CAViaR 模型，以分析不同随机变量之间的尾部相互溢出关系。其向量版表达式与公式（6）相似：

$$q_t = c + Aq_{t-1} + B|r_{t-1}|。^9 (8)$$

为了融入混合频率数据，本文从一个简单的双变量形式开始：

$$\begin{aligned} q_{1t} &= c_1 + a_{11}q_{1t-1} + a_{12}q_{2t-1} \\ &\quad + b_{11}|r_{1t-1}| + b_{12}|r_{2t-1}|, \\ q_{2t} &= c_2 + a_{21}q_{1t-1} + a_{22}q_{2t-1} \\ &\quad + b_{21}|r_{1t-1}| + b_{22}|r_{2t-1}|。 \end{aligned} (9)$$

并在公式（7）（9）的基础上推导出 QR-MV-GARCH-MIDAS 模型：

$$\begin{aligned} q_{i,t}^1 &= c_1 \exp\left(\theta_1 \sum_{k=1}^K \phi_k(\omega_1) X_{t-k}\right) \\ &\quad + \exp\left(\theta_1 \sum_{k=1}^K \phi_k(\omega_1) \Delta X_{t-k}\right) \\ &\quad * \left[a_{11} q_{i-1,t}^1 + a_{12} q_{i-1,t}^2 \right. \\ &\quad \left. + b_{11} |r_{i-1,t}^1| + b_{12} |r_{i-1,t}^2| \right], \\ q_{i,t}^2 &= c_2 \exp\left(\theta_2 \sum_{k=1}^K \phi_k(\omega_2) X_{t-k}\right) \end{aligned}$$

⁷ β 是参数矩阵， y 是随机变量，如资产收益率。

⁸ a, b, c, θ, ω 均为待估参数；当 $i > 1$ 时，

$\exp(\theta \sum_{k=1}^K \phi(w) \Delta x_{t-k}) = 1$ 。

⁹ r_{t-1} 是目标的资产收益率， q_t 是分位值或称为风险价值， A, B and c 是待估参数矩阵。

¹⁰ $q_{i,t}^1$ 为 $Q_\xi(r_{it}|\psi_{i-1})$ 的简化表达形式，上标 1 表示第 1

$$+ \exp\left(\theta_2 \sum_{k=1}^K \phi_k(\omega_2) \Delta X_{t-k}\right) * \left[a_{21} q_{i-1,t}^1 + a_{22} q_{i-1,t}^2 \right. \\ \left. + b_{21} |r_{i-1,t}^1| + b_{22} |r_{i-1,t}^2| \right]。^{10} (10)$$

此新模型既是 GARCH-MIDAS 模型在分位数回归框架下的多变量拓展，也可视为 MVMQ-CAViaR 模型纳入混频数据处理模型的优化方法。

根据 Koenker 和 Bassett（1978）^[31]，最优参数可以通过最小化分位数回归方程得到，具体如下：

$$\text{Min}_{\theta} \sum_{t=1}^T \sum_{i=1}^{n_t} \rho(R_{it} - Q_\xi(r_{it}|\Psi_{t-1}))。^{11} (11)$$

2、CoVaR 和 ΔCoVaR 模型

Adrian 和 Brunnermeier（2016）^[1]创造性的提出 CoVaR 与 ΔCoVaR ，以度量具有依赖与传染特征的系统性风险：

$$\text{CoVaR}_\xi^i = \text{VaR}_\xi^{\text{system}} | x^i = \text{VaR}_\xi^i。 (12)$$

ΔCoVaR 定义为在某个金融机构相对于中值状态落入困境时，金融系统因此发生的风险价值变化：

$$\Delta\text{CoVaR}_\xi^i = \text{CoVaR}_\xi^i - \text{CoVaR}_\xi^{\text{system}} | \text{VaR}_{50}^i (13)$$

CoVaR 的概念不局限于上述表达的机构 i 对金融系统做出的条件风险“贡献”（Contribution），即 $\text{CoVaR}_\xi^{\text{system} | i}$ ，另有从反向角度，机构 i 暴露于处于风险状态系统中的“暴露”（Exposure）风险，即 $\text{CoVaR}_\xi^{i | \text{system}}$ ，与从双向角度的两两机构间的“网络”（Network）条件风险，即 $\text{CoVaR}_\xi^{i | j}$ 。

本研究借鉴网络条件风险的概念，将系统性测度指标 CoVaR 与 ΔCoVaR 融入构建的 QR-MV-GARCH-MIDAS 模型中，可得含有混频信息的两两机构或市场的系统性风险测度指标：

$$\begin{aligned} \text{CoVaR}_{i,t}^1 &= c_1 \exp\left(\theta_1 \sum_{k=1}^K \phi_k(\omega_1) X_{t-k}\right) \\ &\quad + \exp\left(\theta_1 \sum_{k=1}^K \phi_k(\omega_1) \Delta X_{t-k}\right) \\ &\quad * \left[a_{11} \text{VaR}_{i-1,t}^1 + a_{12} \text{VaR}_{i-1,t}^2 \right. \\ &\quad \left. + b_{11} |r_{i-1,t}^1| + b_{12} |\text{VaR}_{i-1,t}^2| \right], \\ \text{CoVaR}_{i,t}^2 &= c_2 \exp\left(\theta_2 \sum_{k=1}^K \phi_k(\omega_2) X_{t-k}\right) \end{aligned}$$

个因变量， $c_1, c_2, a_1, a_2, b_1, b_2, \theta_1, \theta_2, \omega_1, \omega_2$ 均为待估参数；当 $i > 1$ 时，即非月首日，乘子部分

$\exp(\theta_1 \text{ or } \theta_2 \sum_{k=1}^K \phi_k(\omega_1 \text{ or } \omega_2) \Delta X_{t-k})$ 值为 1，可忽略。

¹¹ $\theta = (c_1, c_2, a_1, a_2, b_1, b_2, \theta_1, \theta_2, \omega_1, \omega_2)$ 为参数矩阵， $\rho(v) = (\xi - I(v < 0))v$ ， $I(\cdot)$ 为示性函数。

$$+ \exp(\theta_2 \sum_{k=1}^K \phi_k(\omega_2) \Delta X_{t-k})$$

$$* \left[\begin{array}{l} a_{21} VaR_{i-1,t}^1 + a_{22} VaR_{i-1,t}^2 \\ + b_{21} |VaR_{i-1,t}^1| + b_{22} |r_{i-1,t}^2| \end{array} \right]^{12}$$

(14)

进一步可得：

$$\Delta CoVaR_{i,t}^1 = CoVaR_{i,t}^1 - CoVaR_{i,t}^{1,r_2=VaR_{\xi=50}}$$

$$= b_{12} \left(|VaR_{i-1,t}^2| - |VaR_{i-1,t}^{2,\xi=50}| \right),$$

$$\Delta CoVaR_{i,t}^2 = CoVaR_{i,t}^2 - CoVaR_{i,t}^{2,r_1=VaR_{\xi=50}}$$

$$= b_{21} \left(|VaR_{i-1,t}^1| - |VaR_{i-1,t}^{1,\xi=50}| \right)。$$

(15)

3、 $\Delta CoVaR$ -Ratio 指标

$\Delta CoVaR$ 的量级仍与 VaR 的量级大小有关，为了将不同市场放在一起比较外部风险冲击的程度，本文创建表达冲击百分比的 $\Delta CoVaR$ -Ratio 指标，消除风险量级对冲击程度指标的影响，公式如下：

$$\Delta CoVaR_Ratio^1 = \Delta CoVaR_{i,t}^1 / CoVaR_{i,t}^{1,r_2=VaR_{\xi=50}}。$$

表 1：日度收益率的描述性统计

Markets	Mean	Max	Min	Std. Dev.	Skewness	Kurtosis	Q(15)	Q(25)
WTI_FUT	0.011	16.410	-16.545	2.368	-0.110	7.151	30.632	45.758
WTI_SPOT	0.011	16.414	-17.092	2.429	-0.131	7.424	43.446	53.186
BRENT_FUT	0.014	13.639	-14.437	2.196	-0.170	6.192	40.602	55.932
BRENT_SPOT	0.014	18.130	-19.891	2.249	-0.152	7.914	36.867	50.281
NATUREGAS_FUT	-0.006	32.435	-19.899	3.384	0.545	8.942	40.709	57.182
NATUREGAS_SPOT	-0.005	57.666	-56.818	4.573	0.725	26.016	240.530	263.850
S&P500	0.014	10.957	-9.470	1.193	-0.249	11.562	85.457	136.600
FTSE 100	-0.001	9.384	-9.266	1.161	-0.146	9.395	76.233	94.625
NIKKEI 225	0.002	13.235	-12.111	1.464	-0.441	10.016	13.498	23.497
S&P/ASX 200	0.014	5.628	-10.261	0.986	-0.616	10.558	33.666	45.060
DAX 30	0.011	10.797	-12.631	1.475	-0.158	8.500	52.154	63.239
CAC 40	-0.002	10.595	-11.450	1.431	-0.121	8.715	73.700	90.565
TSX 300	0.013	9.370	-9.788	1.068	-0.666	13.513	72.486	98.433
RTS	0.043	20.204	-21.199	2.133	-0.351	12.837	79.273	100.110
KOSPI	0.014	11.284	-13.270	1.475	-0.555	10.885	24.730	39.463
SENSEX 30	0.040	15.990	-12.796	1.446	-0.305	12.928	65.833	96.201
SSEC	0.015	9.401	-12.764	1.544	-0.422	9.060	54.007	83.298

注：加粗统计量表示在 1% 统计水平上显著。Q(15) 和 Q(25) 分别指滞后阶数为 15 和 25 的 Ljung-Box 自相关检验统计量。

三、数据描述

本文选取的全球原油、天然气的市场有：WTI 现货、期货，布伦特现货、期货，天然气亨利港现货、纽约商品交易所天然气期货；股票市场选取重要地区标志性股指收盘价，如美国标普 500、英国富时 100、日经 225、澳洲标普 200、德国 DAX、法国 CAC40、多伦多 300、俄罗斯 RTS 指数、韩国综合指数、印度 SENSEX30、中国上证指数。共 17 个目标市场进行风险溢出与系统性风险研究。经济政策不确定性选择全球经济政策不确定性指数 GEPU 指数，因其在已有单一原油、股票等市场预测中的良好表现 (Ma 等, 2019^[24]; Wang 等, 2021^[32])。数据区间选择 2000 年 1 月至 2020 年 2 月，共 5031 日数据、对应 242 个月数据，其中 2019 年 1 月至 2020 年 2 月用于样本外预测，550 个日数据、对应 26 个月数据。

¹² 为简化公式，分位水平 $\xi\%$ 省略，可设为 1%、5% 等。当 $i > 1$ ， $\exp(\theta_1 \sum_{k=1}^K \phi_k(\omega_1) \Delta X_{t-k}) = 1$ ，第 2 行公

式同。

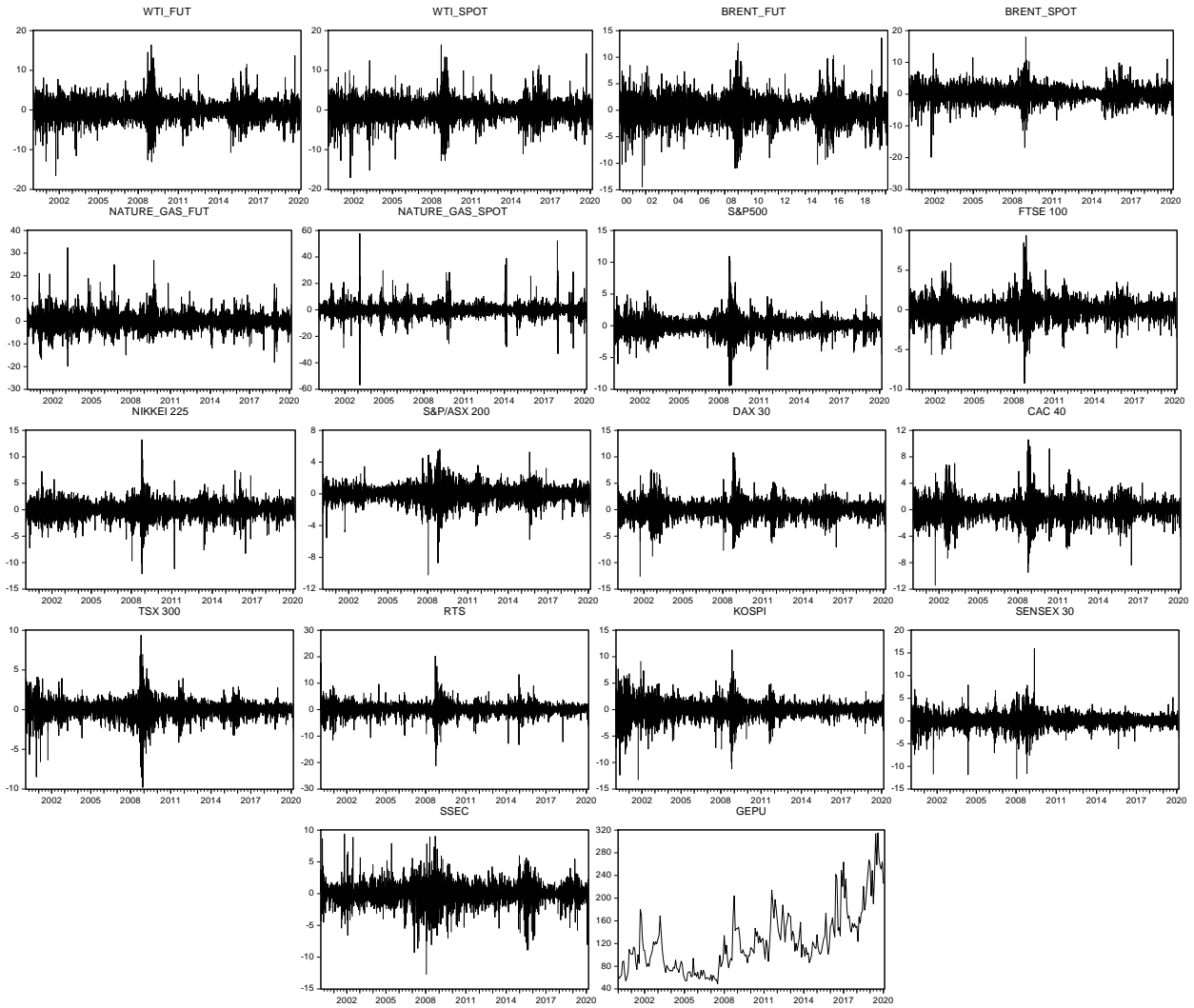


图 1：目标 17 个市场日度收益率及月度 GEP 指数时间序列图

如表 1 所示，所选的市场收益率序列均存在一定偏度，所有峰度系数均大于 6，说明相对于正态分布而言，所有市场收益率序列有尖峰后尾现象。除 N225 股指、KOSPI 股指外，其他市场收益率的自相关检验统计量 Q 均在滞后 15 阶和 25 阶显著，说明市场波动率时间序列存在显著的自相关性，支持下文以 GARCH 模型基础模型继续分析的合理性。此外，图 1 绘制了 17 个市场收益率的时间序列图，图像显示这些市场收益率均具有波动聚集性，且高波动区间常与宏观经济震荡期重合。

四、实证分析

1、原油、天然气与股票市场间风险溢出关系分析

本文利用新构建的 MV-QR-GARCH-MIDAS 模型，对以原油、天然气为代表的能源期货、现货市场，以 11 个国家代表性股指为代表的金融市场，共

17 个重要市场，采用分位数回归方法对两两市场进行 VaR 求解，再通过条件风险价值公式求两市场的 CoVaR 及 Δ CoVaR 数值。17 个市场两两测算共 136 种结果，以 WTI 期货市场（作为第一个目标市场）与其他 16 个市场（分别作为第二个目标市场）两两测度（1% 风险水平）为例重点分析。外生宏观变量选择单一 GEP 指数为代表。最长滞后阶数（月数） K 首先由以 BIC 指标为目标优化求解，这里设定为 24。实证分析主要体现在以下四个方面：

（1）市场间风险溢出关系。由表 2 可知，第一， a_{11} 、 a_{22} 本市场滞后一阶 VaR 的参数， a_{12} 、 a_{21} 交叉市场滞后一阶 VaR 的参数基本显著，说明 WTI 期货市场与其他 16 个市场的风险价值存在明显的风险溢出关系。 b_{11} 、 b_{22} 本市场滞后一阶市场收益率的参数大部分显著， b_{12} 、 b_{21} 交叉市场滞后

一阶收益率的参数部分显著,其中 WTI 期货与 WTI 现货、布伦特期货市场的交叉参数 b_{12} 、 b_{21} 显著性良好,说明同类市场间的风险价值与滞后一阶市场收益率具有更好的相关性。

(2) 低频变量影响的差异。参数 θ 与 ω 体现外生低频或混频变量对目标市场的影响程度, θ 的量级这里受到外生变量 GEPu 指数的量级影响, ω 在一定程度上体现外生变量对目标风险价值的影响程度。在第二个目标市场切换时, WTI 期货市场的 ω_1 也因回归优化的特性而略有变动。当第二个目标收益率为各国股指时, ω_1 与 ω_2 基本 50 以上数值,由图 2 可知 ω 值越大,权重衰减越快,对应更近滞后期的外生变量信息的影响力占比更大、远期信息影响力微弱。而澳大利亚、俄国、印度股指对应的 ω_2 数值接近于 1,说明 GEPu 对澳、俄、印股指的影响持续时间较长,对其他股指的影响主要体现在近一个月的历史信息的冲击。

(3) 样本外预测与后验测试。本文利用 QR-MV-GARCH-MIDAS 模型进行了样本外数据预测,并采用击穿比 (Hit ratio) 指标、动态分位数 (Dynamic Quantile, DQ) 检验^[28]、似然比 (Likelihood Ratio, LR) 检验^[33]进行后验测试。由于采用 1% 的风险水平,如表 2, Hit ratio 的样本内结果十分接近于 1%; 样本外预测,与 WTI 现货市场、与布伦特期货市场分别组合的 Hit ratio 数值更接近于 1%,天然气期货与现货市场结果次之;与股票市场组合的数据接近 2%,其中加拿大、俄国、澳大利亚的数值最大,表现出预测结果可能低估了其风险价值。样本内数据均通过 DQ 检验。另本文还采用了三种 LR 方法无条件覆盖检验(LR_uc)、独立性检验(LR_ind)和条件覆盖检验(LR_cc)同时对模型结果进行检验,所有结果均通过 LRind 检验,绝大部分市场结果也通过 LRuc 及 LRcc 检验,模型适用性良好。

(4) ΔCoVaR 与 $\Delta\text{CoVaR-Ratio}$ 的特征与差异。表 2 中还列示了两两市场的 VaR、CoVaR、 ΔCoVaR 时间序列结果的均值,可从整体了解风险大小、条件风险变化等,但均值无法体现数据波动的幅度与

时变特征。图 3 (图 a、c 属于第一目标市场 WTI 期货,图 b、d 属于第二目标市场 S&P500) 中展示了 WTI 期货与 S&P500 市场收益率的 $\text{CoVaR}_{1\%}$ 、 $\text{CoVaR}_{50\%}$ 、 ΔCoVaR 、 $\Delta\text{CoVaR-Ratio}$ 的时变特征,可见前三个指标的波动方向大体同步,在前三个指标表现风险加剧的同时, $\Delta\text{CoVaR-Ratio}$ 指标也出现大幅波动。除此之外,表 2 中,布伦特现货与天然气期货的 ΔCoVaR 均值分别为 -2.582 和 -2.985,数值相近,但 CoVaR 数值分别为 -6.865 和 -12.427,将近两倍的数值差异; ΔCoVaR 代表条件风险的变化值而不是变化率,不便直接对比一个市场的风险状态对另一个市场的冲击程度百分比,仅用 ΔCoVaR 这一差额数值无法真实表现风险冲击的水平差异,此时 $\Delta\text{CoVaR-Ratio}$ 可起到去量纲的效果。

2、经济政策不确定性对风险预测的影响效果分析

为了研究经济政策不确定性对两两市场条件风险的影响,首先关注对单一市场的影响检验。在单一市场的风险测度中,Xu 等 (2021)^[24]使用原油期货、现货市场数据比较了不含 GEPu 指数影响的 CAViaR 模型与含该指数的 QR-GARCH-MIDAS 模型进行比较,结果证明 GEPu 指数的低频变量加入可以有效提高单一 WTI 期货市场的风险预测水平。

为对比混频数据处理模型对风险预测结果的影响,选择不含混频数据的 MVMQ-CAViaR 模型与含 MIDAS 混频数据处理方法的 QR-MV-GARCH-MIDAS 模型进行两两市场风险预测分析。为了突出与上述单一市场测度比较的同质性,本次两两市场选择 WTI 期货市场与 WTI 现货市场组合、WTI 期货市场与布伦特期货市场组合、WTI 期货市场与布伦特现货市场组合,三组进行验证。

如表 3,样本外预测结果中,含 MIDAS 模型的 Hit ratio 指标明显小于不含 MIDAS 结果的指标值,更接近于 1% 的风险水平设定值。根据样本外 DQ 检验结果,含 MIDAS 模型在 WTI 现货组与布伦特现货组中适用性更好。LR 检验结果中,两种模型均通过 LR_ind 检验,但在 LR_uc、LR_cc 检验中,仅有含 MIDAS 模型通过检验。综上,经济政策不确定性的加入可有效提高原油市场间条件风险价值预

测水平。

3、多市场网络状系统性风险分析

本文进行 GEPU 影响下两两市场风险溢出关系分析,进一步研究多个能源、股票市场间的辐射状、甚至网络状风险关系。如图 4 左图,以 WTI 期货市场为第一目标市场,参考 ΔCoVaR 数值设定辐射线粗细与箭头大小,箭头为风险冲击方向,直观表现辐射状风险冲击关系。由图可知,当 WTI 期货市场处于风险状态,布伦特现货市场收益率风险受到的冲击可能最大,天然气现货市场、美国 S&P500、俄国 RTS 等次之。WTI 期货市场是全球主要的原油期货市场,布伦特现货市场占全球原油现货交易的主导地位;由于期货的交易先于现货交割,期货市场表现出具有“价格发现”功能,结果中显示的 WTI 期货市场对布伦特现货市场的突出风险冲击符合现实情况。天然气作为原油的关联商品,故其现货市场也会受到 WTI 期货的明显冲击;美国与俄国作为原油与天然气的主要出口国,其股票市场同样面临风险传染效应。

除了由点出发向外辐射的贡献系统性风险 (Contribution- ΔCoVaR) 表达外,另有暴露 ΔCoVaR (Exposure- ΔCoVaR) 的概念可借鉴表达为以点为

目标的承受系统性风险的程度。以此类推,网络 ΔCoVaR (Network- ΔCoVaR) 更能表现更多市场的相互风险贡献与暴露程度。由于每个市场的基础风险水平不同, CoVaR 与 ΔCoVaR 的大小也会因此不同,无法更直观的表达其他市场受到风险冲击的百分比程度。故采用 ΔCoVaR -Ratio 指标绘制多市场、双向、网络状系统性风险状态图。

如图 4 右图所示,第一,股票市场间存在着较为活跃的风险传染关系,尤其是 S&P500 的风险贡献最强,如对英国、日本、印度、韩国股票市场等影响显著,其中对澳大利亚股指的影响幅度最大; S&P500 对能源市场的风险冲击相对股票市场较小; S&P500 受到的暴露风险也不可忽视,其中来自英国及韩国股市的风险冲击最大。第二,天然气期货市场对其现货市场表现出单向强烈冲击。第三,WTI 期货市场对布伦特现货市场的影响程度大于布伦特期货市场的影响,可见原油期货市场中 WTI 占据较为主导的地位,WTI 现货市场的风险贡献与暴露相对较小。第四,从暴露风险的角度来看,日本、澳大利亚、韩国、印度、加拿大等股票市场受到系统性风险相对集中。第五,17 个市场中,中国上证指数与其他市场间的风险贡献与暴露相对最小。

表 2: QR-MV-GARCH-MIDAS 模型的样本内估计与样本外检验结果

WTI_FUT:	WTI_SPOT	BRENT_FUT	BRENT_SPOT	N_GAS_FUT	N_GAS_SPOT	S&P 500	FTSE 100	N225	S&P/A SX200	DAX 30	CAC 40	TSX 300	RTS	KOSPI	SEN SEX30	SSEC
a11	0.449	0.428	0.724	0.924	0.496	0.846	0.876	0.949	0.592	0.861	0.401	0.663	0.916	0.470	0.952	0.934
a12	0.372	0.412	0.187	0.032	0.196	0.013	0.000	0.018	0.428	0.004	0.761	0.353	0.000	0.338	0.003	0.000
a21	0.588	0.349	0.553	0.033	0.461	0.012	0.061	0.020	0.286	0.061	0.299	0.307	0.035	0.640	0.003	0.002
a22	0.297	0.497	0.275	0.905	0.450	0.889	0.824	0.808	0.232	0.839	0.350	0.347	0.828	0.214	0.893	0.974
b11	-0.154	-0.334	-0.126	-0.157	-0.312	-0.226	-0.216	-0.116	-0.271	-0.250	-0.292	-0.215	-0.141	-0.211	-0.111	-0.121
b12	-0.094	0.000	-0.052	0.056	0.089	-0.169	-0.117	0.048	-0.125	-0.085	-0.005	-0.181	-0.053	-0.531	0.018	-0.032
b21	-0.133	-0.190	-0.483	0.085	-0.536	-0.019	0.058	0.003	-0.065	0.046	-0.023	0.059	-0.052	-0.073	-0.020	0.015
b22	-0.216	-0.044	0.163	-0.215	-0.741	-0.203	-0.334	-0.414	-0.512	-0.282	-0.369	-0.431	-0.385	-0.064	-0.278	-0.115
c1	-0.323	-0.238	-0.194	-0.030	-0.374	-0.195	-0.150	-0.042	-0.348	-0.165	0.036	-0.366	-0.116	-0.623	-0.051	-0.077
c2	-0.132	-0.364	-0.108	-0.079	-0.274	-0.047	0.010	-0.120	-0.429	-0.006	-0.222	0.190	-0.314	0.587	-0.962	-0.003
θ1	0.003	0.005	0.002	0.004	0.003	0.003	0.002	0.004	0.002	0.002	0.002	0.001	0.001	0.004	0.003	0.003
θ2	0.001	-0.001	0.001	0.004	-0.007	0.001	0.004	0.002	-0.017	0.004	0.003	0.001	-0.010	0.006	-0.031	-0.002
ω1	32.8	12.7	231.7	7.2	91.4	157.8	158.6	203.1	43.6	195.5	102.0	176.7	179.5	245.9	164.7	262.7
ω2	95.2	156.6	32.6	240.4	235.3	18.9	218.8	57.6	1.0	133.4	171.2	46.7	1.0	45.3	1.2	183.9
LR_uc	0.251	0.156	0.014	0.444	0.251	0.003	0.014	0.251	0.092	0.156	0.235	0.052	0.092	0.000	0.028	0.007
LR_ind	0.493	0.466	0.366	0.451	0.493	0.072	0.353	0.493	0.440	0.466	0.422	0.414	0.440	0.493	0.402	0.355
LR_cc	0.409	0.280	0.033	0.297	0.409	0.003	0.033	0.409	0.180	0.280	0.181	0.109	0.180	0.000	0.063	0.017
DQ_in	0.774	0.593	0.750	0.805	0.257	0.829	0.851	0.786	0.904	0.785	0.809	0.697	0.850	0.897	0.772	0.818
DQ_out	0.042	0.033	0.021	0.012	0.022	0.033	0.022	0.033	0.004	0.024	0.039	0.003	0.003	0.002	0.031	0.043
Hit_in	1.002	0.927	0.977	1.077	1.052	1.002	1.002	1.002	1.027	1.002	1.027	1.027	1.002	1.002	1.002	1.002
Hit_out	1.455	1.455	2.000	1.636	1.636	2.000	2.000	1.818	2.182	2.000	1.818	2.364	2.182	1.818	1.818	1.818
m_VaR_1	-5.487	-5.452	-5.403	-5.404	-5.649	-5.283	-5.338	-5.418	-5.171	-5.323	-5.241	-5.171	-5.258	-5.700	-5.411	-5.369
m_CoVaR_1	-5.859	-5.452	-5.585	-5.138	-4.974	-5.613	-5.563	-5.295	-5.409	-5.522	-5.253	-5.483	-5.457	-6.934	-5.368	-5.465
m_d_CoVaR_1	-0.529	0.000	-0.261	0.392	0.920	-0.453	-0.315	0.169	-0.322	-0.279	-0.018	-0.423	-0.267	-1.671	0.057	-0.129
m_VaR_2	-5.632	-5.148	-5.065	-7.091	-10.299	-2.730	-2.710	-3.546	-2.608	-3.346	-3.534	-2.398	-5.149	-3.196	-3.176	-4.048
m_CoVaR_2	-6.138	-5.865	-6.865	-6.770	-12.427	-2.797	-2.498	-3.534	-2.833	-3.178	-3.614	-2.192	-5.334	-3.488	-3.250	-3.991
m_d_CoVaR_2	-0.727	-1.034	-2.582	0.456	-2.985	-0.098	0.303	0.016	-0.332	0.240	-0.117	0.300	-0.270	-0.411	-0.107	0.081

注:加粗统计量在 5%统计意义上显著。表中均为以 WTI 期货市场为第一个因变量, WTI 现货等 16 个市场作为第二个因变量进行 VaR 回归求解的结果。缩写“m_d_CoVaR_1”代表第一个因变量的 Δ CoVaR 时间序列数值的平均值。DQ 与 LR 行是检验结果的 p 值, 加粗为在 5%水平上通过检验。

WTI_fut :	WTI_spot		Brent_fut		Brent_spot	
	无	有	无	有	无	有
	MIDAS	MIDAS	MIDAS	MIDAS	MIDAS	MIDAS
RQ	546.4	547.9	513.4	518.6	525.1	523.8
Hit_in	1.002	1.002	1.002	0.927	1.002	0.977
DQ_in	0.906	0.847	0.255	0.166	0.189	0.210
Hit_out	2.182	1.455	2.364	1.455	2.182	2.000
DQ_out	0.000	0.922	0.000	0.000	0.002	0.745
LRuc	0.002	0.251	0.000	0.156	0.000	0.014
LRind	0.301	0.493	0.227	0.466	0.244	0.366
LRcc	0.004	0.409	0.000	0.280	0.000	0.033

注:风险水平设定为 1%。加粗统计量在 5%统计意义上显著。DQ 与 LR 行是检验结果的 p 值, 加粗为在 5%水平上通过检验。

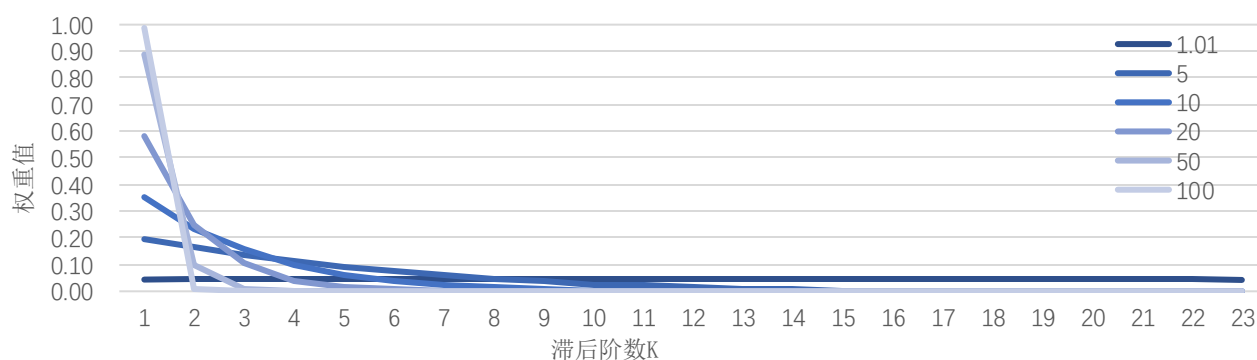
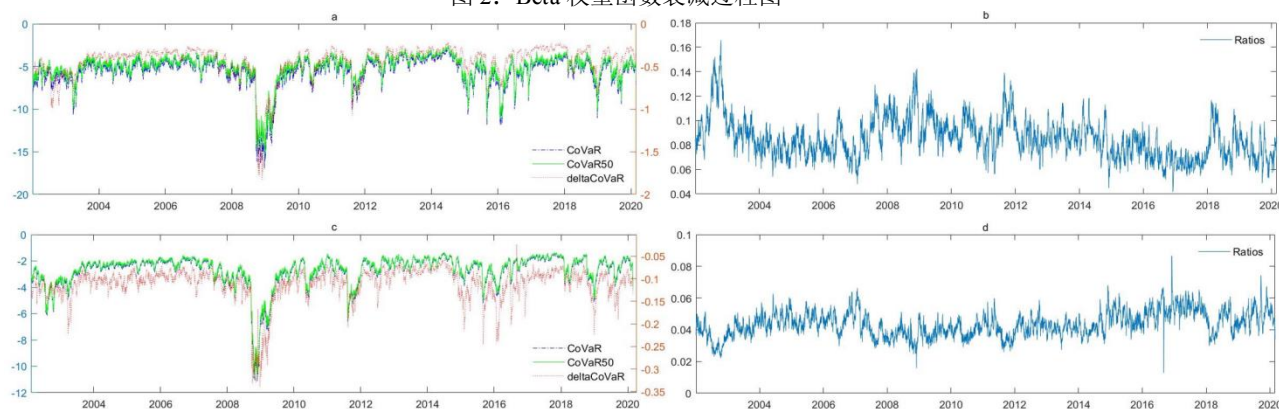
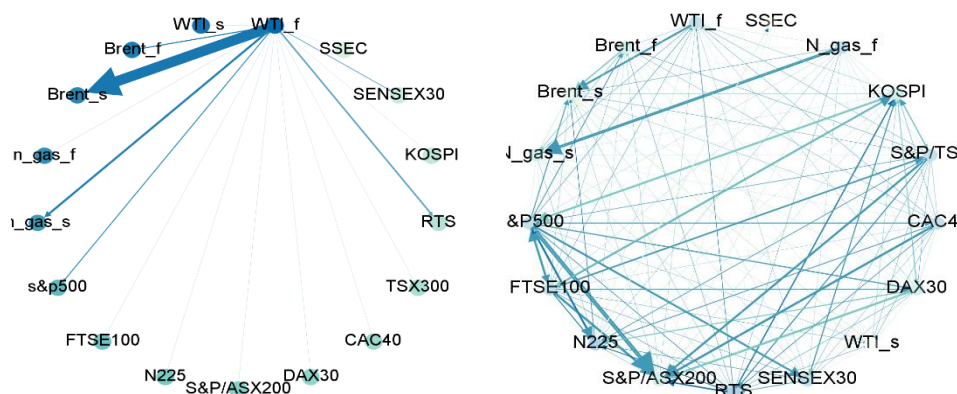


图 2: Beta 权重函数衰减过程图

图 3: WTI 期货与 S&P500 市场收益率 VaR、CoVaR、 ΔCoVaR 、 ΔCoVaR -Ratio 时间序列图图 4: 基于 ΔCoVaR 及 Ratio 指标的辐射状、网络状系统性风险影响关系

五、总结

为了研究能源与金融类的代表性市场间交叉风险溢出关系与系统性风险网络状关系,本文以原油、天然气期货与现货为代表的能源市场,以全球主要经济体的特征股指为代表的金融市场,共17个市场进行 VaR、CoVaR、 ΔCoVaR 、 $\Delta\text{CoVaR-Ratio}$ 测算与预测分析。基于 MVMQ-CAViaR 模型与 GARCH-MIDAS 模型原理,构建 QR-MV-GARCH-MIDAS 模型,实现宏观低频变量参与高频市场收益率间双向条件风险预测,使模型更好适用于具有波动特征的宏观环境,进一步提升风险预测的精度。 $\Delta\text{CoVaR-Ratio}$ 指标的构建可以有效消除 CoVaR、 ΔCoVaR 受到 VaR 量级大小的影响,便于同质比较市场间的风险冲击程度。

实证结果表明,能源与股票市场间存在一定的风险溢出关系,以美国股票市场的贡献与暴露风险最为显著,中国上证指数表现的贡献或暴露风险均相对较小;股票市场间的系统性风险贡献与暴露关系较原油与期货市场更加活跃;原油与天然气市场中 WTI 期货市场对现货市场的影响远胜布伦特期货市场,天然气期货市场对现货市场具有显著系统性风险贡献。以上分析与结论,有利于投资者、市场监管者、政策制定者等更好地判断各市场面临的外在风险程度。

在此研究基础上还可进一步丰富目标市场及选取的宏观影响因素进行深度探索,加强对经济政策不确定性、地缘政治风险、汇率等宏观市场环境因素的冲击监控,提高预判系统性风险的能力,为国家战略投资与管控、能源与外汇储备等方面提供系统性风险预警信息。

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绿色转型发展整体评价与区域差异研究 ——基于“三维一体”驱动模型

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摘要：绿色转型发展已成为实现经济与环境协同发展的必然选择，而推动绿色转型发展需要全社会共同努力。因此，本文基于 2006-2019 年省际面板数据，以“三维一体”驱动模型为框架，构建了绿色转型评价指标体系，并运用纵横向拉开档次法+全局熵权-TOPSIS-灰色关联分析综合评价方法测度绿色转型发展水平。此外，本文还采用 Dagum 基尼系数及分解方法、kernel 密度估计和 Moran's I 方法对我国绿色转型发展区域差异的时空特征展开系统分析。结果表明：（1）在评价年内，四大区域和整体绿色转型发展水平总体都呈增长趋势，但增速在 2013 年之后逐渐减缓，其中东部地区综合指数最高，其次是中部和东北地区，西部地区最低，政府环境治理和企业绿色生产维度对绿色转型发展起促进作用，而居民绿色消费维度有制约作用。（2）我国绿色转型发展水平区域差异主要是由区域间相对差异引起的。四大区域绿色转型发展水平区域内差异都呈缩小趋势，东部地区最先处于稳定的均衡发展状态；东部与另外三个地区间的相对差异较大，但差异在不断缩小。（3）我国整体和各区域绿色转型发展水平的绝对差异在逐步减小，区域内各省份发展趋于均衡，逐渐形成稳定的 H-H 聚集和 L-L 聚集效应。其中东部和中部地区主要呈现 H-H 聚集状态，西部和东北地区主要呈现 L-L 聚集状态。据此提出了相关建议。

关键词：绿色转型发展水平，评价指标体系，三维一体，时空差异分析

Overall evaluation and regional differences of green transformation development: Analysis based on "three-dimensional integrated" driving model

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Abstract: Green transformation development (GTD) has become an inevitable choice to realize the coordinated progress of the economy and environment, while promoting GTD requires the joint efforts of the whole society. Therefore, based on China's provincial data from 2006 to 2019, a GTD evaluation indicator system with the framework of the "three-dimensional integrated" driving model was constructed. The level of GTD was measured by using the comprehensive evaluation method of vertical-and-horizontal scatter degree method and global entropy weight -TOPSIS- grey relational analysis method. In addition, the Dagum Gini coefficient and its decomposition, Kernel density estimation and Moran's I methods were used to further analyze the spatio-temporal characteristics of regional differences in GTD. The results showed that: (1) In 2006-2019, China's overall and four major regions' GTD indexes showed an overall growth trend, but the growth rate gradually slowed down after 2013. Governments' environmental governance and enterprises' green production dimensions contributed to the GTD, while residents' green consumption dimension constrained it. (2) The regional differences in China's GTD level were mainly caused by the inter-regional differences. The intra-regional differences in GTD levels of the four major regions were all on a decreasing trend. (3) The absolute differences in China's overall and four major regions' GTD indexes were gradually decreasing, and the GTD of provinces tended to be balanced, gradually forming stable H-H aggregation and L-L aggregation effects. Finally, the recommendations were put forward according to the results.

Key Words: green transformation development, evaluation indicator system, government-enterprise-resident, spatiotemporal difference analysis

一、引言

绿色转型发展是在 2008 年美国金融危机之后,各国在联合国环境规划署 (UNEP) “绿色新政” 和 “绿色经济” 倡议下追求的发展新概念 (Barbier, 2010 年; Mundaca 等, 2016 年)^{[1][2]}。许多学者在已有的 “绿色经济” 理论的基础上阐述了绿色转型概念 (Pearce 等, 1989)^[3], 即绿色转型是一个节能减排的过渡过程, 目标是实现经济、资源和环境的协调可持续发展。世界各国经济发展实践表明, 粗放扩张型的经济增长模式严重破坏了自然生态系统的平衡。因此, 转变经济发展方式已成为许多国家缓解发展压力、寻求长期可持续发展的当务之急。(Chen, 2015; Pirgmaier, 2017; Wang, Li, 2019 年)^[4-6]。

在 2008 年 12 月发布的《太原市绿色转型促进条例》^[10]中提出了绿色转型概念, 虽然我国绿色转型发展起步较晚, 但整体进程较快。目前关于绿色转型发展的研究主要集中于探究工业企业绿色转型发展水平与环境规制、碳排放强度间的相互作用 (谢婷婷和刘锦华, 2019; Mao 等, 2019; Zhong 和 Peng, 2022)^[7-9], 研究对象过于单一, 难以反映出我国整体的绿色转型发展进程。大多数学者都认同在评价绿色转型发展进程时, 应考虑多个维度的影响, 构建全面多元的指标评价体系能更准确地衡量绿色转型发展水平 (Li 等, 2019; Tong 等, 2020)^{[10][11]}。此外, 由于区域间在区位、经济、人才、技术创新等方面的差异, 导致各地区绿色转型发展水平也存在显著空间异质性 (Feng 等, 2020; Zhai 和 An, 2021)^{[12][13]}, 现有文献关于绿色转型发展水平的研究主要集中在特定地区、城市群和省份 (Weng 等, 2020; Hu 等, 2021 年)^{[14][15]}, 且定量

研究和区域差异研究不足。因此, 本研究采用指标评价的方法对我国绿色转型发展水平展开测度, 并对各区域绿色转型发展指数的时空变化特征展开定量分析。

二、文献综述

依据指标体系构建逻辑不同, 绿色转型发展指标体系主要可分为以下两类: 第一类是依据绿色转型的概念, 从经济、社会、资源和环境四个维度构建指标体系 (Zhang 等, 2017; Ma 等, 2019; Liu 等, 2021)^[16-18], 所选指标侧重于生态环境和经济的协调发展 (Chen 和 Zhang, 2021; Yi 等, 2019b)^{[19][20]}, 该类指标体系对不同维度的界定比较模糊, 对指标选取具有较强的随意性。第二类是基于国家发改委 (2016)^[19]制定的《绿色发展指标体系》, 从资源利用、环境治理、环境质量、生态保护、增长质量和绿色生活 6 个方面构建绿色转型发展指标体系 (Yang 和 Huang, 2019)^[20], 此类指标体系指标数量过多, 实际可操作性较弱, 如 Fang 等 (2020)^[21]绿色转型发展指标体系中的 “公众满意度” 指标等。鉴于此, 本研究选择基于三维参与主体 “政府-企业-居民” 来构建绿色转型发展指标体系 (肖贵蓉等, 2016)^[22]。如图 1 所示, 政府作为宏观层面的政策制定者, 其环境治理能力对绿色转型发展具有重要引导作用。企业和消费者作为微观市场主体, 依据产品的生命周期理论, 在绿色转型过程中, 形成一个完整的绿色 “生产-消费” 循环系统 (王宇等, 2020)^[23], 三位参与主体间的循环作用促进绿色转型发展。在遵循指标构建全面性、代表性和可比性原则的基础上, 参考有关文献设计如表 1 所示的绿色转型指标体系。

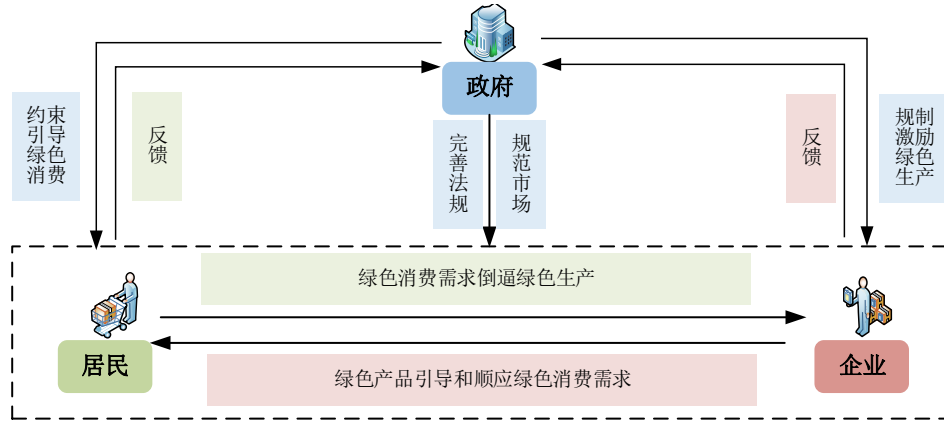


图 1: “三维一体”驱动模型的绿色转型发展循环作用流程图

关于绿色转型发展指标体系评价方法，现有研究主要关注以下二个问题：一是赋权方法的选择。确定权重的方法主要分为：主观赋权（Acosta 等 2020; Solangi 等, 2021）^{[24][25]}和熵值法（Cheng 和 Ge, 2020）^[26]、主成分分析（PCA）（Dabkiene 等, 2021）^[27]和拉开档次法（Yi 等, 2019a）^[28]等客观赋权法。其中主观赋权法易受人为主观因素影响，具有一定的随意性和不可重复性；主成分分析法提取出的主成分往往难以给出恰当的解释；熵值法和拉开档次法则更适用于静态评价。二是信息集结方法选择。集结方式主要有 TOPSIS 法（Mateusz 等, 2018）^[29]、粗糙集分析（Hou 等, 2020）^[30]、灰色关联分析（Yi 等, 2021）^[31]等方法。因此，本文采用纵横向拉开档次法结合全局熵权法来确定权重，综合使用这两种方法，可以尽可能的保留原始数据信息。关

于信息集结方式，由于粗糙集分析存在一定的主观性，易受决策者偏好影响（Cheng 等, 2018）^[32]，TOPSIS 法无法体现数据序列动态变化（Li 等, 2018）^[33]；灰色关联分析方法不能得出影响评价对象质量的内在因素（Tang 等, 2019）^[34]。为了客观体现系统实际方案与理想解的动态贴近度，本研究选择 TOPSIS 结合灰色关联分析方法来集结指标数据信息。

三、绿色转型发展水平量化分析方法

1、绿色转型评价指标体系

基于“三维一体”驱动模型，秉持全面性、代表性、可比性和可操作性的原则，构建指标体系表 1 如下：

表 1: 绿色转型发展评价指标体系

一级目标层	二级准则层	三级指标层	单位	指标方向	文献依据
政府 环境治理 (Z1)	生态环境 保护(Y1)	环境污染治理投资额(X1)	亿元	正	[18,20,21]
		城市生活垃圾无害化处理率(X2)	%	正	[20,21,22]
		建成区绿化覆盖率(X3)	%	正	[18,20,21,22]
	资源消耗 控制(Y2)	环境行政规章数(X4)	条	正	[16]
		地方财政节能环保支出(X5)	亿元	正	[22]
		煤炭消费量(X6)	万吨	正	[20,21,22]
企业 绿色生产 (Z2)	绿色生产 基础(Y3)	绿色专利申请数量(X7)	个	正	[21]
		规模以上工业企业 R&D 经费内部支出/主营业务收入(X8)	/10 ⁴ 元	正	[20,21,22]
		六大高耗能产业利息支出/工业产业利息总支出 (X9)	%	负	[7]
		生产资源能 源(Y4)	m ³ / 元	负	[23]
	生产资源能 源(Y4)	工业用水总量/GDP(X10)	m ³ / 元	负	[23]

居民 绿色消费 (Z3)	生产生态环境 (Y5)	能源终端消费量(工业)/GDP(X11)	Kgce /元	负	[18,20,21,23]
		城市工业建设用地面积/GDP(X12)	%	负	[23]
		工业 CO ₂ 排放量/GDP(X13)	t/元	负	[18,23]
		工业 SO ₂ 排放量/GDP(X14)	t/亿 元	负	[7,20,21,23]
		工业废水中 COD 排放量/GDP(X15)	t/亿 元	负	[18,20,21,23]
		工业废水中氨氮排放量/GDP(X16)	t/亿 元	负	[18,20,21,23]
		工业固体废物产生量/GDP(X17)	t/万 元	负	[7,18,23]
	绿色消费基础 (Y6)	高等教育比例(X18)	%	正	[21,23]
		人均公园绿地面积(X19)	m ²	正	[18,20,23]
		每万人拥有公共交通工具数(X20)	标台	正	[18,20,22,23]
		人均可支配收入(X21)	元	正	[18,20,22]
		家庭恩格尔系数(X22)	%	负	[22]
	消费资源能源 (Y7)	人均能源消费量(生活)(X23)	Kgce /人	负	[18,21,23]
		人均私人载客汽车拥有量(X24)	辆/人	负	[21]
		建制镇人均住宅建筑面积(X25)	m ²	负	[23]
	消费生态环境 (Y8)	人均生活 CO ₂ 排放量(X26)	t/人	负	[18,23]
		人均生活 SO ₂ 排放量(X27)	t/人	负	[7,18, 20,21,23]
		人均生活垃圾清运量(X28)	t/人	负	[22,23]

2、数据来源

基于数据的科学性和可获得性,本研究的样本数据是以 2006-2019 年为时序,30 个省份为截面的面板数据。环境行政规章数的数据是借鉴 Chen 等 (2018) [35] 的方法,通过整理我国政府法制信息网 <http://www.chinalaw.gov.cn/> 的地方规章制度库中,评价年内出现“环保”、“环境保护”、“绿色”、“节能”、“生态”等 5 个词汇的规章数量得到的。绿色专利申请数据借鉴齐绍洲等 (2018) [36] 方法,依据世界知识产权局 (WIPO) 发布的《绿色专利清单》,在国家知识产权局官网 <https://www.cnipa.gov.cn/> 查询得到。工业和生活 CO₂ 排放量是依据 Wang 等 (2019) [37] 方法计算得到的。其余指标数据均来自于《中国统计年鉴》、《中国能源统计年鉴》、《我国科技统计年鉴》、《中国环境统计年鉴》和各省份的统计年鉴。此外,文中涉及到以元为单位的指标数据都以 2006 年为基期,做了平减处理。

3、指标评价模型

(1) “纵横向拉开档次法+全局熵权-TOPSIS-

灰色关联分析”方法

首先,用纵横向拉开档次法,确定八个二级指标的评价值。

$$x'_{ij} = \begin{cases} \frac{x_{ij}(t_k) - \min_{1 \leq i \leq n} \min_{1 \leq k \leq T} \{x_{ij}(t_k)\}}{\max_{1 \leq i \leq n} \max_{1 \leq k \leq T} \{x_{ij}(t_k)\} - \min_{1 \leq i \leq n} \min_{1 \leq k \leq T} \{x_{ij}(t_k)\}}, & + \\ \frac{\max_{1 \leq i \leq n} \max_{1 \leq k \leq T} \{x_{ij}(t_k)\} - x_{ij}(t_k)}{\max_{1 \leq i \leq n} \max_{1 \leq k \leq T} \{x_{ij}(t_k)\} - \min_{1 \leq i \leq n} \min_{1 \leq k \leq T} \{x_{ij}(t_k)\}}, & - \end{cases} \quad (1)$$

$$\begin{aligned} & \max \quad \omega^T H \omega \\ & s. t. \quad \begin{cases} \|\omega\| = 1 \\ \omega > 0 \end{cases} \end{aligned} \quad (2)$$

$$\begin{aligned} & \omega = (\omega_1, \omega_2, \dots, \omega_j)^T, H_k = A_k^T A_k, \\ & A_k = \begin{pmatrix} x'_{11}(t_k) & \cdots & x'_{1m}(t_k) \\ \vdots & \ddots & \vdots \\ x'_{n1}(t_k) & \cdots & x'_{nm}(t_k) \end{pmatrix} \end{aligned} \quad (3)$$

$$y_{i1}(t_k) = \sum_{j=1}^m \omega_j x'_{ij}(t_k).$$

通过全局熵权法得到二级指标 Y1、Y2 的权重 w_l , 再使用 TOPSIS 方法得到一级指标 Z1 评价得分 $z_{i1}(t_k)$ 为:

$$\frac{\sqrt{\sum_{i=1}^n \sum_{k=1}^T (Q_{ik}^+ - r_{il}(t_k))^2}}{\sqrt{\sum_{i=1}^n \sum_{k=1}^T (Q_{ik}^+ - r_{il}(t_k))^2} + \sqrt{\sum_{i=1}^n \sum_{k=1}^T (Q_{ik}^- - r_{il}(t_k))^2}} \quad (4)$$

进一步计算得到绿色转型发展指数 $zz_i(t_k)$ 。

$$u_{rs} = \frac{(1 + |s_r| + |s_s|)}{(1 + |s_r| + |s_s| + |s_r - s_s|)} \quad (5)$$

$$\alpha_{rs} = \theta \mu_{rs} + (1 - \theta) v_{rs} \quad (6)$$

$$|s_r| = |\sum_{k=2}^{T-1} z_{rk}^0 + z_{rT}^0 / 2| \quad (7)$$

$$z_r' = \sum_{s=1}^P w_{(p)} \beta_{rs} z_s \quad (8)$$

$$C_r = |z_r| / (|z_r| + |z_r - z_r'|) \quad (9)$$

$$ZZ = \sqrt{\prod_{r=1}^P C_r \sum_{p=1}^P w_{(p)} \times z_p} \quad (10)$$

其中 $i \in [1, n]$ ($n = 30$) 表示第 i 个省份, $j \in [1, m]$ ($m = 3$) 表示第 j 个三级指标, $k \in [1, T]$ ($T = 12$), $l \in [1, L]$ ($L = 2$) 表示 ZI 的第 l 个二级指标。

$Q_{ik}^+ = (\max r_{i1}(t_1), \max r_{i2}(t_1), \dots, \max r_{in}(t_T))$, $Q_{ik}^- = (\min r_{i1}(t_1), \min r_{i2}(t_1), \dots, \min r_{in}(t_T))$, z_{rk}^0 是指在初始序列 $X_r = (z_{r1}, z_{r2}, \dots, z_{rT})$ 零化像中第 k 年的值, 本研究 θ 取 0.5。

(2) Dagum 基尼系数及分解

Dagum 基尼系数可用来衡量区域内及区域间的相对差异, 进一步分解可得到相对差异的来源与构成, 具体计算方法如下:

$$G = G_w + G_{nb} + G_t \quad (11)$$

$$G = \sum_{j=1}^k \sum_{h=1}^k \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} |zz_{ji} - zz_{hr}| / 2n^2 \bar{zz} \quad (12)$$

$$G_{jj} = \sum_{i=1}^{n_j} \sum_{r=1}^{n_j} |zz_{ji} - zz_{jr}| / 2n_j^2 \bar{zz}_j \quad (13)$$

$$G_w = \sum_{j=1}^k G_{jj} p_j s_j \quad (14)$$

$$G_{jh} = \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} |zz_{ji} - zz_{hr}| / n_j n_h (\bar{zz}_j + \bar{zz}_h) \quad (15)$$

$$G_{nb} = \sum_{j=2}^k \sum_{h=1}^{j-1} G_{jh} (p_j s_h + p_h s_j) D_{jh} \quad (16)$$

$$G_t = \sum_{j=2}^k \sum_{h=1}^{j-1} G_{jh} (p_j s_h + p_h s_j) (1 - D_{jh}) \quad (17)$$

$$D_{jh} = (d_{jh} - p_{jh}) / (d_{jh} + p_{jh}) \quad (18)$$

$$d_{jh} = \int_0^\infty dF_j(y) \int_0^y (y-x) dF_h(x) \quad (19)$$

$$p_{jh} = \int_0^\infty dF_h(y) \int_0^y (y-x) dF_j(x) \quad (20)$$

其中, n_j, n_h 表示区域 j, h 中的省份数, G 表示整体基尼系数, G_{jj} 表示区域 j 内基尼系数, G_w 为区域内相对差异贡献率, d_{jh} 表示区域 j, h 绿色转型发展指数间的差值, p_{jh} 表示为超变一阶矩, F_j, F_h 分别为区域 j 和 h 的累积密度分布函数。

(3) Kernel 密度估计 (KDE)

本文选取 Epanechnikov 曲线作为 Kernel 密度估计的核函数 $K(x)$, 依据积分均方误差 (IMSE) 最小来确定最优带宽 h 。

$$\hat{f}_h(x) = \frac{1}{nh} \sum_{k=1}^N K\left(\frac{x-x_k}{h}\right) \quad (21)$$

$$K(x) = \begin{cases} \frac{3}{4}(1-x^2) & \text{if } |x| \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad (22)$$

其中, h 为带宽, 反映了 KDE 曲线整体的平滑程度, n 为省份数。

(4) 莫兰指数 (Moran's I)

Moran's I 分为 Global Moran's I 和 Local Moran's I。计算公式如下:

$$G \text{ Moran's } I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (zz_i - \bar{zz})(zz_j - \bar{zz})}{(\sum_{i=1}^n \sum_{j=1}^n w_{ij}) \sum_{i=1}^n (zz_i - \bar{zz})^2} \quad (23)$$

$$LMoran's I = \frac{n (zz_j - \bar{zz}) \sum_{i=1}^n w_{ij} (zz_i - \bar{zz})}{\sum_{i=1}^n (zz_i - \bar{zz})^2} \quad (24)$$

其中: zz_i, zz_j 表示省份 i, j 的绿色转型发展指数, n 表示省份数, \bar{zz} 表示所有省份的绿色转型发展指数均值, W 为 0-1 空间权重矩阵。

四、实证分析与讨论

1、绿色转型发展水平总体描述

(1) 整体视角

本文借鉴 Hou 等 (2020) [29] 关于绿色生产率指标评价分级原则, 将绿色转型发展指数分为五个等级: [0,0.2)-深灰, [0.2,0.4)-灰色, [0.4,0.6)-浅绿 (过渡), [0.6,0.8)-绿色 (可接受), [0.8,1.0)-深绿 (成熟)。如表 2、图 2 和图 3 所示, 2006 年, 贵州绿色转型发展水平最低, 还处于灰色阶段, 只有北京达到了深绿成熟阶段, 此外有 14 个省份达到绿色可接受阶段, 14 个省份处于浅绿过渡阶段。2019 年, 新疆的绿色转型发展水平最低, 但也达到了绿色可接受阶段, 发展水平较高的有广东、北京和山东, 共有 19 个省份达到了深绿成熟阶段。在评价年内, 我国绿色转型发展水平整体呈上升趋势, 增速在 2013 年之后开始减缓由 3.63% 降至 1.04%, 增长动力明显不足。

表 2：2006-2019 省际绿色转型发展指数

地区	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
北 京	0.83	0.81	0.81	0.82	0.83	0.84	0.84	0.88	0.88	0.88	0.88	0.90	0.91	0.90
天 津	0.75	0.78	0.77	0.75	0.78	0.80	0.80	0.80	0.80	0.81	0.82	0.82	0.83	0.86
河 北	0.64	0.64	0.65	0.66	0.73	0.74	0.75	0.78	0.77	0.79	0.79	0.82	0.82	0.82
山 西	0.43	0.54	0.62	0.63	0.66	0.68	0.69	0.73	0.73	0.73	0.74	0.74	0.74	0.75
内 蒙 古	0.54	0.59	0.59	0.61	0.64	0.63	0.67	0.72	0.73	0.75	0.75	0.75	0.75	0.74
辽 宁	0.66	0.66	0.69	0.68	0.72	0.76	0.79	0.81	0.79	0.80	0.79	0.83	0.82	0.81
吉 林	0.53	0.62	0.58	0.63	0.62	0.64	0.66	0.67	0.72	0.73	0.73	0.73	0.75	0.77
黑 龙 江	0.51	0.51	0.51	0.54	0.59	0.63	0.65	0.70	0.72	0.74	0.75	0.75	0.77	0.81
上 海	0.64	0.74	0.73	0.71	0.78	0.72	0.77	0.80	0.84	0.85	0.85	0.86	0.86	0.86
江 苏	0.74	0.78	0.80	0.80	0.80	0.81	0.83	0.85	0.85	0.86	0.87	0.88	0.88	0.87
浙 江	0.75	0.76	0.78	0.81	0.82	0.83	0.85	0.86	0.86	0.83	0.85	0.86	0.86	0.85
安 徽	0.52	0.57	0.58	0.60	0.64	0.76	0.78	0.80	0.81	0.78	0.81	0.83	0.86	0.86
福 建	0.61	0.71	0.74	0.76	0.78	0.79	0.77	0.79	0.79	0.81	0.82	0.84	0.85	0.84
江 西	0.58	0.63	0.67	0.74	0.75	0.77	0.78	0.80	0.80	0.81	0.79	0.80	0.82	0.84
山 东	0.72	0.76	0.76	0.80	0.82	0.83	0.84	0.87	0.85	0.85	0.88	0.87	0.89	0.88
河 南	0.63	0.64	0.65	0.69	0.72	0.73	0.75	0.77	0.77	0.79	0.81	0.83	0.84	0.85
湖 北	0.54	0.55	0.58	0.60	0.62	0.67	0.72	0.74	0.76	0.76	0.79	0.82	0.83	0.83
湖 南	0.54	0.58	0.60	0.67	0.73	0.75	0.73	0.75	0.78	0.79	0.81	0.82	0.84	0.85
广 东	0.67	0.70	0.72	0.75	0.82	0.80	0.84	0.86	0.87	0.89	0.91	0.94	0.93	0.92
广 西	0.57	0.60	0.66	0.70	0.74	0.76	0.78	0.79	0.79	0.80	0.77	0.78	0.79	0.79
海 南	0.67	0.68	0.69	0.70	0.72	0.79	0.81	0.82	0.81	0.79	0.80	0.81	0.80	0.80
重 庆	0.55	0.67	0.71	0.76	0.80	0.81	0.80	0.80	0.80	0.83	0.84	0.85	0.86	0.84
四 川	0.59	0.67	0.70	0.69	0.73	0.73	0.76	0.78	0.78	0.79	0.81	0.82	0.83	0.84
贵 州	0.32	0.34	0.36	0.38	0.45	0.66	0.67	0.69	0.69	0.71	0.73	0.73	0.76	0.76
云 南	0.51	0.64	0.64	0.68	0.72	0.68	0.72	0.73	0.75	0.74	0.76	0.77	0.79	0.79
陕 西	0.66	0.68	0.72	0.71	0.73	0.75	0.77	0.82	0.79	0.81	0.81	0.82	0.81	0.79
甘 肃	0.48	0.48	0.51	0.51	0.55	0.56	0.58	0.63	0.66	0.66	0.68	0.77	0.77	0.78
青 海	0.62	0.65	0.65	0.59	0.62	0.70	0.72	0.63	0.69	0.69	0.73	0.73	0.73	0.73
宁 夏	0.57	0.60	0.64	0.63	0.71	0.64	0.65	0.70	0.70	0.70	0.74	0.72	0.73	0.72
新 疆	0.58	0.59	0.62	0.62	0.65	0.67	0.66	0.66	0.67	0.67	0.68	0.70	0.70	0.71



(a)2006 年



(b)2019 年

图 2：我国省际绿色转型发展指数分布图

(2) 子维度视角

如表 3 和图 3 所示。在评价年内，三个维度的贡献度都比较显著，但评价得分变化趋势存在较大差异。

表 3：绿色转型发展指标体系目标层和准则层权重

一级指标	权重	二级指标	权重
政府环境治理	0.44	生态环境保护	0.28
		资源消耗控制	0.16
		绿色生产基础	0.13
企业绿色生产	0.33	生产资源能源	0.14
		生产生态环境	0.05
		绿色消费基础	0.10
居民绿色消费	0.23	消费资源能源	0.09
		消费生态环境	0.05

我国政府环境治理评价得分总体呈增长趋势，整体增速为 5.54%。由于十八大会议政府对绿色转型发展提出了更高的要求，2013 年之后增速有所减缓。我国企业绿色生产评价得分总体呈线性增长趋势，整体增速为 3.79%，增速比较稳定，由于企业在技术创新方面仍然缺乏主动，未从根本上突破绿

色生产瓶颈，导致评分增速较低。我国企业绿色消费评价得分总体呈波动衰退趋势，从 2013 年之后减速明显，变化速率由 0.28%降至-0.85%，综合评价得分较低仅为 0.492，随着城乡居民整体消费能力的不断提升，过度消费生活资源能源问题逐渐突出。

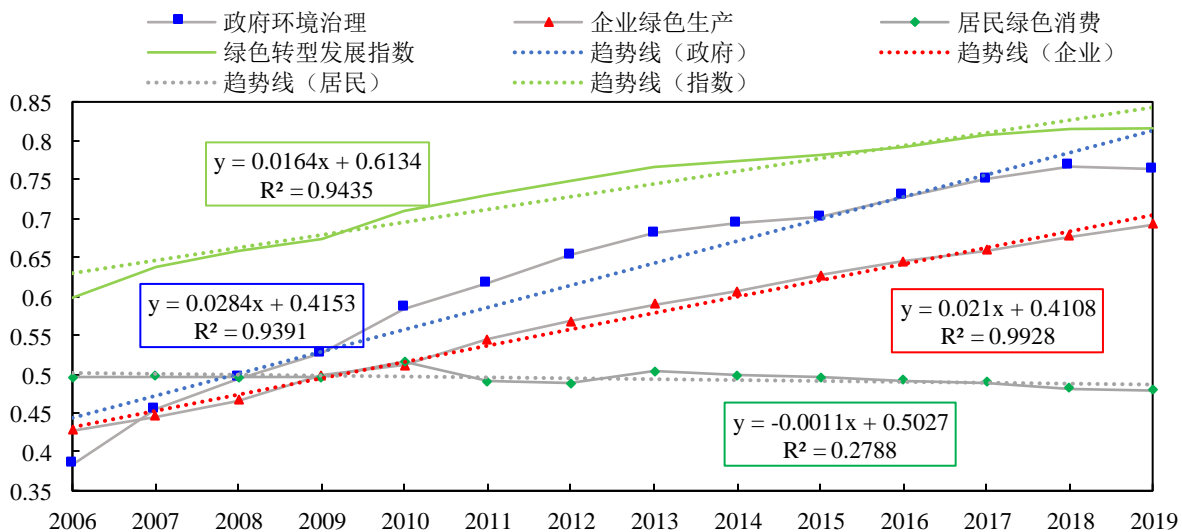


图 3：2006-2019 年我国整体和三个子维度绿色转型发展指数变化趋势图

(3) 区域视角

如图 4 所示，四大区域的绿色转型发展指数变化趋势与全国水平相似，总体都呈增长趋势，但各地区存在较大差异。东部地区的绿色转型发展综合指数最高为 0.831，高于全国水平，其次是中部地区为 0.769，接近全国水平，最后是东北和西部地区分别为 0.734 和 0.730，明显低于全国水平。东部地区绿色转型发展指数一直高于全国水平呈缓慢增长

趋势。中部地区绿色转型发展起点较低为 0.542，但年均增速较高为 3.36%，在不断缩小与全国水平的差距。西部和东北地区绿色转型发展指数一直低于全国水平，西部地区年均增速为 2.77%，增速在 2013 年之后开始下降，东北地区的年均增速为 2.43%，增长速率不稳定，呈波动增长趋势，与全国水平的差距在不断缩小。

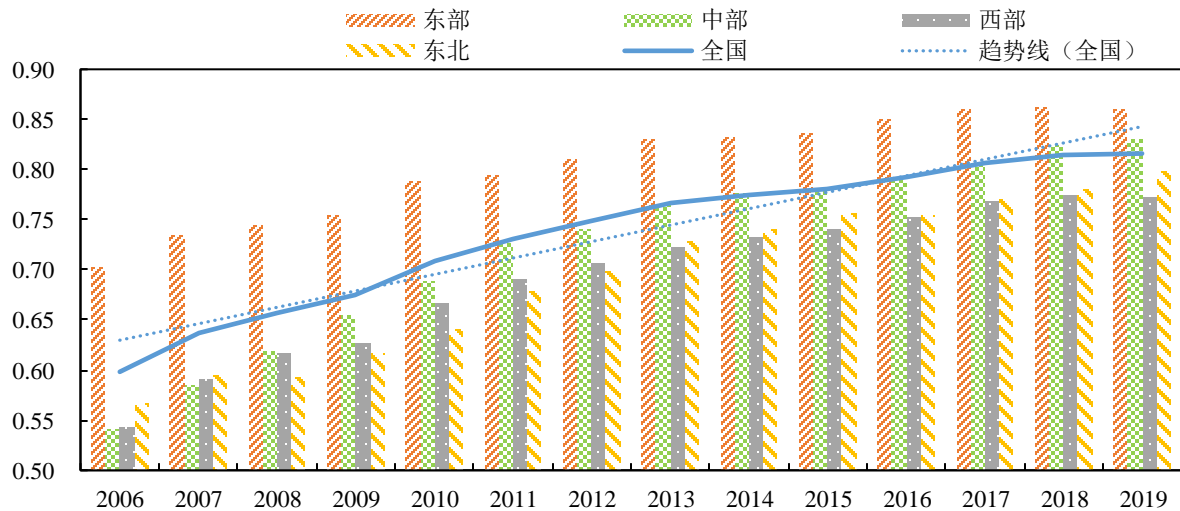


图4：2006-2019年我国整体和四大区域绿色转型发展指数变化趋势图

2、绿色转型发展水平区域差异及来源

根据上述分析可得，我国绿色转型发展指数存在明显的区域差异，为了进一步探究区域差异的大小及来源，本文采用 Dagum 基尼系数及分解方法对绿色转型发展指数展开深入定量分析。

（1）区域内差异分析

如图5所示，我国绿色转型发展水平整体基尼系数和各区域内基尼系数都呈下降趋势，但各区域内基尼系数存在明显波动性变化。在评价年内，整体基尼系数呈逐年下降，由0.095降至0.037，年均减速为-6.83%，且在每一个五年规划开局或收官之年，变化幅度更加显著，这表明五年规划设计有助于绿色转型均衡发展。东部地区内基尼系数总体呈“大缩小-小扩大”波动递减趋势，由0.052降至0.023，年均减速为-5.29%。中部地区内基尼系数和东部地区内基尼系数相近，总体呈“多缩小-少扩大”波动递减趋势，由0.059降至0.021，年均减速为-5.09%。除2008-2011年外，西部地区内基尼系数总体呈“大缩小-小扩大”和“多缩小-少扩大”波动递减趋势，由0.078降至0.011，年均减速最快为-10.60%。除2013年、2015年外，东北地区内基尼系数总体呈等幅度的“缩小-扩大”交替波动递减趋势，由0.061降至0.031，年均减速最慢为-1.21%。

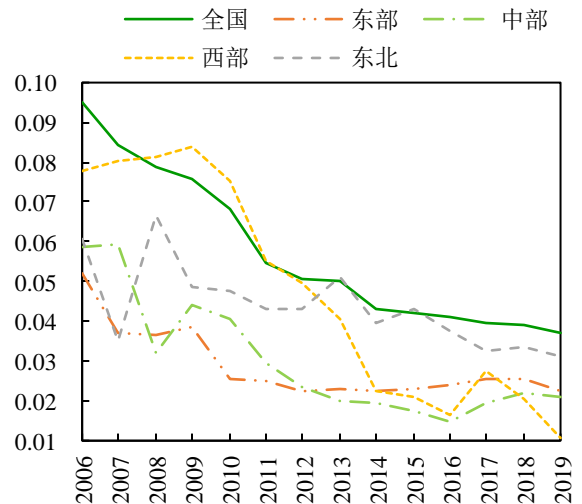


图5：2006-2019年绿色转型发展指数整体及四大区域内相对差异变化趋势

（2）区域间差异分析

如图6所示，在评价年内，各区域间相对差异总体呈缩小趋势，东-东北、东-西部和东-中部地区间基尼系数起点较高，除个别年份外，整体呈逐渐下降趋势，年均减速分别为-6.03%、-8.40%和-10.16%，东-中部地区间基尼系数减速最快。中-西、中-东北和西-东北地区间基尼系数起点较低，中-西和中-东北地区间基尼系数在2016-2018年有所回升，整体呈“多缩小-少扩大”波动递减趋势，年均减速分别为-5.92%、-2.86%和-6.10%，波动幅度较小。

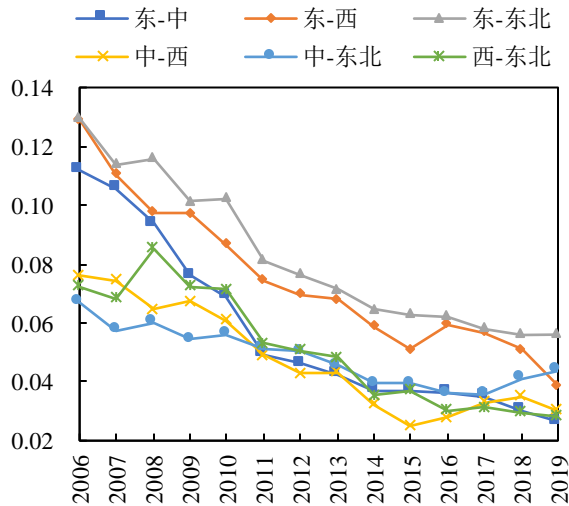


图6：绿色转型发展指数四大区域间相对差异变化趋势

(3) 区域差异构成及贡献率

如图7所示，在评价年内，我国绿色转型发展水平区域差异中，区域间差异贡献率最大，其次是区域内差异，最后是超变密度，各自的平均贡献率分别为64.51%、20.91%和15.58%。区域内差异贡献率变化比较平稳，在19.72%-23.07%之间小幅波动，年均增速为0.27%；区域间差异贡献率总体呈“下降-上升-波动”的增长趋势，整体变化范围为65.54%-69.39%，年均增速为0.76%。超变密度贡献率变化趋势与区域间贡献率变化趋势相反，存在此消彼长的变化关系，总体呈“上升-下降-波动”的下降趋势。综上所述，在评价年内，区域间相对差异是绿色转型发展指数存在区域差异的主要原因，此外，区域间交叉重叠现象逐渐减弱，区域间差异贡献率略有增长。

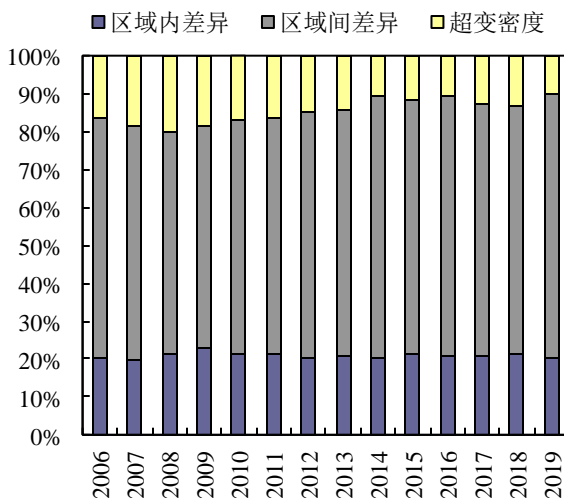


图7：绿色转型发展指数区域差异构成贡献度变化趋势

3、绿色转型发展水平区域差异的动态演化与空间聚集特征

(1) 时序动态演化

整体视角。如图8所示，在评价年内，核密度曲线逐渐右移，主峰波峰逐渐变高，宽度逐渐变窄，极化现象得到改善，这表明绿色转型发展水平在逐渐提升，各省份间的差距在逐渐减小，整体逐渐趋于协调发展状态。2006年核密度曲线呈现“主峰+右侧峰”分布，有2个右侧峰，2019年，双主峰已过渡为单个主峰，呈现稳定的高-高聚集和低-低聚集的“主峰+左侧峰”分布。

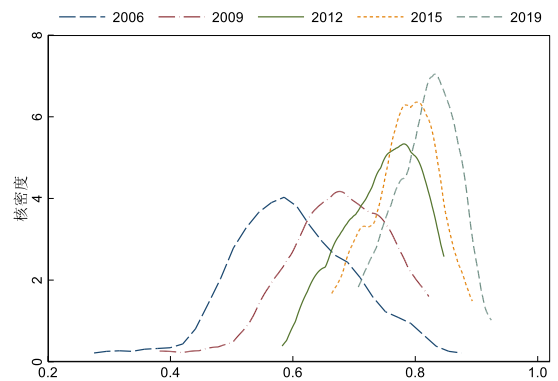
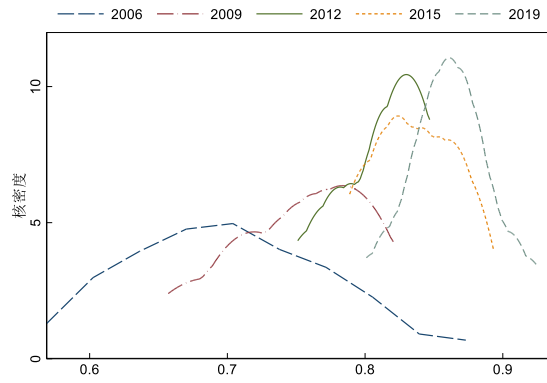
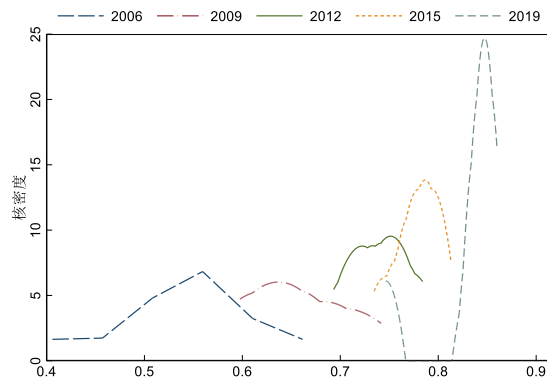


图8：整体绿色转型发展水平演进图

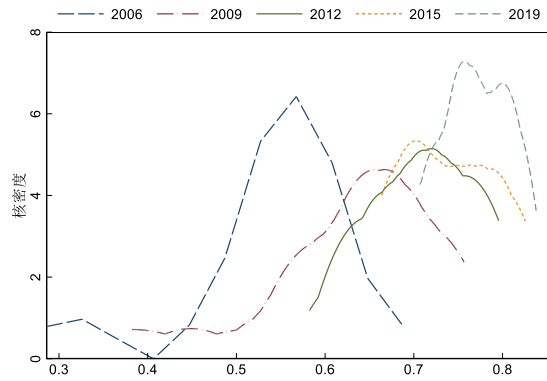
区域视角。如图9所示，东部地区核密度曲线在2006年没有侧峰，存在右拖尾现象，到2019年，极化现象明显得到缓解，呈现稳定的高水平单峰聚集现象。中部地区在2006年没有侧峰，存在左拖尾现象，到2019年核密度曲线主峰波峰高度明显增加，极化现象有所加剧，呈现“主峰+左侧峰”分布状态。西部地区核密度曲线在2006存在左侧峰，存在左拖尾现象，到2019年，侧峰数量明显减少，呈现稳定的“主峰+右侧峰”分布。东北地区在样本年都没有侧峰，无明显极化现象，到2019年，转变为左拖尾，整体呈现单峰聚集现象。



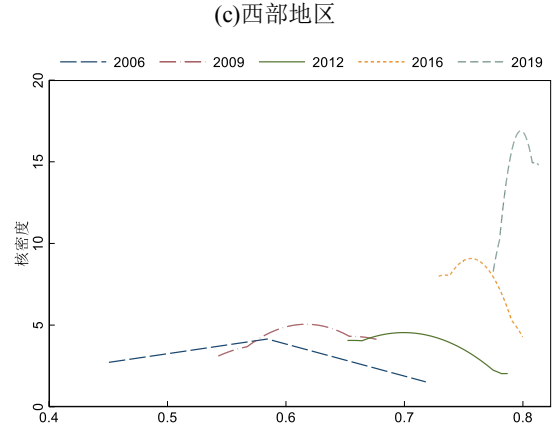
(a)东部地区



(b)中部地区



(c)西部地区



(d)东北地区

图 9：四大区域绿色转型发展水平的演进图

(2) 空间聚集特征

如表 4 所示,2006-2019 年,全局 Moran's $I > 0$, 在 5% 的显著性水平下, 各省份绿色转型发展指数整体呈空间正相关。在评价年内, 全局 Moran's I 取值分布在 0.184~0.546 之间, 具备一定的波动性。为了深入探究各地区空间聚集效应的变化情况, 本文还分析了 2006 年和 2019 年局部 Moran's I 值, 如图 10a 和 10b 所示, 2006 年, 局部 Moran's I 为 0.330, 空间正相关。东部地区省份主要呈 H-H 聚集, 中部地区省份主要呈 L-H 聚集, 西部地区省份主要呈 L-L 聚集, 东北地区省份主要呈 L-L 聚集。2019 年, 局部 Moran's I 为 0.446, 聚集效应进一步增强。东部地区省份主要都属于 H-H 聚集; 中部地区省份主要为 H-H 聚集, 西部地区省份主要任属于属于 L-L 聚集, 东北地区省份都属于 L-L 聚集。

表 4：我国绿色转型发展指数的全局 Moran's I 值

年份	Moran's I	E(I)	Sd(I)	z	P-value
2006	0.330***	-0.034	0.121	3.020	0.001
2007	0.262***	-0.034	0.119	2.483	0.007
2008	0.227**	-0.034	0.119	2.199	0.014
2009	0.184**	-0.034	0.119	1.835	0.033
2010	0.231**	-0.034	0.121	2.201	0.014
2011	0.460***	-0.034	0.124	3.998	0.000
2012	0.495***	-0.034	0.123	4.291	0.000
2013	0.508***	-0.034	0.124	4.380	0.000
2014	0.546***	-0.034	0.124	4.681	0.000
2015	0.487***	-0.034	0.124	4.223	0.000
2016	0.486***	-0.034	0.123	4.223	0.000
2017	0.385***	-0.034	0.123	3.401	0.000
2018	0.434***	-0.034	0.124	3.792	0.000
2019	0.446***	-0.034	0.123	3.894	0.000

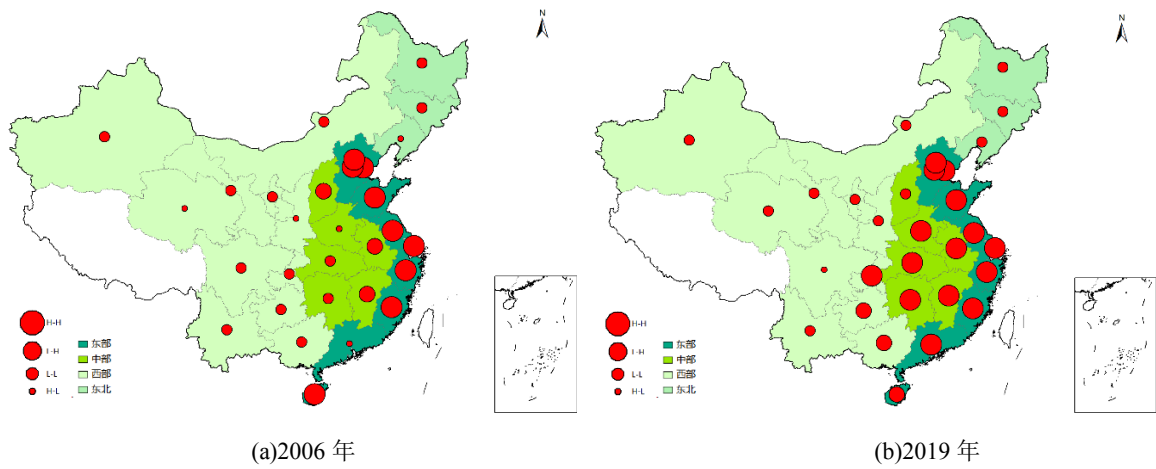


图 10：我国绿色转型发展指数局部 Moran's I 分布图

五、结论和政策建议

1、研究结论

本研究的研究结论可概括为以下几点：

在评价年内，我国绿色转型发展水平整体呈稳定增长趋势，2013 年之后增长动力减弱。三个子维度的贡献度都比较显著，但评价得分差异较大，政府环境治理和企业绿色生产评价得分较高且皆呈增长趋势，而居民绿色消费评价得分呈下降趋势，且综合得分较低仅为 0.492，明显低于其他子维度，严重制约绿色转型发展进程。

我国绿色转型发展水平区域差异主要是由区域间相对差异引起的。四大区域绿色转型发展水平区域内差异在逐渐缩小，东部地区最先处于稳定的均衡发展状态，中部地区逐渐达到并优于东部地区，西部地区缩小区域内相对差异的速率较快，而东北地区缩小区域内相对差异的速率较慢，西部和东北地区整体均衡发展程度不高。此外，东部-东北、东部-西部和东部-中部地区间相对差异较大，但彼此间的差异在不断缩小，中部-西部地区和中部-东北地区间的相对差异有所扩大，而西部-东北地区的相

对差异在逐渐缩小。

各区域绿色转型发展水平的绝对差异在逐步减小,逐渐形成稳定的 H-H 聚集和 L-L 聚集现象。东部地区一直处于 H-H 聚集状态,沿海省份对中部地区具有明显的辐射带动作用,中部地区逐渐转变为稳定的 H-H 聚集状态。此外,虽然东部地区的京津冀城市群和西部地区的川渝城市群绿色转型发展水平较高,但其自身已形成稳定的 H-H 聚集状态,对周边属于东北和西部地区的省份无明显辐射带动效应,因此,西部和东北地区整体仍处于 L-L 聚集状态,

2、政策建议

促进政府-企业-居民三位参与主体协同推动绿色转型发展。一方面政府作为现阶段对绿色转型发展影响力最大的参与主体,应尽快提升自身环境治理水平。进一步完善绿色转型发展的顶层设计,建立健全相关法律法规,为绿色转型发展提供法律保障。另一方面政府作为绿色转型发展的宏观主体,还应简政放权,增强绿色转型发展市场活力,让社会公众都参与到绿色转型发展中来,如加快建设碳排放交易市场,落实绿色税制,推行绿色消费券等。政府应充分发挥其在绿色转型中的重要引导作用,尤其是对绿色消费方面的引导

缩小与四大区域绿色转型发展水平的相对差异,促进各区域均衡发展。保持东部地区绿色转型发展领先优势,鼓励东部地区建立绿色技术创新研究基地,吸收国内外绿色技术创新企业和人才,突破绿色转型发展瓶颈,打造绿色转型发展的先进示范区。中部地区自身还需出台相关惠利补贴政策,吸引资本和人才流入,为绿色产业发展提供良好的营商环境和匹配的劳动质量,加快与东部地区生产要素的联通融通。西部地区需完善基础设施设施建设,注重对生态环境资源的保护和开发,充分挖掘区域内自然景观的经济价值。东北地区还需加快实现产业转型升级,勇于走出传统制造业发展的舒适圈,充分利用京津冀城市群的资源和机遇。

缓解我国绿色转型发展水平 H-H 聚集和 L-L 聚集两级分化现象,强化绿色转型发展高水平地区的

辐射带动作用。关于西部地区主要呈 L-L 聚集现象,东部和中部地区需增加对西部地区人才、资金和技术等要素的支持,充分发挥川渝城市群的辐射带动作用,促进西部地区旅游产业的发展。关于东北地区主要呈 L-L 聚集现象,东部地区应扩大京津冀城市群的辐射范围,将部分优势产业转移至东北地区,带动东北地区发展特色冰雪旅游产业,打造京津冀城市群与东北地区融合发展的示范区,引导东北地区实现绿色转型发展。

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债权融资还是股权融资？ ——生鲜平台冷链服务创新的融资策略

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摘要：针对供应商、第三方物流服务商（TPL）和平台服务商（平台商）构成的生鲜平台冷链，考虑 TPL 向平台商融资用于冷链服务创新的情形，探究了 TPL 融资策略（债权和股权）对生鲜平台冷链运作的影响。研究发现：债权融资下，服务创新成本因子和融资利率是制约冷链服务创新的重要因素，因其上涨会抑制冷链创新水平的提升，降低冷链绩效；自有资金的下降会使 TPL 受损、平台商受益。股权融资下，服务创新成本因子的影响同债权融资情形，估值水平的上升或固定资产的增加会加大平台商的资金投入力度，激励 TPL 进行冷链创新，故会使 TPL 和供应商受益。对比两种融资策略，发现：股权融资将导致更高的平台佣金率和更低的产品销售价格，进而抑制供应商参与股权融资冷链的动力；TPL 若以提升冷链创新服务水平为目的进行融资，应参照市场规模大小来确定融资策略，市场规模较小（较大）时，选择股权（债权）融资。数值算例显示，债权融资下各成员及系统利润对产品价格弹性变化较之股权融资情形更为敏感，产品价格弹性较低（较高）时，所有成员均倾向于股权（债权）融资。

关键词：TPL；生鲜平台；冷链服务创新；债权融资；股权融资

Debt financing or equity financing? ——Service innovation financing strategies of a fresh-product platform cold chain

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Abstract: This paper focus on a fresh-product platform cold chain composed of a supplier, a third-party logistics service provider (TPL) and a platform service provider (platform). Considering the TPL financing from the platform for cold chain service innovation, we explore the impact of his financing strategies including debt financing and equity financing on the cold chain operation. Research shows the service innovation cost factor and the financing interest rate are both important factors restricting cold chain service innovation in debt financing, since their rise will inhibit the improvement of the innovation level and reduce the cold chain performance. The decline in TPL's own funds will damage himself, and benefit the platform. In equity financing, the impact of the cost factor on the system is the same as that in debt financing. The rise in valuation or the increase in fixed assets will prompt the platform to increase capital investment, thereby encouraging the TPL to carry out service innovation which benefit both the TPL and the supplier. Comparing the two financing strategies, we find that equity financing will lead to a higher platform commission rate and a lower product sales price, which will inhibit supplier's motivation to participate in equity financing. If TPL's financing purpose is to improve innovation service level, he should refer to the market size to determine his financing strategy, that is, when the market is small (larger), equity financing (debt financing) should be preferred. Numerical examples show that the profits of each member and the system in debt financing are more sensitive to the product price elasticity than in equity financing. When the price elasticity is lower (higher), all members prefer equity financing (debt financing).

Key words: TPL; fresh-product platform; cold chain service innovation; debt financing; equity financing

一、引言

受益于电子商务的飞速发展,国内冷链物流在数字贸易中承担的角色愈加重要,尤其自我国进入十四五时期以来,在“完建设现代物流体系,加快发展冷链物流”的宏观政策背景下,冷链物流成为助力乡村振兴、加快农业农村现代化建设,构建国内国际“双循环”新发展格局的一个重要发力点;同时,新冠疫情防控常态化也对冷链物流提出新的更高要求,冷链物流发展面临新的机遇和挑战(《“十四五”冷链物流发展规划》,2021)。可以说,生鲜冷链物流的发展进入了历史最佳时期。

生鲜产品生产的地域性与消费的普遍性之间的对立,决定了远距离冷链运输成为其供应链运作的必然趋势^[1]。供应商在电商平台上直销生鲜产品如新鲜水果、蔬菜、生鲜肉类等打通了距离障碍,但同时也给冷链物流服务提出了更高的要求。冷链物流服务企业通过开展冷链基建、革新冷链技术(如车联网、大数据)等冷链服务创新方式,可提高自身生产力并以高质量服务来吸引更多的消费需求,但资金制约、融资成本高、融资风险大一直是冷链服务创新面临的难题。目前,物流行业常见的融资方式形式多样,如信贷融资、保税仓融资、公开上市、私募股权融资等,依据融资方偿付方式的不同,又可将其区分为债权融资和股权融资两种。前者是指投资方通过借款的方式向融资企业提供资金,融资企业到期偿还借款并附带一定利息;后者则指融资企业获得的资金无须偿还,但要与投资方分享自身的盈利^[2]。不同融资策略对供应链利润分配的影响具有明显的差异性,从而会对供应链运营决策产生不同影响。因此,如何选择不同融资策略提升供应链运作绩效成为近年来供应链金融领域研究的一类热点问题。

现有供应链融资领域的研究仍以“供应商/制造商+零售商”的传统供应链结构为主,融资方为供应链内部的一个成员,融资动机与融资方企业的类型相关,如零售商融资主要用于提升支付能力或开拓市场,而供应商/制造商融资的动机主要用于扩张产能或开拓市场。从资金来源看,融资资金可能

来自于供应链内部或外部。其中,内部融资是指供应链中资金充裕的成员企业向资金不足的成员企业提供资金的模式,如Feng等^[3]考虑了零售商向上游制造商融资的情形,王文利等^[2]和林强等^[17]则考虑了供应商向下游制造商或零售商融资的情形,尽管这些文献研究侧重点有所差异,但均认为融资方的自有资金是影响投资方决策的关键指标,因自有资金的多少反映了融资企业的破产风险。外部融资是指融资方的资金来源于供应链外部的金融机构,如银行、外部投资者等,其因信息不透明往往在风险管控方面更为谨慎,如王宇和于辉^[4]、Yang等^[6]、Xia等^[7]、Dong等^[13]探究了生产成本、市场信誉、资产估值、市场竞争等一系列因素对融资风险的影响。上述研究均考虑了单一的内部或外部融资,还有部分研究同时考虑了供应链内外部融资,提出了内外部混合融资方案,如Jing和Seidmann^[8]、Tang和Yang^[9]、汤婷等^[14]、谭月平等^[16]等。从融资策略看,多数文献考虑了单一的债权融资^[2, 8-15]或股权融资^[3, 4, 18],发现融资企业资产架构(包括自有资金与净资产等)会直接影响融资利率或分红比例,进而影响投融资双方的策略选择。少数文献同时考虑了两种融资策略并对其进行比较,认为企业融资策略选择会受到自有资金量^[2]、企业成长性^[5]、成本优势^[6]、融资风险因素^[7]、消费者偏好^[16]等诸多要素的影响。

少数文献进一步引入TPL服务商,探讨了物流服务外包下的供应链融资问题。黄帅和樊治平^[10]针对“TPL+零售商”型的两级供应链,探究了TPL如何依据零售商的自有资金提供不同融资服务以缓解零售商资金约束。还有研究进一步引入TPL上游企业,扩展至三级供应链的融资问题。例如,Zhou^[11]和Wang等^[15]分别探讨了外部融资(制造商担保和TPL担保)和内部融资(TPL投资)情形下融资方式选择和投资偏好等问题。值得注意的是,上述文献中,融资方仍为零售商或制造商。据我们所掌握的文献,Fu等^[18]首次探讨了TPL为融资方的情形,针对供应商、TPL和平台商构成的供应链,考虑供应商通过平台商在线销售产品且平台商向其收取佣

金获利的情形，探讨了 TPL 通过外部金融机构进行技术创新，进而降低运营成本的股权融资策略。本文拟借鉴文献[18]的供应链结构，探究生鲜平台冷链服务创新的融资策略，不同之处主要在于（本文 VS. 文献[18]）：1）融资动机不同：冷链服务创新 VS. 降低物流成本；2）资金来源不同：平台商（内部）VS. 投资者（外部）；3）融资策略不同：债权融资&股权融资 VS. 股权融资；4）融资财务指标不同：自有资金&固定资产 VS. 总资产估值；5）技术创新风险分析：无 VS. 有。

综上，本文拟针对供应商、TPL 和平台商构成的生鲜平台冷链系统，探究 TPL 冷链服务创新融资策略（债权融资和股权融资）对生鲜平台冷链运作的影响。创新点在于：1）考虑 TPL 在平台冷链系统内部融资，即 TPL 和平台商分别为融资方和投资方的情形，进行冷链服务创新；2）对比分析了债权融资和股权融资对生鲜平台冷链运作的影响；3）考虑服务创新失败率，分析了不同融资策略的抗风险能力。

二、问题描述与基本假设

考虑一个由单供应商、单平台服务商（以下简称平台商）和单 TPL 冷链服务商（以下简称 TPL）组成的三级生鲜平台冷链系统。供应商采取直销的方式，通过平台商提供的在线交易平台向终端市场的消费者销售单一品种的生鲜产品，其单位产品销售价格和运营成本分别为 p 和 c_s ，有 $p > c_s > 0$ ，且每销售一个单位的产品，需向平台商支付佣金 rp ，其中， r 为平台佣金率， $0 < r < 1$ 。平台商提供数字平台交易服务且仅通过向供应商收取佣金获利，其单位运营成本为 c_r ， $c_r > 0$ 。供应商将冷链物流外包给专业的 TPL，TPL 收到运费后即进行物流活动，其单位产品的冷链物流服务价格（以下简称物流价格）和物流成本分别为 l 和 c_l ， $l > c_l > 0$ 。假设所有的贸易程序和数据传输均通过在线交易平台进行，系统成员均为完全理性和风险中性的经济人，各自追求自身利润最大化，系统中所有信息均为各方共识。

为提升生鲜平台冷链的物流服务水平，进而提高生鲜产品的内在价值和冷链运作效率，TPL 拟通

过开展冷链基建、革新冷链技术（如车联网、大数据）等方式开展冷链服务创新。假设 TPL 的冷链服务创新水平为 e ($e \geq 1$)，其中， $e = 1$ 表示冷链服务创新前 TPL 的初始冷链服务水平。鉴于冷链创新投入成本随冷链服务创新水平边际递增，不失一般性，我们假设冷链创新投入成本函数为：

$$c(e) = \frac{\beta e^2}{2}. \quad (1)$$

其中， β 为冷链服务创新成本因子， $\beta > 0$ 。冷链服务创新水平 e 的高低会直接影响到生鲜产品到达终端消费者的新鲜度 $\theta(e)$ ，这源于完善的冷链设施和先进的冷链技术更有利于提高产品新鲜度水平。参考张旭等^[19]，令 $\theta(e) = \theta_0 e$ ，其中， θ_0 为冷链服务创新前生鲜产品的初始新鲜度，且有 $0 < \theta_0 \leq 1$ 。由于生鲜产品的市场需求受其销售价格和新鲜度的综合影响，参考 Cai 等^[20]，假设生鲜产品的市场需求函数为：

$$D(p, e) = Ap^{-b}\theta_0 e. \quad (2)$$

其中， A 为潜在的市场容量 ($A > 0$)， b 为价格弹性系数 ($b > 1$)。 $b > 1$ 是指市场需求对价格敏感的情形，已有实证研究成果表明，果蔬、牛奶、肉蛋等生鲜产品均会因价格上涨导致需求大幅下降^[21]。这一假设在供应链运营管理领域中极为常见，如 Blackburn 和 Scudder^[22]、吴庆等^[23]、熊峰等^[24]均采用了此类的假设。

由于冷链创新投入耗资巨大，TPL 往往面临资金短缺的局面，继而会影响供应链各成员企业及系统的盈利能力与竞争力。相对于依赖银行的外部融资模式，供应链内部融资情形下，作为投资方的企业更了解借款企业生产成本、市场规模等各方面的信息，并会根据自身和供应链整体利益制定最佳融资策略。鉴于实际中大型平台商如阿里、京东等电商平台往往资金充裕，我们拟考虑 TPL 在资金受限情形下向平台商进行内源融资用以冷链服务创新的情形。

为探究资金约束情形下 TPL 在供应链上的内源融资策略，参照王宇和于辉^[4]，假设融资前 TPL 的净资产为 V ($V > 0$)，在不考虑负债和其他资产的情形下，企业净资产为固定资产和自有资金之和。令

$E(E > 0)$ 表示固定资产值, $\eta(\eta > 0)$ 表示自有资金, 则 $V = E + \eta$ 。假设 TPL 资金量能够满足初始冷链服务投入但无法自行满足更大力度的冷链创新投入的需要, 即 $\frac{\beta}{2} \leq \eta \leq c(e)$, 其进行冷链服务创新时优先考虑使用自有资金, 再向平台商进行融资 (股权

融资或债权融资), 故其融资金额为 $c(e) - \eta$ 。为简化问题, 进一步假设平台商资金充裕, 平台商可通过向 TPL 提供融资服务, 来获取利息或分红, 系统结构如图 1 所示。

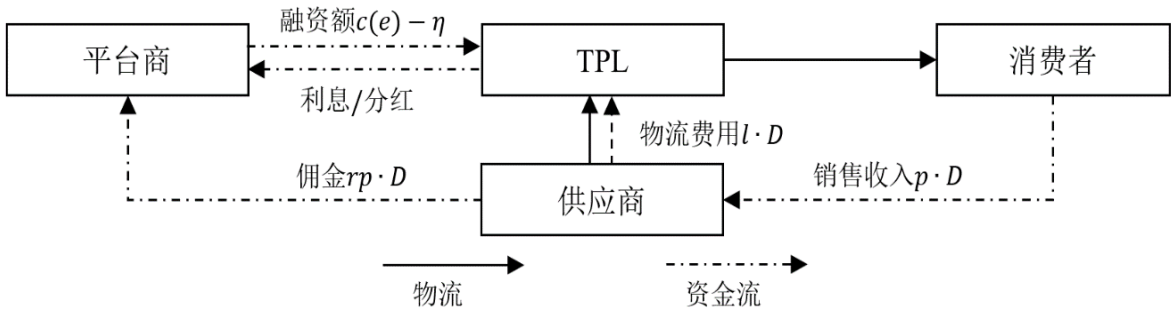


图 1 生鲜平台冷链系统结构图

本文主要用到的符号及符号说明见表 1。

表 1 符号及符号说明表

符号	符号说明	符号	符号说明
决策变量及其最优解/均衡解		系统参数	
p, p^i	供应商决策的单位产品的销售价格	θ_0	生鲜产品初始新鲜度
r, r^i	平台商向供应商收取佣金的佣金率	β	冷链服务创新成本因子
l, l^i	TPL 向供应商收取的物流价格	$c(e)$	冷链服务创新投入成本
e, e^i	冷链服务创新水平	$\theta(e)$	生鲜产品新鲜度
系统期望利润函数及最优/均衡状态下的期望利润		A	产品的潜在市场规模
π_s, π_s^i	供应商期望利润	b	产品市场需求价格弹性
π_r, π_r^i	平台商期望利润	D	产品市场需求函数
π_l, π_l^i	TPL 的期望利润	V	TPL 净资产价值
Π, Π^i	供应链成员总利润	E	TPL 固定资产价值
系统参数		η	TPL 自有资金
c_s	供应商单位运营成本	δ	TPL 固定资产抵押率
c_r	平台商单位运营成本	α	市净率法估值水平
c_l	TPL 单位物流成本	I	债权融资利率

注: $i = DF$ 表示债权融资下的均衡结果; $i = EF$ 表示股权融资下的均衡结果。

三、数学模型及均衡分析

本节将引入两种典型的融资策略，即债权融资和股权融资，考虑 TPL 采用两种融资策略向平台商融资的情形，考虑平台商为主导者，供应商和 TPL 为跟随者的情形，三方之间进行 Stackelberg 博弈，其具体博弈过程为：(1) 平台商决策平台佣金率 r ；

(2) TPL 依据平台佣金率 r ，决策物流价格 l 和冷链服务创新水平 e ；(3) 供应商根据平台收取的佣金率 r 、TPL 的物流价格 l 和冷链服务创新水平 e ，决策产品销售价格 p 。

1、债权融资策略情形 (DF 情形)

结合第 2 节的问题描述，当采用供应链内部融资方式进行债权融资时，TPL 向资金充裕的平台商进行融资，融资金额为 $c(e) - \eta$ 。假设平台商设定的债权融资利率为 $I(I \geq 0)$ ， I 为外生变量，由金融市场供需状况决定，则债务到期时，TPL 应向平台商偿还的本金和利息之和为 $(1+I)(c(e) - \eta)$ 。一方面，受信用评价等级和信息对称性等因素的影响，平台商往往要求 TPL 以固定资产作为抵押，设抵押率为 $\delta(0 < \delta \leq 1)$ ，由于 TPL 抵押物价值有限，故融资额本息和应不高于最高抵押贷款额度 δE ；另一方面，结合应收账款融资、库存融资、预付款融资与战略融资等一系列供应链融资手段，TPL 可贷到超出固定资产抵押贷款额度的资金^[25]，设超出比例为 $\varphi(\varphi > 0)$ ，此时，可借贷金额为 $\delta E(1 + \varphi)$ ，因此， $0 \leq c(e) - \eta \leq \delta E(1 + \varphi)$ ，再结合 $e \geq 1$ ，可得： $\max\left\{1, \sqrt{\frac{2\eta}{\beta}}\right\} \leq e \leq \sqrt{\frac{2(\delta E(1+\varphi)+\eta)}{\beta}}$ 。又因我们在第 2 节中假设 $\eta \geq \frac{\beta}{2}$ ，故 $\sqrt{\frac{2\eta}{\beta}} \geq 1$ ，从而， $\sqrt{\frac{2\eta}{\beta}} \leq e \leq \sqrt{\frac{2(\delta E(1+\varphi)+\eta)}{\beta}}$ 。

(1) 供应商决策

基于第 2 节的问题描述，DF 情形下，对于任意给定的冷链服务创新水平 e 、平台佣金率 r 和物流价格 l ，供应商的利润函数可表示为：

$$\pi_s(p|e, r, l) = ((1-r)p - l - c_s) \cdot D(p, e). \quad (3)$$

由式 (3) 易知，DF 情形下供应商利润函数是关于 p 的严格凹函数，易得定理 1。

定理 1. DF 情形下，对于任意给定的冷链服务创新水平 e 、平台佣金率 r 和物流价格 l ，供应商存在

唯一最优的产品销售价格为：

$$p^{DE}(l, r) = \frac{b(l+c_s)}{(b-1)(1-r)}. \quad (4)$$

定理 1 及后文所有定理及推论的证明过程均见附录。

由式 (4) 易知， $\frac{\partial p^{DE}(l, r)}{\partial r} > 0$ ， $\frac{\partial p^{DE}(l, r)}{\partial l} > 0$ ，即供应商的产品销售价格随平台佣金率和物流价格的增加而递增。此外， $\frac{\partial p^{DE}(l, r)}{\partial b} = -\frac{l+c_s}{(b-1)^2(1-r)} < 0$ ，即供应商的销售价格还会随产品价格弹性系数的增加而递减，此时，供应商往往会针对高价格弹性商品采取低价抛售的方式来吸引消费者购买。

(2) TPL 的决策

DF 情形下，基于给定的平台佣金率 r ，TPL 决策冷链服务创新水平 e 和物流价格 l ，实现自身利润最大化，故 TPL 的利润函数可刻画为

$$\pi_l(l, e|r) = (l - c_l) \cdot D(p, e) - \eta - (1+I)(c(e) - \eta). \quad (5)$$

由于 TPL 依据供应商的反应函数进行决策，故将式 (4) 带入式 (5) 中，整理可得：

$$\pi_l(l, e|r) = A\theta_0 \left(\frac{b(l+c_s)}{(b-1)(1-r)} \right)^{-b} (l - c_l)e - \frac{\beta(1+I)e^2}{2} + I\eta. \quad (6)$$

结合式 (6)，采用序贯的方法求解 TPL 的最优决策，首先，基于给定的冷链服务创新水平 e ，求解最优的物流价格 l ，可得定理 2。

定理 2. DF 情形下，对于给定的冷链服务创新水平 e 和平台佣金率 r ，TPL 的利润函数是关于 l 的单峰函数，存在唯一最优的物流价格满足：

$$l^{DF} = \frac{bc_l + c_s}{b-1}. \quad (7)$$

式 (7) 说明 TPL 的物流价格仅与其自身及供应商的单位运营成本、产品的价格弹性系数相关，而与债权融资相关的指标无关。此外， $\frac{\partial l^{DF}}{\partial b} = -\frac{c_l}{(b-1)^2} < 0$ ，即物流价格随产品价格弹性系数的增加而递减，这是由于当产品价格弹性系数增加时，需求对价格更加敏感，降低物流价格可获取更多来自需求量增长的利润，并达到刺激市场活性的目的。

将式 (7) 带入式 (6)，可得：

$$= -\frac{\beta(1+I)e^2}{2} + I\eta + \frac{A\theta_0(c_l+c_s)^{1-b}(1-r)^b e}{b^{2b}(b-1)^{1-2b}}. \quad (8)$$

再结合式(8), 求解最优的冷链服务创新水平 e , 可得定理 3.

定理 3. DF 情形下, 对于给定的平台佣金率 r , TPL 利润函数是关于 e 的严格凹函数, 存在唯一最优的冷链服务创新水平满足:

$$e^{DF}(r) = \begin{cases} \sqrt{\frac{2(\lambda E(1+\varphi)+\eta)}{\beta}} & 0 < \beta < \beta_1, \\ \frac{A\theta_0(c_l+c_s)^{1-b}(1-r)^b}{b^{2b}(b-1)^{1-2b}\beta(1+I)} & \beta_1 \leq \beta \leq \beta_2, \\ \sqrt{\frac{2\eta}{\beta}} & \beta_2 < \beta \leq 2\eta. \end{cases}$$

其中, $\beta_1 = \frac{A^2\theta_0^2(c_l+c_s)^{2-2b}(1-r)^{2b}}{2(\delta E(1+\varphi)+\eta)b^{4b}(b-1)^{2-4b}(1+I)^2}$, $\beta_2 = \frac{\eta}{\beta_1(\delta E(1+\varphi)+\eta)}$.

定理 3 说明, 由于冷链服务创新水平满足 $\sqrt{\frac{2\eta}{\beta}} \leq e \leq \sqrt{\frac{2(\delta E(1+\varphi)+\eta)}{\beta}}$, 故其均衡结果为分段函数, 取值与冷链服务创新成本因子 β 密切相关。当 $\beta_0 \leq \beta < \beta_1$ 时, 由于冷链服务创新投入对冷链服务创新水平不敏感, 故冷链服务创新带来的利润增加总能超过成本支出, 此时, TPL 会选择最大限度的进行融资但会受限于可融资的金额, 从中也可看出, 更高的质押率有利于 TPL 加大创新力度; 相反, 当 $\beta_2 < \beta$ 时, 由于冷链服务创新投入对冷链服务创新水平过于敏感, 造成 TPL 缺少融资的动力, 继而为降低创新投入成本而仅依靠自有资金做出最低限度的冷链服务创新。当 $\beta_1 \leq \beta \leq \beta_2$ 时, 即冷链服务创新成本因子处于两个阈值之间时, TPL 最优的冷链创新服务水平取得内点最优解, 此时, 容易看出, 冷链服务创新水平与冷链创新服务因子、融资利率和平台佣金率负相关, 与市场规模、TPL 和供应商的边际成本正相关。

(3) 平台商决策

DF 情形下, 平台商基于供应商和 TPL 的反应函数, 决策平台佣金率 r , 使得自身利润最大化, 其利润函数可刻画为:

$$\pi_r(r) = (rp - c_r) \cdot D(p, e) + I(c(e) - \eta). \quad (10)$$

将式(4)、(7)和(9)带入式(10), 整理可得式(11):

$$\pi_r(r) = \frac{A^2\theta_0^2(2(b-1)^2c_r(1+I)(r-1) + (2b^2r + I((l - 2\beta b^{4b}(b-1)^{3-4b}(c_l+c_s)^{2b-1}(1-r) - I\eta))}{2\beta b^{4b}(b-1)^{3-4b}(c_l+c_s)^{2b-1}(1-r)}$$

结合式(11), 求解最优的平台佣金率, 可得定理 4.

定理 4. DF 情形下, 平台商的利润函数 $\pi_r(r)$ 关于 r 是单峰的, 存在唯一最优的佣金率满足:

$$r^{DF} = \frac{2(b-1)^2(1+I)c_r + (b+I)(c_s+c_l)}{\bar{c}} \quad (12)$$

其中, $\bar{c} = 2(b-1)^2(1+I)c_r + (2b^2(1+I) - bI + I)(c_s+c_l)$.

联立三方决策, 可得到 DF 情形下, 均衡状态下物流价格和平台佣金率分别满足式(9)和式(12), 冷链服务创新水平、产品销售价格及市场需求分别为:

$$e^{DF} = \frac{A\theta_0 \bar{c}^{-b}(c_l+c_s)}{\beta b^b(b-1)^{1-2b}(2b-1)^b(1+I)^{1-b}}, \quad (13)$$

$$p^{DF} = \frac{b\bar{c}}{(b-1)^2(2b-1)(1+I)}, \quad (14)$$

$$D^{DF} = \frac{A^2\theta_0^2 \bar{c}^{-2b}(c_l+c_s)}{\beta b^{2b}(b-1)^{1-4b}(2b-1)^{-2b}(1+I)^{1-2b}}. \quad (15)$$

定理 4 给出了平台供应链中各方成员在 DF 情形下博弈的内点均衡结果。对上述参数进行灵敏度分析, 容易得到推论 1。

推论 1. DF 情形下, 系统取得内点均衡时, 1) $\frac{\partial e^{DF}}{\partial \beta} < 0$, $\frac{\partial D^{DF}}{\partial \beta} < 0$, $\frac{\partial p^{DF}}{\partial \beta} = \frac{\partial l^{DF}}{\partial \beta} = \frac{\partial r^{DF}}{\partial \beta} = 0$; 2) $\frac{\partial e^{DF}}{\partial I} < 0$, $\frac{\partial D^{DF}}{\partial I} < 0$, $\frac{\partial p^{DF}}{\partial I} < 0$, $\frac{\partial l^{DF}}{\partial I} < 0$, $\frac{\partial r^{DF}}{\partial I} = 0$; 3) $\frac{\partial p^{DF}}{\partial b} < 0$, $\frac{\partial l^{DF}}{\partial b} < 0$, 当 $0 < c_r < \frac{(2b^2+4bl-I)(c_l+c_s)}{2(3b^2-4bl+1)(1+I)}$ 时, $\frac{\partial r^{DF}}{\partial b} < 0$, 当 $c_r > \frac{(2b^2+4bl-I)(c_l+c_s)}{2(3b^2-4bl+1)(1+I)}$ 时, $\frac{\partial r^{DF}}{\partial b} > 0$ 。

推论 1 表明, DF 情形下, 冷链服务创新成本因子和债权融资利率的上涨, 均会增加 TPL 冷链服务创新的支出, 进而抑制 TPL 进行冷链服务创新融资、提升冷链创新服务水平以及开拓市场的意愿, 进而导致市场需求量随之下降。不同的是, 债权融资利率上涨时, 产品销售价格和佣金率随之下降, 此外,

产品销售价格和物流价格均与产品价格弹性系数负相关，这一点较为常见。将式(7)、式(12)~(15)

分别带入式(3)、(8)和(11)，可得冷链各成员及系统整体利润分别为：

$$\pi_l^{DF} = \frac{A^2 \theta_0^2 \bar{c}^{-2b} (c_l + c_s)^2}{2\beta b^{2b} (b-1)^{2-4b} (2b-1)^{-2b} (1+I)^{1-2b}} + I\eta, \quad (16)$$

$$\pi_s^{DF} = \frac{A^2 \theta_0^2 \bar{c}^{-2b} (c_l + c_s)^2}{\beta b^{2b-1} (b-1)^{3-4b} (2b-1)^{-2b} (1+I)^{1-2b}}, \quad (17)$$

$$\pi_r^{DF} = \frac{A^2 \theta_0^2 \bar{c}^{1-2b} (c_l + c_s)}{2\beta b^{2b} (b-1)^{3-4b} (2b-1)^{1-2b} (1+I)^{2-2b}} - I\eta, \quad (18)$$

$$\Pi^{DF} = \frac{A^2 \theta_0^2 \bar{c}^{-2b} (c_l + c_s) (2(b-1)^2 (1+I) c_r + (8b^2 (1+I) - b(5+6I) + 1+2I) (c_l + c_s))}{2\beta I^2 (b-1)^{3-4b} (2b-1)^{1-2b} (1+I)}. \quad (19)$$

结合式(16)~(19)，分别对关键参数进行灵敏度分析，可得推论2。

推论 2. DF 情形下，系统取得内点均衡时，1) $\frac{\partial \pi_l^{DF}}{\partial \beta} < 0, \frac{\partial \pi_s^{DF}}{\partial \beta} < 0, \frac{\partial \pi_r^{DF}}{\partial \beta} < 0, \frac{\partial \Pi^{DF}}{\partial \beta} < 0$; 2) $\frac{\partial \pi_l^{DF}}{\partial I} < 0, \frac{\partial \pi_s^{DF}}{\partial I} < 0, \frac{\partial \pi_r^{DF}}{\partial I} < 0, \frac{\partial \Pi^{DF}}{\partial I} < 0$; 3) $\frac{\partial \pi_l^{DF}}{\partial \eta} > 0, \frac{\partial \pi_r^{DF}}{\partial \eta} < 0, \frac{\partial \Pi^{DF}}{\partial \eta} = 0$ 。

推论 2 表明，DF 情形下，冷链服务创新成本因子和融资利率的上涨会抑制冷链创新水平的提升和市场需求的上涨，进而导致供应链所有成员利润受损、供应链整体运作效率下降。值得注意的是，尽管融资利率的上升会给平台商带来额外利息，但其低于冷链服务创新水平下降造成的市场损失，故平台商利润也会随之下降，同时这也印证了文献[17]和[26]中的投资方可能会出现无息贷款的情况。此外，TPL 的自有资金会影响其自身及平台商利润，自有资金增加时，TPL 利润上涨而平台商由于融资收入下降而利润下跌，但由于供应商不参与融资，故其利润不受影响。同时，在 TPL 的自有资金无法满足冷链服务创新需要时，容易发现，自有资金类似于批发价格均为供应链内部的转移支付，故其不

会影响冷链系统的整体利润。

2、股权融资策略情形 (EF 情形)

股权融资 (Equity Financing) 是指企业股东让出部分企业所有权，通过增资来引进新股东的融资，总股本同时增加。参考于辉和王宇^[5]，EF 情形下，TPL 向平台商提出股权融资申请时，投融资双方会事先采用市净率法就 TPL 的净资产 V 进行估值并假设其估值水平 (市净率) 为 $\alpha (\alpha > 0)$ ， α 为外生参数。为简化问题，不考虑 TPL 的负债和其他资产，则其估值为 αV 且应满足 $\alpha V > \eta$ 。

当 TPL 通过股权融资筹集到资本 $c(e) - \eta$ 时，企业价值变为 $\alpha V + c(e) - \eta$ ，企业由原始股东 (TPL) 和投资者 (平台商) 共同拥有。为确保股权投资者作为财务投资者不干预 TPL 的运营，股权融资后 TPL 的运营决策仍由其原股东制定，有 $0 \leq c(e) - \eta \leq \alpha V$ 。TPL 的股东通过决策自身冷链服务创新水平，实现自身利润最大化的同时会按照其持有股权份额来获取利润，参考方磊等^[27]，TPL 在期末时按照股权比例与平台商进行分红。此时，股权融资策略下的 TPL 的利润函数为：

$$\pi_l(l, e|r) = \frac{\alpha V}{\alpha V - \eta + c(e)} \cdot (l - c_l) \cdot D(p, e) - \eta. \quad (20)$$

同理，平台商的利润函数为：

$$\pi_r(r) = \frac{c(e) - \eta}{\alpha V + c(e) - \eta} \cdot (l - c_l) \cdot D(p, e) + (rp - c_r) \cdot D(p, e) - (c(e) - \eta). \quad (21)$$

由于供应商不参与投融资，故其利润函数形式保持不变，同式(3)。

参照 DF 情形，采用逆向归纳法，可得定理 5。

定理 5. EF 情形下，若 $\alpha V \geq 2\eta$ ，则生鲜平台冷

链系统存在唯一的内点均衡解满足：

$$l^{EF} = \frac{bc_l + c_s}{b-1}, \quad (22)$$

$$e^{EF} = \sqrt{\frac{2(\alpha V - \eta)}{\beta}}, \quad (23)$$

$$r^{EF} = \frac{2(b-1)^2(\alpha V - \eta)c_r + ((b+1)\alpha V - 2\eta)(c_l + c_s)}{\bar{c}}, \quad (24)$$

$$p^{EF} = \frac{\bar{c}}{2(b-1)^3(\alpha V - \eta)}. \quad (25)$$

将式 (23) 和 (25) 带入式 (2)，可得：

$$D^{EF} = \frac{2^{\frac{1}{2}+b} A \theta_0 \bar{c}^{-b} (\alpha V - \eta)^{\frac{1}{2}+b}}{\sqrt{\beta} b^b (b-1)^{-3b}}. \quad (26)$$

其中， $\bar{c} = 2(b-1)^2(\alpha V - \eta)c_r + ((2b^2 - b + 1)\alpha V - 2(b^2 - b + 1)\eta)(c_l + c_s)$ 。

从定理 5 可以看出，EF 情形下，TPL 的物流价格与 DF 情形相同，即融资策略不会影响 TPL 的物流价格，但会导致其他决策的变化。对上述参数进行灵敏度分析，容易得到推论 3。

推论 3. EF 情形下，系统取得内点均衡时，1) $\frac{\partial e^{EF}}{\partial \alpha} < 0$, $\frac{\partial D^{EF}}{\partial \alpha} < 0$, $\frac{\partial p^{EF}}{\partial \alpha} = \frac{\partial l^{EF}}{\partial \beta} = \frac{\partial r^{EF}}{\partial \beta} = 0$; 2) $\frac{\partial e^{EF}}{\partial \alpha} > 0$, $\frac{\partial D^{EF}}{\partial \alpha} > 0$, $\frac{\partial p^{EF}}{\partial \alpha} < 0$, $\frac{\partial l^{EF}}{\partial \alpha} < 0$, $\frac{\partial r^{EF}}{\partial \alpha} = 0$; 3) $\frac{\partial p^{EF}}{\partial b} < 0$, $\frac{\partial l^{EF}}{\partial b} < 0$, $\frac{\partial e^{EF}}{\partial b} = 0$, 当 $0 < c_r < \frac{2(b-1)^2(\alpha V - \eta)}{((b^2 + 2b - 1)\alpha V + (2 - 4b)\eta)(c_l + c_s)}$ 时, $\frac{\partial r^{EF}}{\partial b} < 0$; 当 $c_r > \frac{2(b-1)^2(\alpha V - \eta)}{((b^2 + 2b - 1)\alpha V + (2 - 4b)\eta)(c_l + c_s)}$ 时, $\frac{\partial r^{EF}}{\partial b} > 0$ 。

推论 3 表明，EF 情形下，冷链服务创新水平及

市场需求均与冷链服务创新成本因子负相关，而产品销售价格、物流价格和平台佣金率均与其无关，其原因同 DF 情形。估值水平同样不影响物流价格，但不同的是，估值水平上升会导致 TPL 因股权分红比例上升而激励其进行冷链创新，进而促使冷链创新水平上升、市场需求上涨，这也促使让供应商有了更多的降价空间以获取更多利润，平台商也会降低自身的佣金率。

将式 (23) ~ (26) 分别带入式 (20)、(3) 和 (21) 中，可得冷链各成员及系统整体利润分别为：

$$\pi_l^{EF} = \frac{A \theta_0 \bar{c}^{-b} \alpha V (2\alpha V - 2\eta)^{b-\frac{1}{2}} (c_l + c_s)}{\sqrt{\beta} b^b (b-1)^{1-3b}} - \eta, \quad (27)$$

$$\pi_s^{EF} = \frac{A \theta_0 \bar{c}^{-b} (2\alpha V - 2\eta)^{b+\frac{1}{2}} (c_l + c_s)}{\sqrt{\beta} b^{b-1} (b-1)^{2-3b}}, \quad (28)$$

$$\pi_r^{EF} = \frac{A \theta_0 \bar{c}^{1-b} (2\alpha V - 2\eta)^{b-\frac{1}{2}}}{\sqrt{\beta} b^b (b-1)^{3-3b}} - \alpha V + 2\eta, \quad (29)$$

$$\Pi^{EF} = \frac{A \theta_0 \bar{c}^{-b} (2(b-1)^2(\alpha V - \eta)c_r + ((5b^2 - 5b + 2)\alpha V - 2(2b^2 - 2b + 1)\eta)(c_l + c_s))}{2^{\frac{1}{2}-b} \sqrt{\beta} b^b (b-1)^{3-3b} (\alpha V - \eta)^{\frac{1}{2}-b}} - \alpha V + \eta. \quad (30)$$

结合式 (27) ~ (30)，分别对关键参数进行灵敏度分析，可得推论 4。

推论 4. EF 情形下，系统取得内点均衡时，1) $\frac{\partial \pi_l^{EF}}{\partial \beta} < 0, \frac{\partial \pi_s^{EF}}{\partial \beta} < 0, \frac{\partial \pi_r^{EF}}{\partial \beta} < 0, \frac{\partial \Pi^{DF}}{\partial \beta} < 0$; 2) $\frac{\partial \pi_l^{EF}}{\partial \alpha} > 0, \frac{\partial \pi_s^{DF}}{\partial \alpha} > 0$; 3) $\frac{\partial \pi_l^{EF}}{\partial E} > 0, \frac{\partial \pi_s^{EF}}{\partial E} > 0$ 。

推论 4 表明，EF 情形下，冷链服务创新成本因子的上涨会导致冷链所有成员及系统利润受损，其原因同 DF 情形。与之相反，估值水平的上升或固定资产的增加会导致供应商和 TPL 的利润随之上涨，这是由于估值水平上升或更高额的固定资产会加大平台商股权融资资金投入力度，进而激励 TPL 进行冷链创新，供应商可以从中获利，而平台商和系统总体利润变化不明确。

四、比较分析

本节主要探讨不同融资策略对冷链系统成员决策及各方利润的影响。结合式 (7)，式 (12)~(15) 及式 (22) ~ (26)，比较两种融资策略下的内点均衡结果，可得推论 5。

推论 5. 两种融资策略下，系统取得内点均衡时，1) $p^{EF} < p^{DF}, r^{EF} > r^{DF}, l^{EF} = l^{DF}$;

2) 若 $0 < A < \frac{Ac^b(1+l)^{1-b}}{(b-1)^{2b-1}(2b-1)^{-b}}$ ，则 $e^{EF} > e^{DF}$ ，

反之，若 $A \geq \frac{Ac^b(1+l)^{1-b}}{(b-1)^{2b-1}(2b-1)^{-b}}$ ，则 $e^{EF} \leq e^{DF}$;

3) 若 $0 < A < \frac{Ac^2b\bar{c}^{-b}(\alpha V - \eta)^b(1+l)^{1-2b}}{(b-1)^{b-1}(2b-1)^{2b}}$ ，则 $D^{EF} > D^{DF}$ ，反之，若 $A \geq \frac{Ac^2b\bar{c}^{-b}(\alpha V - \eta)^b(1+l)^{1-2b}}{(b-1)^{b-1}(2b-1)^{2b}}$ ，则 $D^{EF} \leq D^{DF}$ 。

其中， $\bar{A} = \frac{2^b \sqrt{2\beta(\alpha V - \eta)}}{\theta_0 b^{-b}(c_l + c_s)}$ 。

推论 5 表明，融资策略变化不会改变 TPL 的物流价格，物流价格仅受其自身和供应商运营成本及价格弹性系数的影响。与债权融资相比，股权融资将导致更高的平台佣金率和更低的产品销售价格，故其会挤压供应商的边际利润，这在一定程度上将抑制供应商参与股权融资冷链的动力，这也是 TPL 选择融资策略时需关注的问题。

鉴于两种融资策略下，冷链各成员及系统利润较为复杂，以下通过数值算例来进行对比分析。假设系统参数取值为： $A = 1000, \theta_0 = 1, b = 3, c_l = c_r = 0.1, c_s = 0.2, \beta = 40, \lambda = 0.7, \alpha = 3, \varphi = 0.5, l = 0.01, E = 200, \eta = 70$ ，由于 $14.4 = \beta_1 \leq \beta \leq \beta_2 \leq 2\eta < \alpha V = 810$ ，故参数取值满足要求。令 b 的取值在 (1.5, 3) 范围内变化，可得冷链各成员及系统整体利润随产品价格弹性的变化趋势，如图 2 和 3 所示。

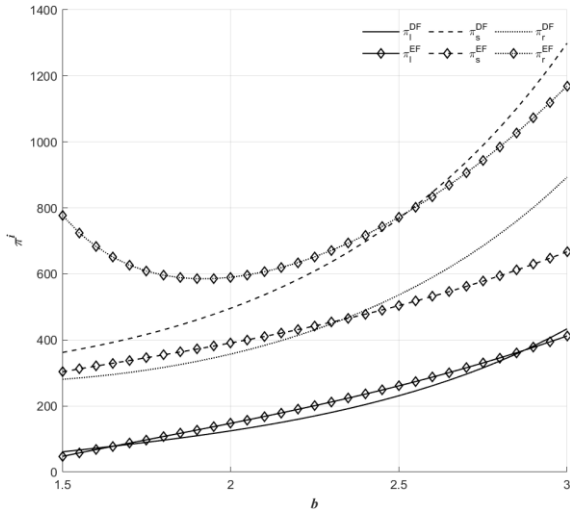


图 2 b 对冷链成员利润的影响

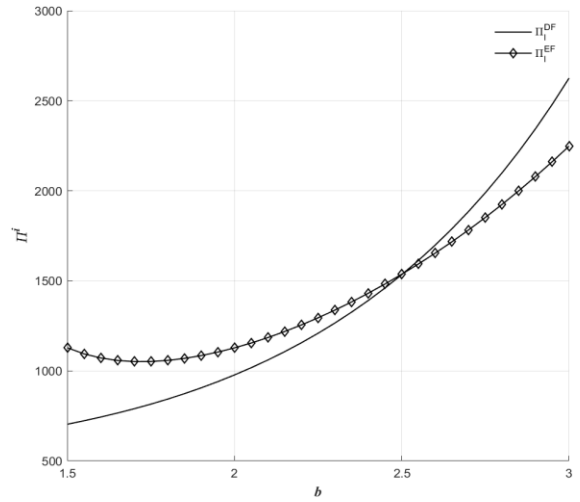


图 3 b 对冷链总利润的影响

图 2 和图 3 分别展示了产品价格弹性系数对两种融资策略下冷链成员利润和整体利润的影响。由图 2 可知, 1) 两种融资策略下, 受权力结构的影响, 三方成员中, TPL 作为博弈跟随者获取的利润总是最低的; DF 情形下平台商利润最高, 而 EF 情形下供应商利润最高。2) 整体来看, DF 情形下各成员利润和系统整体利润对产品价格弹性变化更为敏感, EF 情形下由于风险共担, 各成员利润曲线变化相对平缓。3) 产品价格弹性系数较低($1.66 < b < 2.33$)时, EF 情形下三方成员利润均高于 DF 情形, 即 EF 为 DF 的帕累托改善, 此时, 三成员均倾向于股权融资; 同样, 产品价格弹性系数较高($b > 2.88$)时, DF 也可成为 EF 的帕累托改善, 即三方成员均倾向于债权融资。由图 3 可知, 冷链整体利润也存在一个阈值($b = 2.51$), 当低于(高于)该阈值时, EF 情形下的冷链运作效率高于(低于)DF 情形。

五、结论

本文探究了 TPL 服务创新融资策略对生鲜平台冷链运作的影响。结果表明: 1) DF 情形下, 冷链服务创新成本因子的上涨或融资利率上升均会抑制冷链创新水平的提升和市场需求的上涨, 进而导致供应链成员利润受损、整体运作效率下降。因此, 创新成本因子和融资利率是制约冷链服务创新的重要因素, 合理设置债权融资利率以平衡利润增长与风险损失, 是平台商和 TPL 决策时应考虑的重点问题; TPL 自有资金仅会影响其自身及平台商的利润分配, 不会影响供应商及系统总体利润。2) EF 情形下, 冷链服务创新成本因子上涨也会导致冷链所有成员及系统利润受损, 其原因同 DF 情形。估值水平上升或固定资产增加均会加大平台商股权融资资金投入力度, 进而激励 TPL 进行冷链创新, 进而导致供应商和 TPL 的利润随之上涨。3) 融资策略变化不会改变 TPL 的物流价格; 与债权融资相比, 股权融资将导致更高的平台佣金率和更低的产品销售价格, 这将抑制供应商参与股权融资冷链的动力; 两种融资策略下的冷链服务创新水平大小与市场规模相关, TPL 若以提升冷链创新服务水平为

目的, 则市场规模较小(较大)时, 选择股权(债权)融资。4) DF 情形下各成员利润和系统整体利润对产品价格弹性变化更为敏感, 产品价格弹性系数较低时, EF 为 DF 的帕累托改善, 较高时, DF 也可为 EF 的帕累托改善, 故价格弹性较低(较高)时, 各方成员均倾向于股权(债权)融资。

本文研究结论一方面为 TPL 服务创新资金短缺时, 如何寻求融资途径、选择融资策略、提升冷链服务水平提供较好的理论支撑, 另一方面也为平台商如何合理决策平台佣金、设置融资利率等提供了借鉴。本文的研究尚有一定的局限性, 如我们仅考虑了供应链内部融资, 未来可扩展至内部和外部融资共同存在的情形, 分析不同融资策略的融资风险并引入更为复杂的分布函数。

附录：

定理 1 的证明：结合式 (3)，求 $\pi_s(p|e, r, l)$ 关于 p 的一阶偏导数，可得：

$$\begin{aligned} \frac{\partial \pi_s(p|e, r, l)}{\partial p} &= A\theta_0 p^{-b-1} e \cdot (b(l+c_s) - (1-r)(b-1)p). \end{aligned} \quad (A1)$$

令 $\frac{\partial \pi_s(p|e, r, l)}{\partial p} = 0$ ，可得： $p^{DF}(r, l) = \frac{b(l+c_s)}{(b-1)(1-r)}$ 。易知， $p < p^{DF}(r, l)$ 时， $\frac{\partial \pi_s(p|e, r, l)}{\partial p} > 0$ ； $p > p^{DF}(r, l)$ 时， $\frac{\partial \pi_s(p|e, r, l)}{\partial p} < 0$ ，故 $\pi_s(p|e, r, l)$ 是关于 p 的单峰函数，存在唯一最优的 $p^{DF}(r, l)$ 使得 $\pi_s(p|e, r, l)$ 取得最大值。

定理 2 的证明：结合式 (6)，求 $\pi_l(l, e|r)$ 关于 l 的一阶偏导数，可得：

$$\begin{aligned} \frac{\partial \pi_l(l, e|r)}{\partial l} &= \frac{A\theta_0 e(b(c_l - l) + l + c_s)}{l + c_s} \cdot \left(\frac{b(l + c_s)}{(b-1)(1-r)} \right)^{-b}. \end{aligned} \quad (A2)$$

$$\frac{\partial \pi_r(r)}{\partial r} = \frac{A^2 \theta_0^2 (2(b-1)^2 (1+l)(1-r)c_r - (l(r-1) + 2b^2(1+l)r - b(1+lr))(c_l + c_s))}{\beta b^{4b-1} (b-1)^{3-4b} (c_l + c_s)^{2b-1} (1-r)^{2-2b} (1+l)^2}. \quad (A4)$$

令 $\frac{\partial \pi_r(r)}{\partial r} = 0$ ，整理可得： $r^{DF} = \frac{2(b-1)^2 \partial r}{2(b-1)^2 (1+l)c_r + (b+l)(c_s+c_l)}$ 。易知， $0 < r < r^{DF}$ 时， $\frac{\partial \pi_r(r)}{\partial r} > 0$ ； $r^{DF} < r < 1$ 时， $\frac{\partial \pi_r(r)}{\partial r} < 0$ ，因此， $\pi_r(r)$ 是关于 r 的单峰函数，存在唯一最优的 r^{DF} 使得 $\pi_r(r)$ 取得最大值。

定理 5 的证明：同定理 1~4 (略)。

推论 1 的证明：1) 结合式 (7)、式 (12)~(15)，分别求其关于 β 的一阶偏导数，可得：

$$\begin{aligned} \frac{\partial e^{DF}}{\partial \beta} &= -\frac{A\theta_0 (c_l + c_s) c^{-b}}{\beta^2 b^b (b-1)^{1-2b} (2b-1)^b (1+l)^{1-b}} < 0, \\ \frac{\partial D^{DF}}{\partial \beta} &= -\frac{A^2 \theta_0^2 (c_l + c_s) c^{-2b}}{\beta^2 b^{2b} (b-1)^{1-4b} (2b-1)^{-2b} (1+l)^{1-2b}} < 0, \\ \frac{\partial l^{DF}}{\partial \beta} &= \frac{\partial r^{DF}}{\partial \beta} = 0. \end{aligned}$$

2) 结合式 (7)、式 (12)~(15)，分别求关于 l 的一阶偏导数，可得：

$$\begin{aligned} \frac{\partial e^{DF}}{\partial l} &= -\frac{A\theta_0 R c^{-1-b} (c_l + c_s)}{\beta b^b (b-1)^{1-2b} (2b-1)^{-b} (1+l)^{2-b}} < 0, \\ \frac{\partial D^{DF}}{\partial l} &= -\frac{A^2 \theta_0^2 R c^{-1-2b} (c_l + c_s)}{\beta b^{2b} (b-1)^{1-4b} (2b-1)^{-2b} (1+l)^{2-2b}} < 0, \\ \frac{\partial p^{DF}}{\partial l} &= -\frac{b(c_l + c_s)}{(b-1)(2b-1)(1+l)^2} < 0, \quad \frac{\partial r^{DF}}{\partial l} = \text{值, 可得:} \\ \frac{p^{EF}}{p^{DF}} &= \frac{2(b-1)(\alpha V - \eta)(2(1+l)c_1^F + c_2^F)}{(2b-1)(1+l)(2c_1^F + c_3^F)}. \end{aligned} \quad (A5)$$

由于 $\frac{A\theta_0 e}{l+c_s} \cdot \left(\frac{b(l+c_s)}{(b-1)(1-r)} \right)^{-b} > 0$ ，故仅需对式 $b(c_l - l) + l + c_s$ 进行讨论即可。令 $b(c_l - l) + l + c_s = 0$ ，可得： $l^{DF} = \frac{bc_l + c_s}{b-1}$ 。易知， $0 < l < l^{DF}$ 时， $\frac{\partial \pi_l(l, e|r)}{\partial l} > 0$ ； $l > l^{DF}$ 时， $\frac{\partial \pi_l(l, e|r)}{\partial l} < 0$ ，因此， $\pi_l(l, e|r)$ 在 l 上是单峰的，存在唯一最优的 l^{DF} 使得 $\pi_l(l, e|r)$ 取得最大值。

定理 3 的证明：结合式 (8)，分别求 $\pi_l(e|r)$ 关于 e 的一阶和二阶偏导数，可得：

$$\begin{aligned} \frac{\partial \pi_l(e|r)}{\partial e} &= \frac{A\theta_0 (c_l + c_s)^{1-b} (1-r)^b}{b^{2b} (b-1)^{1-2b}} - \beta(1+l)e. \\ \text{由于 } \frac{\partial^2 \pi_l(e|r)}{\partial e^2} &= -\beta(1+l) < 0, \text{ 因此, } \pi_l(e|r) \text{ 是关于 } e \text{ 的严格凹函数. 令 } \frac{\partial \pi_l(e|r)}{\partial e} = 0, \text{ 可得: } e(r) = \frac{A\theta_0 (c_l + c_s)^{1-b} (1-r)^b}{b^{2b} (b-1)^{1-2b} \beta(1+l)}. \end{aligned}$$

再由 3.1 节可知， e 的取值需满足： $\sqrt{\frac{2\eta}{\beta}} \leq e \leq \sqrt{\frac{2(\delta E(1+\varphi)+\eta)}{\beta}}$ ，故若 $e(r) < \sqrt{\frac{2\eta}{\beta}}$ ，则 $e^{DF}(r) = \sqrt{\frac{2\eta}{\beta}}$ ；若 $e(r) > \sqrt{\frac{2(\delta E(1+\varphi)+\eta)}{\beta}}$ ，则 $e^{DF}(r) = \sqrt{\frac{2(\delta E(1+\varphi)+\eta)}{\beta}}$ ；若 $\sqrt{\frac{2\eta}{\beta}} \leq e(r) \leq \sqrt{\frac{2(\delta E(1+\varphi)+\eta)}{\beta}}$ ，则 $e^{DF}(r) = \frac{A\theta_0 (c_l + c_s)^{1-b} (1-r)^b}{b^{2b} (b-1)^{1-2b} \beta(1+l)}$ 。整理可得式 (9)。

定理 4 的证明：结合式 (11)，求 $\pi_r(r)$ 关于 r 的一阶偏导数，可得：

$$-\frac{b(2b^2-3b+1)(c_l+c_s)^2}{R^2} < 0, \quad \frac{\partial l^{DF}}{\partial l} = 0.$$

3) 结合式 (14)、式 (7) 和式 (12)，分别求关于 b 的一阶偏导数，可得：

$$\begin{aligned} \frac{\partial p^{DF}}{\partial b} &= \frac{(l(1-b)-2b^3(5+4l)+b^2(6+4l))(c_l+c_s)-2(b-1)^3(1+l)c_r}{(2b-1)^2(b-1)^3(1+l)} < 0, \\ \frac{\partial l^{DF}}{\partial b} &= -\frac{c_l+c_s}{(b-1)^2} < 0, \\ \frac{\partial r^{DF}}{\partial b} &= \frac{(1+l)(c_l+c_s)((2b^2+4bl-l)(c_l+c_s)+2(3b^2-4b+1)(1+l)c_r)}{R^2}. \end{aligned}$$

令 $\frac{\partial r^{DF}}{\partial b} = 0$ ，可得： $c_r = \frac{(2b^2+4bl-l)(c_l+c_s)}{2(3b^2-4b+1)(1+l)}$ ，当 $0 < c_r < \frac{(2b^2+4bl-l)(c_l+c_s)}{2(3b^2-4b+1)(1+l)}$ 时， $\frac{\partial r^{DF}}{\partial b} < 0$ ， r^{DF} 在 c_r 上严格递增；当 $c_r > \frac{(2b^2+4bl-l)(c_l+c_s)}{2(3b^2-4b+1)(1+l)}$ 时， $\frac{\partial r^{DF}}{\partial b} > 0$ ， r^{DF} 在 c_r 上严格递减，即当 $c_r = \frac{(2b^2+4bl-l)(c_l+c_s)}{2(3b^2-4b+1)(1+l)}$ 时，佣金率 r^{DF} 取得均衡条件下的最大值。

推论 2~4 的证明：同推论 1 (略)。

推论 5 的证明：1) 求式 (25) 与式 (14) 的比值，可得：

$$\frac{p^{EF}}{p^{DF}} = \frac{2(b-1)(\alpha V - \eta)(2(1+l)c_1^F + c_2^F)}{(2b-1)(1+l)(2c_1^F + c_3^F)}. \quad (A5)$$

$$\begin{aligned} \text{其中, } c_1^F &= (b-1)^2 c_r, \quad c_2^F = (2b^2(1+I) - 2(b^2-b+1)\eta)(c_l + c_s), \text{将式(A5)中的分子与分母} \\ I(b-1))(c_l + c_s), \quad c_3^F &= ((2b^2-b+1)\alpha V - \text{作差可得:} \\ Eq.(1) &= -2(1+I)(\alpha V - \eta)c_1^F + (2(-b^2+3b+I-1)\eta - (2b^2I + b(3-I) + I - \\ 1)\alpha V)(c_l + c_s). \end{aligned} \quad (A6)$$

由于 $\alpha V > 2\eta$, 且随着 αV 的增长, $Eq.(1)$ 呈下降趋势, 故有 $Eq.(1) \leq -2\eta(1+I)(\alpha V - \eta)c_1^F - 2(b^2(1+2I) - 2bI + I)\eta)(c_l + c_s) < 0$, 因此, $p^{EF} < p^{DF}$.

求式 (24) 与式 (12) 的比值, 可得:

$$\frac{r^{EF}}{r^{DF}} = \frac{(2(1+I)c_1^F + c_2^F)(2(\alpha V - \eta)c_1^F + c_4^F)}{(2(1+I)c_1^F + c_5^F)(2(\alpha V - \eta)c_1^F + c_3^F)}$$

其中, $c_4^F = ((b+1)\alpha V - 2\eta)(c_l + c_s)$, $c_5^F = (b+I)(c_l + c_s)$, 观察到 $\frac{2(\alpha V - \eta)c_1^F c_2^F}{2(\alpha V - \eta)c_1^F c_5^F} > 1$, 又因 $c_4^F > b\alpha V(c_l + c_s)$, $c_3^F < (2b^2 - b + 1)\alpha V(c_l + c_s)$, 故有 $c_2^F c_4^F > b\alpha V(2b^2(1+I) - I(b-1))(c_l + c_s)^2 >$

$\alpha V(2b^3 + (2b - b + 1)I - b^2 + b)(c_l + c_s)^2 > c_3^F c_5^F$, 故 $\frac{r^{EF}}{r^{DF}} > 1$.

再比较式 (22) 与式 (7), 易知: $\frac{l^{EF}}{l^{DF}} = 1$.

2) 求式 (23) 与式 (13) 的比值, 可得: $\frac{e^{EF}}{e^{DF}} =$

$$\frac{\bar{A}c^b(1+I)^{1-b}}{A(b-1)^{2b-1}(2b-1)^{-b}}, \quad \text{令 } \frac{e^{EF}}{e^{DF}} > 1, \quad \text{可得: } 0 < A < \frac{\bar{A}c^b(1+I)^{1-b}}{(b-1)^{2b-1}(2b-1)^{-b}}, \quad \text{其中, } \bar{A} = \frac{2^b \sqrt{2\beta(\alpha V - \eta)}}{\theta_0 b^{-b}(c_l + c_s)}.$$

3) 求式 (26) 与式 (15) 的比值, 可得: $\frac{D^{EF}}{D^{DF}} =$

$$\frac{\bar{A}c^{2b}c^{-b}(\alpha V - \eta)^b(1+I)^{1-2b}}{A(b-1)^{2b-1}(2b-1)^{2b}}, \quad \text{令 } \frac{D^{EF}}{D^{DF}} > 1, \quad \text{可得: } 0 < A < \frac{\bar{A}c^{2b}c^{-b}(\alpha V - \eta)^b(1+I)^{1-2b}}{(b-1)^{b-1}(2b-1)^{2b}}.$$

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Fiscal decentralization, green technology innovation and local air pollution in China: A spatial investigation from the perspective of intergovernmental competition

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Abstract: Fiscal decentralization (FD), as an institutional arrangement for the fiscal division between the central and local governments, gives local governments the enthusiasm and autonomy to provide public products and services. As the dominant part of environmental governance, how can local governments avoid inter-government "race to the bottom" issues through green innovation is a matter of regional green development and continuous improvement of atmospheric environmental quality. Based on a sample of 30 provinces in China from 2003 to 2018, this paper examines the relationship between fiscal decentralization, green innovation and regional air pollution and its spatial heterogeneity from the perspective of inter-governmental competition by using the Spatial Durbin Model (SDM). The results indicate that the fiscal decentralization and green innovation in various provinces have a significant and regionally differentiated inhibitory effect on local air pollution. In western China, due to regional competition among local governments in terms of economic development, economic development-oriented fiscal expenditures crowd out environmental governance-oriented fiscal expenditures, which has led to the consequence that fiscal decentralization can intensify local air pollution and has a positive spillover effect, but the demonstration effect of green technological innovation can well moderate the effect of fiscal decentralization on air pollution. Fiscal decentralization in the eastern region has played a positive role in promoting regional air quality improvement. However, its green technological innovation has not played a positive role in reducing emissions, and it plays a significant negative regulatory role in the emission reduction effect led by fiscal decentralization. Finally, the article puts forward some policy recommendations from the perspective of inter-government competition in terms of fiscal decentralization system, green technological innovation, and performance evaluation mechanism.

Keywords: air pollution; fiscal decentralization; green innovation; spillover effects; spatial Dubin model

行业差异视角下中国股市 beta 系数的时变性研究

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摘要：中国经济金融体系不稳定衍生出复杂多变的系统性风险，作为衡量证券市场系统性风险的重要工具，beta系数具有典型时变特征。本文引入离散数据的函数化动态建模思想，从连续动态视角测度中国股市beta系数的时变轨迹及行业异质性。(1) 基于拓展的双参数广义交叉验证模型，函数化重构滚动窗口回归的离散beta系数，从动态视角刻画各行业beta系数的时变特征。(2) 利用函数型方差分析，从绝对水平及速度、加速度三个层面检验beta系数在行业间的动态差异。(3) 实施相位分析技术，可视化展示股市总体及各行业beta系数的动态演变过程。研究发现：(1) 中国股市总体系统性风险居高不下，波动频繁且愈发难以控制。(2) 行业间beta系数在绝对水平和速度上存在显著差异，但在加速度上差异并不显著。(3) Beta系数的波动具有阶段性特征，强周期性与弱周期性行业beta系数发展模式不同。本文从行业差异视角探明了中国股市beta系数的时变规律和内在机理，也为监管部门防控市场系统性风险提供了具有针对性的政策建议。

关键词：时变贝塔；行业差异；函数型数据分析；相位分析；滚动窗口

Visualizing the time-varying of beta coefficients in Chinese stock markets from the perspective of industry differences

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Abstract: The instability of China's economic and financial system has given rise to complex and volatile systemic risks. As an important tool for measuring systemic risks in the securities market, the beta coefficient has typical time-varying characteristics. This paper introduces the idea of functionalized dynamic modeling of discrete data to measure the time-varying trajectory and sectoral heterogeneity of the beta coefficient of the Chinese stock market from a continuous dynamic perspective. (1) Based on an extended two-parameter generalized cross-validation model, the discrete beta coefficients obtained from rolling window regressions are functionally reconstructed to portray the time-varying characteristics of the beta coefficients of each industry from a dynamic perspective. (2) Using the functional ANOVA test, the dynamic differences in beta coefficients across industries are examined at three levels: absolute level, velocity, and acceleration. (3) Leveraging the phase analysis, the dynamic evolution of the beta coefficients of the stock market is visualized from the general stock market and individual sectors. The results show that: (1) The overall systemic risk in the Chinese stock market remains high, and volatility is frequent and increasingly difficult to control. (2) There are significant differences in the absolute level and velocity of beta coefficients between sectors, but not in the acceleration. (3) The fluctuations in beta coefficients are phased, with different patterns of beta coefficient development in strongly cyclical and weakly cyclical industries. This paper explores the time-varying pattern and intrinsic mechanism of the beta coefficient of the Chinese stock market from the perspective of industry differences, and also provides targeted policy recommendations for regulators to prevent and control market systemic risks.

Keywords: Time-varying beta; Industry differences; Functional data analysis; Phase analysis; Rolling windows

我国上市公司“触链”动机：“价值创造”还是“借机减持”？

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摘要：本文以 2016—2020 年中国 A 股上市公司为样本，考察了我国上市公司开展区块链相关业务（“触链”）的动机，运用事件研究法及倾向得分匹配法和双重差分法分别研究了上市公司发布“触链”公告对企业价值和内部人减持的影响。研究发现，上市公司“触链”虽可刺激股价脉冲式上涨，但在中长期内无法创造超额收益，故无法验证“价值创造”假设；“触链”公告前后内部人减持比例显著提高，证实了“借机减持”动机。进一步研究后发现，内部人更偏向于主动在正式公告中披露“触链”信息以达到减持目的。本文的结论为现实中出现的上市公司“触链”热潮提供了一种合理的解释，为监管部门清楚认识我国上市公司的创新行为与概念炒作提供借鉴及启示。

关键词：区块链；价值创造；股票减持；信息披露

Motivation of "blockchain adoption" in China's listed companies: "value creation" or "insider selling"?

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Abstract: Using the sample of China's A-share listed companies from 2016 to 2020, this paper investigates the motivation of Chinese listed companies to carry out blockchain-related businesses ("blockchain adoption"), and uses event study method, propensity score matching method and differential difference method to study the impact of listed companies' "blockchain adoption" announcements on enterprise value and insider divesting. The results show that although the "blockchain adoption" of listed companies can stimulate the stock price pulse rise, it cannot create excess returns in the medium and long term, so the "value creation" hypothesis is not validated. Around the "blockchain adoption" announcements period, the insiders reduced the proportion of significantly higher, confirmed the "take the opportunity to reduce" motivation. After further research, it is found that insiders tend to release "blockchain adoption" information in official announcements to achieve the purpose of reducing their holdings. The conclusion of this paper not only provides a reasonable explanation for the "blockchain adoption" craze of listed companies, but provides reference and inspiration for the regulatory authorities to clearly understand the innovation behavior and concept speculation of listed companies in China as well.

Keywords: blockchain, value creation, stock holdings, information disclosure

财税政策对新能源汽车创新绩效的影响及机理研究 ——研发经费和研发人员投入的中介效应检验

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摘要：近年来，关于财政政策工具对企业创新绩效影响因素研究较为丰富，但对财税政策是否有效激励企业创新尚未形成统一定论，且缺乏财政政策对企业创新作用路径的研究。且已有研究侧重于理论研究，部分实证研究也多以宏观数据为研究样本，对于新能源汽车产业财税激励政策效果及作用机理关注较少。本文以新能源汽车企业为研究对象，选取 2015-2020 年 42 家新能源汽车上市公司面板数据，运用逐步分析法和 Bootstrap 检验法进行实证分析，研究发现：一是政府补助对研发经费投入激励效果显著，对研发人员投入激励效果不显著，税收优惠对二者的激励效果均不显著；二是政府补助对新能源车企创新绩效有正向激励作用，而税收优惠的激励作用未得到证明；三是研发经费投入在政府补助对创新绩效的作用路径中起到部分中介作用，而研发人员投入的中介效应并不显著。

关键词：政府补助；创新绩效；研发经费投入；研发人员投入

Research on the impact and mechanism of fiscal and tax policies on the innovation performance of new energy vehicles ——Intermediary effect test of R & D funds and R & D personnel investment

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Abstract: In recent years, the research on the influencing factors of fiscal policy tools on enterprise innovation performance is relatively rich, but there is no unified conclusion on whether fiscal and tax policies are effective in stimulating innovation, and there is a lack of research on the path of fiscal policy on enterprise innovation. And most of the existing studies are theoretical studies, and some empirical studies mostly take macro data as research samples, paying less attention to the effect and mechanism of fiscal and tax incentive policies for the new energy vehicle industry. This paper takes the new energy vehicle enterprises as the research object, selects the panel data of 42 listed companies of new energy vehicles from 2015 to 2020, and makes an empirical analysis by using the stepwise analysis method and bootstrap test method. The research finds that: first, the government subsidy has a significant incentive effect on R & D funds, but not on R & D personnel, and the tax preference has no significant incentive effect on both; Second, government subsidies have a positive incentive effect on the innovation performance of new energy vehicle enterprises, but the incentive effect of tax preference has not been proved; Third, R & D investment plays a partial intermediary role in the role path of government subsidies on innovation performance, while the intermediary effect of R & D personnel investment is not significant.

Key Words: Government Subsidies; Innovation performance; Innovation investment; R & D capital investment; R & D personnel investment

金融集聚能减少环境污染吗？基于产业与空间的双重关联

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摘要：金融集聚在经济增长中发挥至关重要的作用，但其污染减排的辐射功能仍不确定且存在争议。本文关注于金融集聚对实体经济绿色发展的影响，采用投入产出法识别金融业相关产业，并基于 2007–2019 年中国 286 个地级市的面板数据构建空间杜宾模型探索了金融集聚对环境污染的空间影响和区域异质性。实证结果表明，租赁和商务服务业以及制造业均为金融业的相关行业。金融集聚对本地区的废水污染具有负向影响，而租赁和商业服务业集聚则会增加环境污染。此外，金融集聚对工业废水排放强度呈现负空间溢出效应。区域异质性分析表明金融集聚会使得东部经济带的工业废水污染加剧，而中西部地区的污染程度则会减少。本研究的整体思路和发现为跨行业以及地区间协调合作催生集聚经济并助推绿色城市建设提供参考。

关键词：环境效应，金融集聚，产业关联，空间关联，空间面板模型

Does financial agglomeration reduce environmental pollution? Based on the dual correlations of industry and space

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Abstract: Financial agglomeration plays a critical part in economic growth, but the radiation pollution reduction function is still uncertain and arguable. This paper is concerned with the environment effects of financial agglomeration supporting the green development for entity economy. Input-output method have been implemented to identify related industries of the financial industry, and spatial Durbin model was performed to study the spatial impact and regional heterogeneity based on the panel data of Chinese 286 prefecture-level cities in 2007–2019. The analysis reports that the leasing and business services and the manufacturing industry were both related industries of the financial industry. Financial agglomeration had a negative impact on the local wastewater pollution, whereas the agglomeration of the leasing and business services increased environmental pollution. In addition, financial agglomeration showed a negative spatial spillover effect on industrial wastewater emission intensity. The regional heterogeneity of financial agglomeration projected an increase on industrial wastewater pollution in the eastern economic belts and a decrease in the central and western regions. Overall ideas and findings highlight that inter-industry and regional coordination are essential to agglomeration economy developing green city.

Keywords: environmental effects, financial agglomeration, industrial correlation, spatial correlation, spatial panel model

1. Introduction

Industrial agglomeration is a phenomenon with highly concentrated industries gathering in a specific area, which generates external economies of scale and keeps sustained competitive in the prompt of continuous industrial capital concentration (Hu et al., 2015). High-quality economic development and industrial transformation and updating call for finance to truly serve the real economy and to build a strong financial center to achieve agglomeration effects. With the vigorous development of industrialization and globalization, there are increasing energy consumption and environmental pollution except for the social progress and economic growth. According to the data of 2018 BP Statistical Review of World Energy, China's energy consumption increased by 3.1% in 2017, accounting for 23.2% of total global energy consumption (https://www.bp.com/zh_cn/china/home/news/reports/statistical-review-2018.html). By 2018, China's emissions of carbon dioxide pollution, sulfur dioxide pollution, and fine particulate matter pollution were among the highest in the world. For long, the Report for the 19th National Congress of the Communist Party of China in 2017 emphasized to form a green, low-carbon and recyclable economic system. Particularly, financial industry itself consumes less energy as a clean service sector, and the agglomeration of the financial industry can promote economic growth and technological innovation to reduce resource consumption and pollution emission per unit of output through scale economy and technology spillover; whereas the application of new energy development and integration technologies expands the use of natural resources and produces new pollutants. Further, the integration, interaction and interdependence between financial industry and its upstream or downstream related industries showed a close spatial connection (Wang et al., 2021). Externalities had no regional

boundaries (Rosentha and Strange, 2001), and the technology spillover and capital flow generated by financial agglomeration produced an impact on the surrounding environment. Therefore, this paper aims to analyze and evaluate the environmental effects of financial agglomeration based on the industrial and spatial correlations and to provide some implications for how China can control environmental pollution with ever-expanding financial agglomeration to improve the green and sustainable financial and economic quality.

There are three main viewpoints regarding the relationship between industrial agglomeration and environment: First, some studies hold that industrial agglomeration aggravates environmental pollution (Frank, 2001; Virkanen, 1998), and the agglomeration level and environmental conditions in the surrounding areas affected the local manufacturing industry (Cheng, 2016). Similarly, pollution-intensive industrial agglomeration showed a significant positive spatial effect, yet some sectors and regions could realize emission reduction through spatial spillover and government intervention (Wang and Wang, 2019). Second, another view is that industrial agglomeration reduces environmental pollution through some intermediate variables such as environmental regulation and technological innovation (Viard and Fu, 2015; Li and Ma, 2021). Moreover, some scholars confirmed the environmental EKC hypothesis that the industrial agglomeration level exceeds a certain critical value, which ultimately reduces environmental pollution (Dong et al., 2018; Chen et al., 2020). Third, there was no clear relationship between industrial agglomeration and environmental pollution because of the interaction of direct industrial agglomeration effect, crowding effect and other mechanisms (He and Wang, 2012; Hong et al., 2020). For instance, the intermediary variables of industrial scale, technology and income

level, and the tightness of environmental protection standards both produced various influences on environment (He et al., 2014; Fang et al., 2020). The final result of agglomeration increased or decreased pollution depended on the combined impact of positive and negative effects (Zheng and Lin, 2018). On the other hand, studies on financial related industries intuitively observed the industrial correlation between the financial industry and three major industries and other sub-sectors such as logistics using input-output method (Shahzad et al., 2022), others discussed the classic issue of the impact of financial development and financial industry correlation on economic growth (Usman et al., 2022). Several studies emphasized the influence of financial development on renewable energy consumption and upgrading of energy and industrial structure with the emergent topic of environmental protection (Eren et al., 2019; Ji and Zhang, 2019).

Overall, the previous research mainly revealed the environmental impacts of manufacturing, industry and producer services agglomeration, few studies explored the relationship between financial agglomeration and environmental pollution with a growing and low-carbon financial *characteristics*. In addition, fewer researches constructed both the industrial correlation and spatial spillover effects of financial agglomeration on environmental pollution and formed a comprehensive analysis framework of “financial and related industries - agglomeration - environmental effects”. In terms of this, the value of this paper lies in: 1) filling the lack of literature research on the impact of financial development and economic growth on environmental pollution under the status of agglomeration; 2) enriching the studies on spatial spillover effects in the aspects of financial agglomeration influencing environmental pollution; 3) adding the industrial correlation in the spatial analysis

of financial agglomeration to supplement the research on green development of various industrial agglomeration.

Further, the empirical results in Chinese prefecture-level cities provide some practical contributions: 1) providing several environmental governance ways with the cooperation of industries and regions to manage environmental green development based on the examination of the environmental effects for spatial and industrial correlation; 2) giving some suggestions to better serve the sustainability and green prosperity for real economy of financial development not only the increasing economic volume.

Generally, the purposes of this paper are to systematically analyzing the impact of financial service industry agglomeration on environmental pollution from multiple aspects of industrial relevance, spatial correlation, regional heterogeneity, and spillover effects. The remaining structure is: Section 2 presents a brief mechanism description. Section 3 discusses the model and data, we construct a spatial panel Durbin model and use location entropy to measure industrial agglomeration level, as well as input-output analysis method to identify related industries. Section 4 and Section 5 are results and discussion. The last section concludes the main findings, policy implications and shortcomings.

2. Mechanism description and hypothesis

The negative externality of financial agglomeration affecting environmental pollution is characterized by expanding the economic scale with the financial spatial gathering and enhancing the input of numerous production factors and energy resources, which directly increases pollution emissions, as well as the growing labor productivity, production capacity and output value of related industries indirectly consume more energies. Other more noticeable feature of industrial agglomeration is the positive externality

through the spatial spillover effects of scale economies, technological spillover and industrial structure optimization (as shown in Fig. 1).

2.1. Scale economics effect

In essence, the upstream and downstream affiliated companies gradually tend to be concentrated in the pursuit of scale economies driven by transportation costs and the convenience of economic exchanges (Krugman, 1991). Financial agglomeration centralized numerous financial institutions and

resources to promote the agglomeration of relevant industries and resources, which was conducive to the large-scale construction and the intensive use of infrastructure and production equipment, and achieving energy savings (Maji et al., 2017); whereas the agglomeration of similar enterprises is easier to form a perfectly competitive market and reduce information asymmetry, and the activities of enterprises to reduce costs and improve product quality to keep competitive will ultimately promote green productivity.

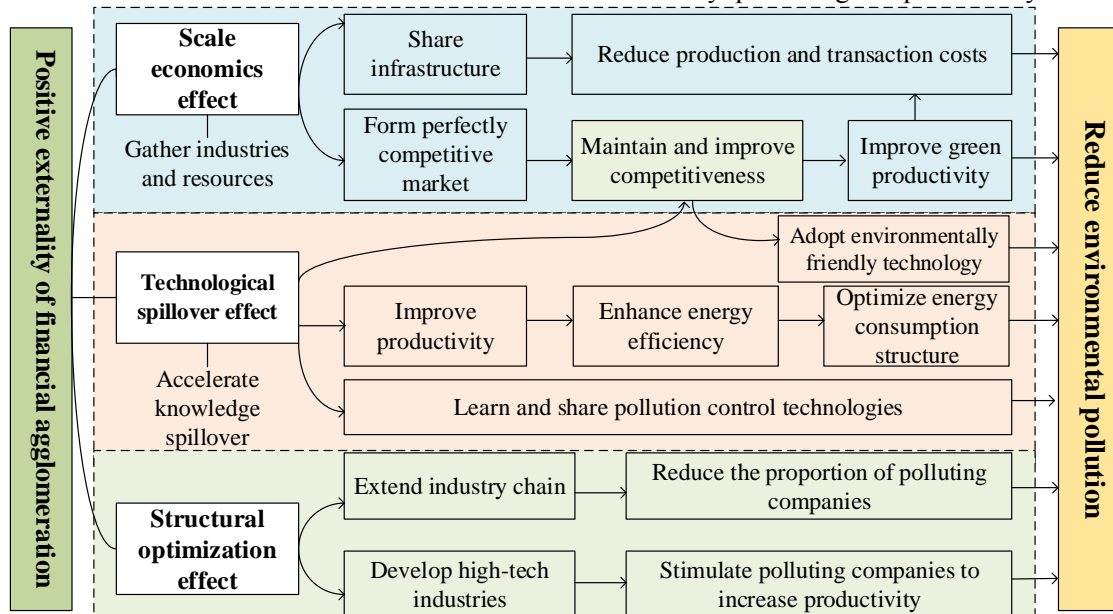


Fig. 1. Mechanism of financial agglomeration affecting environmental pollution

2.2. Technological spillover effect

It is critical to improve technological level and develop low-carbon economy prompted by capital and profit with the expansion of financial agglomeration (Xie et al., 2021). The rising level of financial agglomeration promotes the dissemination of knowledge and technology between regions to realize the environmental self-purification effect: (1) Enterprises adopt new and environmentally-friendly technologies to reduce emissions and increase competitiveness; (2) Enterprises further increase energy utilization rate, optimize energy consumption structure, and reduce pollution emissions to enhance productivity; (3) Enterprises can learn from pollution control technologies.

2.3. Structural optimization effect

The structural adjustment effect of financial agglomeration on environmental pollution is an indirect channel. The temporal and spatial inseparability of financial industry in production and consumption showed more significant spatial agglomeration, the agglomeration of financial service industry had extended the industrial chain to create greater economic value, implemented an in-depth division and refinement, reduced the proportion of industrial enterprises, and promoted the optimization and upgrading of industrial structure, which alleviated the city's environmental pollution emissions (Qu et al., 2020). In the agglomeration area, the labor productivity of high-tech industries has been improved through

learning, communication and imitation, whereas the processing companies with serious pollution are encouraged to increase productivity and reduce pollution to enhance competitiveness.

Overall, the above three mechanisms all analyze the positive effects of industrial agglomeration on emission and pollution reduction. Hence, Hypothesis 1 (**H1**) and 2 (**H2**) are:

H1: The higher the agglomeration level of various industries, the more conducive to pollution reduction.

H2: The environmental pollution effect of industrial agglomeration has a negative spatial spillover effect, high financial agglomeration level in the surrounding cities reduces the pollution of adjacent regions.

3. Model setting and data source

3.1. Model setting

$$EP_{it} = \lambda \sum_{i \neq j}^n W_{ij} EP_{jt} + \alpha AG_{it} + \beta_1 \ln GDP_{it} + \beta_2 \ln^2 GDP_{it} + \beta_3 \ln^3 GDP_{it} + \beta_4 UR_{it} + \beta_5 IND_{it} + \beta_6 FDI_{it} + \beta_7 EI_{it} + \beta_8 TE_{it} + \beta_9 ER_{it} + \varepsilon_{it}, \varepsilon \sim N(0, \delta^2 I_n) \quad (1)$$

Where EP denotes environmental pollution variable, including the emissions of per unit industrial output of industrial wastewater (EP_1), sulfur dioxide (EP_2), and industrial smoke (EP_3) respectively. W_{ij} is a row-standardized spatial weight matrix, i and j are two different cities. Our study is mainly based on the geographical spatial adjacent weight matrix W_1 , as well as we test the robustness of the model estimation results using the reciprocal distance spatial weight matrix W_2 based on the geographic spatial distance and the economic distance weight matrix W_3 based on the adjacent characteristics of social and economic development level; λ is spatial autoregression coefficient; AG is the agglomeration

Spatial panel model can better reflect the impact of different variables on environmental pollution from the perspective of spatial correlation. Meanwhile, economic development level, urbanization, and environmental regulation intensity are potential influencing factors. EKC hypothesis holds that there is an inverted U-shaped relationship between economic development and environmental quality. Environmental quality deteriorated in the early stage of economic development and would be optimized with economic growth (Grossman and Kruege, 1995). Later studies reveal there were a U-shaped, N-shaped or inverted N-shaped curve (Andrée et al., 2019). Therefore, the first, second and third terms of economic growth variable were added. Equation (1) was the spatial auto-regressive model (SAR) covering these variables.

level of financial and its related industries, α is the regression coefficient, β_1, β_2, \dots , and β_9 are the estimation coefficients of the logarithm of economic level ($\ln GDP$), the second terms ($\ln^2 GDP$) and the third terms ($\ln^3 GDP$), urbanization (UR), industrial structure (IND), openness (FDI), energy intensity (EI), technological progress (TE), and environmental regulation (ER), respectively. ε_{it} is a random error term obeying a normal distribution, and t represents the year.

Equation (2) was the spatial error model (SEM), which showed the local environmental pollution was affected by other factors in the neighboring area without including in the explanatory variables.

$$EP_{it} = \alpha AG_{it} + \beta_1 \ln GDP_{it} + \beta_2 \ln^2 GDP_{it} + \beta_3 \ln^3 GDP_{it} + \beta_4 UR_{it} + \beta_5 IND_{it} + \beta_6 FDI_{it} + \beta_7 EI_{it} + \beta_8 TE_{it} + \beta_9 ER_{it} + \mu_{it}, \mu_{it} = \lambda \sum_{i \neq j}^n W_{ij} \mu_{it} + \varepsilon_{it}, \varepsilon \sim N(0, \delta^2 I_n) \quad (2)$$

Where μ_{it} is the disturbance term.

Considering the spatial lag term of explanatory

and explained variables, the spatial Durbin model

(SDM) was implemented in Equation (3).

$$EP_{it} = \lambda \sum_{i \neq j}^n W_{ij} EP_{it} + \alpha AG_{it} + \beta_1 \ln GDP_{it} + \beta_2 \ln^2 GDP_{it} + \beta_3 \ln^3 GDP_{it} + \beta_4 UR_{it} + \beta_5 IND_{it} + \beta_6 FDI_{it} + \beta_7 EI_{it} + \beta_8 TE_{it} + \beta_9 ER_{it} + \sum_{i \neq j}^n W_{ij} * (\rho AG_{it} + \theta_1 \ln GDP_{it} + \theta_2 \ln^2 GDP_{it} + \dots + \theta_8 TE_{it} + \theta_9 ER_{it}) + \varepsilon_{it}, \varepsilon \sim N(0, \delta^2 I_n) \quad (3)$$

Where α and β denote the estimated coefficients of the independent variables, ρ and θ are spatial lag coefficients of industrial agglomeration variables and other explanatory variables. Wald, LR and LM test were used to distinguish and select a decent spatial econometric model.

3.2. Data and variables

The period of this paper is 2007-2019, the final

objectives are 286 prefecture-level cities in China excluding 13 cities with administrative division changes. The data is collected by the China City Statistical Yearbook, and the measurement of related industries is based on the 2007, 2012, and 2017 input-output tables in China from the Department of National Accounts of National Bureau of Statistics.

Table 1 Descriptive statistics

Variable	Measure	Symbol	Unit	Mean	S.D.	Max.	Min.
industrial wastewater emission intensity	=industrial wastewater emissions / total industrial output value	EP_1	tons/ten thousand yuan	4.9352	11.8050	411.0546	0.0003
sulfur dioxide emission intensity	=sulfur dioxide emissions / total industrial output value	EP_2	tons/ten thousand yuan	0.0045	0.0082	0.1537	0.0002
industrial smoke emission intensity	=industrial smoke emissions / total industrial output value	EP_3	tons/ten thousand yuan	0.0027	0.0091	0.2698	0.0003
economic development level	=GDP / total population at the end of the year	GDP	ten thousand yuan/people	4.6783	4.8866	53.2351	0.1729
urbanization	=urban population / total population at the end of the year	UR	%	0.3592	0.2337	1.0000	0.0437
industrial structure	=added value of secondary industry / GDP	IND	%	0.4772	0.1105	0.9097	0.0193
openness	=FDI / GDP	FDI	%	0.0199	0.0266	0.7748	0.0000
energy intensity	=annual industrial electricity consumption / GDP	EI	KWh/yuan	0.0514	0.0954	2.3764	0.0003
technological progress	=science and technology investment / GDP	TE	%	0.0028	0.0037	0.0936	0.0001
environmental regulation	—	ER	—	0.8809	1.4932	91.5822	0.0217

Pollution emissions intensity (*EP*): sulfur dioxide (SO₂) and smoke (dust) emissions are the main pollutants mentioned in China's "12th Five-Year Plan" and "13th Five-Year Plan", while industrial wastewater emissions is the important environmental monitoring index used by the National Bureau of Statistics, so we finally define the unit industrial output emissions of annual industrial wastewater, SO₂ and smoke (dust) in each city to characterize the environmental pollution status.

Industrial agglomeration degree (*AG*): It describes the density degree of financial industry and related industrial activities in a certain space. Studying to the research of Xie (2021), we calculate the industrial agglomeration degree between cities by using location entropy index.

$$LQ_{ih} = \frac{q_{ih}/q_i}{q_h/q}$$

Where *i* represents the prefecture-level city, *h* is the various industry; LQ_{ih} is the location entropy index of industry *h* of city *i*; q_{ih} denotes the employment number of industry *h* in city *i*, and q_i is the employment number of all industries in city *i*; q_h is the total employment number of all cities *i* in industry *h*, and q is the employment number in all industries and all regions. Generally, the larger the value of LQ , the higher the regional agglomeration level of the industry.

To explore the impact of other factors on environmental pollution, a set of control variables *X* was added, and the measure of main variables was explained in Table 1. Specifically, the description of some variables is as follows.

Openness (*FDI*): the introduction of advanced production technology alleviated local environmental pollution, yet foreign investment also transferred pollution-intensive industries from one region to another, thus exacerbating the degradation of local environment, which was the "pollution shelter" hypothesis (Leal and Marques, 2021).

Technological progress (*TE*): technological progress improves energy efficiency and reduce pollution emissions, whereas it may also trigger an energy rebound effect for the growing energy consumption. The latter fails to meet the expectation of reducing energy consumption and may even increase pollution.

Environmental regulation intensity (*ER*): generally, a higher environmental regulation produces a greater pressure to reduce emissions and possibility to curb environmental pollution. Referred to the calculation of Feng et al. (2019) and selected the linear weighted summation method to measure the environmental regulation value under three single indicators: comprehensive utilization rate of industrial solid waste (%), urban domestic sewage treatment rate (%) and harmless treatment rate of domestic garbage (%).

Table 1 illustrates the descriptive statistical results of mean, standard deviation and maximum value for main variables in 2007-2019.

3.3. Measurement of related industries

We merge sectors of the same industry into 19 main categories to unify the different classifications in 2007 (42 × 42 sectors), 2012 (42 × 42 sectors), and 2017 (149 × 149 sectors) Input-Output tables based on 2017 National Industries Classification (http://www.stats.gov.cn/tjsj/tjbz/hyflbz/201710/t20171012_1541679.html). The input-output method was adopted to reveal the input-output relationship between various departments or units with close economic contacts within a certain region employing input-output table and to explore the economical correlation between the similar or different sectors and industries. In general, the backward correlation industries provide upstream supply, yet the forward correlation industries major in downstream demand.

(1) Backward correlation and consumption

coefficient

Backward related industries, directly or indirectly supplying production factors, products or services to related industries, played a role in promoting supply. Direct consumption coefficient was used to calculate the backward direct correlation.

$$a_{hg} = \frac{x_{hg}}{X_g}, h, g = 1, 2, \dots, n$$

Where a is the element in the direct consumption coefficient matrix A , x_{hg} is the direct consumption quantity of sector h when producing a unit of product g , and X_g is the total consumption of other products during the production of a unit of product g . The high direct consumption coefficient reveals an obvious backward direct correlation and curves a large demand for products or services of the financial industry from the upstream industries.

Further, the backward complete correlation was represented by the complete consumption coefficient.

$$B = (I - A)^{-1} - I$$

Where I represents the identity matrix, and B is the complete consumption coefficient matrix. The significant backward complete correlation means that financial development increases demand for related industries, and the elements in complete consumption

coefficient matrix show larger values.

(2) Forward correlation and distribution coefficient

Forward correlation is the connection between the industries demanded some products and services for related industries, and it was reflected in the demand-pulling effect of downstream industries. The forward direct correlation measured by the direct distribution coefficient.

$$r_{hg} = \frac{y_{hg}}{Y_g}, h, g = 1, 2, \dots, n$$

Where r is the element in the direct distribution coefficient matrix R , y_{hg} is the quantity allocated to sector h as an intermediate product during the production of product g , and Y_g is the total output of product g .

The forward complete correlation was expressed by the complete distribution coefficient.

$$W = (I - R)^{-1} - I$$

Where W is the complete distribution coefficient matrix. The larger value of the distribution coefficient indicates the growing supply from related industries to financial industry.

Under the model setting and variables selection, the main contents arrangement of this paper is shown in Fig. 2.

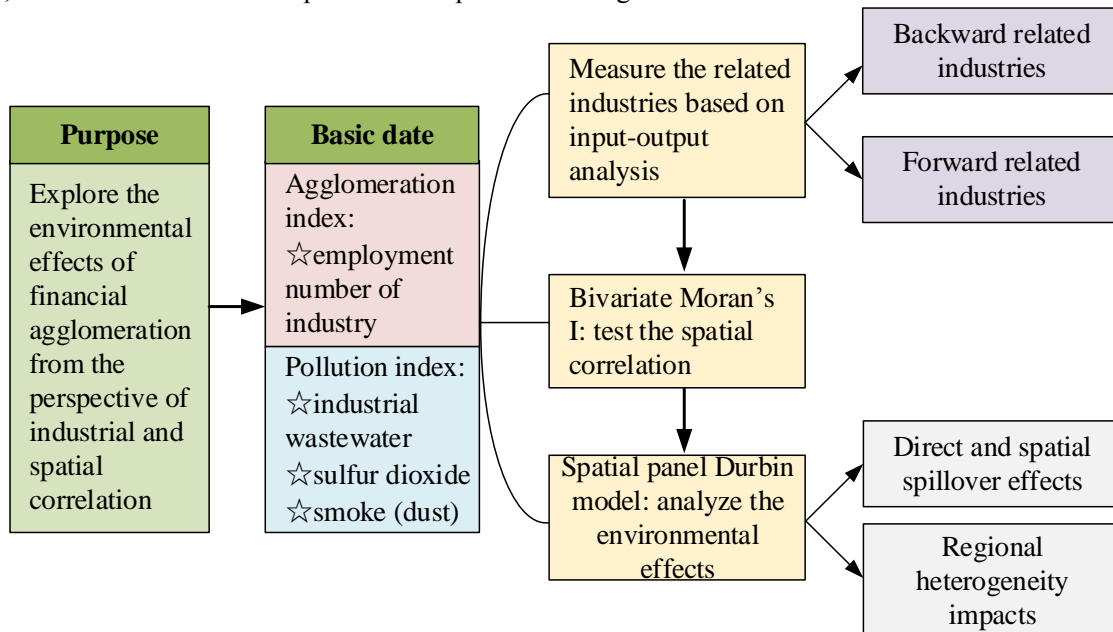


Fig. 2. Framework of main research contents.

4. Results of the environmental effects of financial agglomeration

4.1. Related industries of the financial industry

According to the measurement of consumption coefficient and distribution coefficient matrix with the

input-output method, the column vectors in the consumption coefficient matrix and the row vectors in the distribution coefficient matrix are sorted to get the backward and forward related industries of the financial industry respectively. The results of top 3 industries are listed in Table 2.

Table 2 Top 3 backward and forward related industries of the financial industry in 2007, 2012 and 2017

Rank	Backward related industries measured by the direct consumption coefficient			Backward related industries measured by the complete consumption coefficient		
	Industry	Coefficient	Proportion	Industry	Coefficient	Proportion
2007						
1	Financial industry	0.0642	20.67%	Manufacturing industry	0.3467	42.78%
2	Manufacturing industry	0.0537	17.31%	Financial industry	0.0843	10.41%
3	Leasing and business services	0.0445	14.33%	Leasing and business services	0.0582	7.19%
2012						
Rank	Industry	Coefficient	Proportion	Industry	Coefficient	Proportion
1	Leasing and business services	0.0918	26.22%	Manufacturing industry	0.3919	41.87%
2	Real estate industry	0.0632	18.04%	Leasing and business services	0.1245	13.30%
3	Financial industry	0.0618	17.66%	Financial industry	0.1060	11.33%
2017						
Rank	Industry	Coefficient	Proportion	Industry	Coefficient	Proportion
1	Leasing and business services	0.0892	25.46%	Manufacturing industry	0.2977	31.81%
2	Financial industry	0.0839	23.95%	Leasing and business services	0.1367	14.60%
3	Real estate industry	0.0812	23.18%	Financial industry	0.1335	14.26%
Rank	Forward related industries measured by the direct consumption coefficient			Forward related industries measured by the complete consumption coefficient		
	Industry	Coefficient	Proportion	Industry	Coefficient	Proportion
2007						
1	Manufacturing industry	0.2791	37.35%	Manufacturing industry	1.3048	54.59%
2	Transportation, warehousing and postal services	0.0814	10.90%	Construction	0.1749	7.32%
3	Financial industry	0.0642	8.59%	Electricity, heat, gas and water production and supply industry	0.1510	6.32%
2012						
Rank	Industry	Coefficient	Proportion	Industry	Coefficient	Proportion
1	Manufacturing industry	0.2643	34.12%	Manufacturing industry	1.2631	49.26%
2	Transportation, warehousing and postal services	0.0873	11.26%	Construction	0.2284	8.91%
3	Real estate industry	0.0747	9.65%	Transportation, warehousing and postal services	0.1574	6.14%
2017						
Rank	Industry	Coefficient	Proportion	Industry	Coefficient	Proportion
1	Manufacturing industry	0.1552	20.03%	Manufacturing industry	0.8408	32.79%

2	Transportation, warehousing and postal services	0.1172	15.12%	Construction	0.2556	9.97%
3	Construction	0.0937	12.10%	Transportation, warehousing and postal services	0.1830	7.14%

Table 2 shows the manufacturing industry and the leasing and business services supplied substantial products for the financial sector. In 2012 and 2017, the coefficients of the leasing and business services directly consumed by the unit output of the financial sector were 0.0918 and 0.0892, respectively, accounting for 26.22% and 25.46% and ranking first, indicated that the financial development has an obvious

direct demand driving effect on the leasing and business services. Under the complete consumption coefficient, the manufacturing industry was the largest complete consumption sector of the financial industry in 2007, 2012 and 2017. There was a significant indirect demand pulling effect on the manufacturing industry.

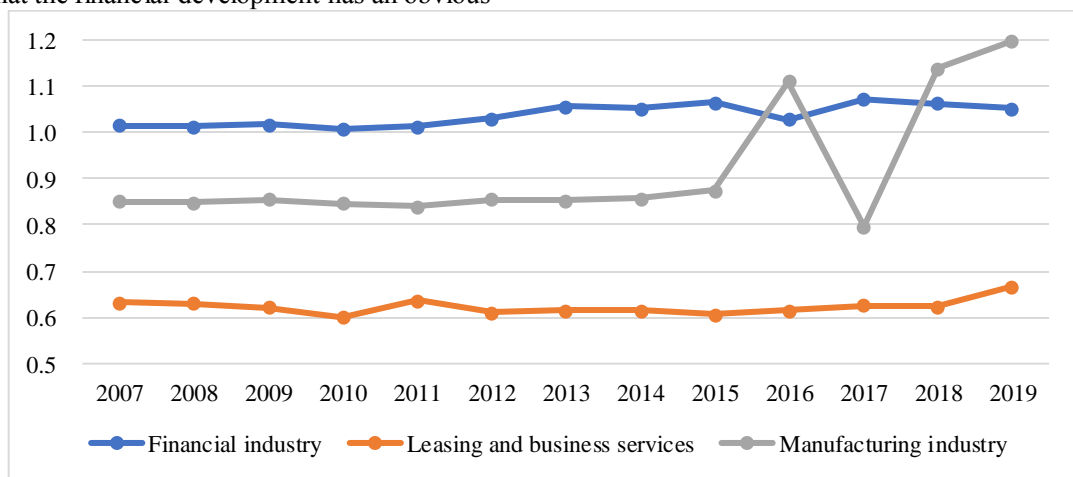


Fig. 3. Average agglomeration level of financial industry and related industries from 2007 to 2019.

In terms of the forward related industries, the direct distribution coefficients of the manufacturing industry in 2007, 2012, and 2017 was 0.2791, 0.2643, and 0.1552, respectively, 37.35%, 34.12%, and 20.03% of financial products were invested in the manufacturing industry, showed that the financial industry plays a remarkable role in directly promoting the development of the manufacturing industry, although the proportion of support for manufacturing was declining. Similarly, the complete distribution coefficients of the manufacturing industry in 2007, 2012 and 2017 were both the largest, and financial industry launched a prominent function in indirectly

supplying the manufacturing.

Overall, the supply function of leasing and business services and the dual supply and demand of the manufacturing industry were closely related to the financial industry. In Fig. 3, the average agglomeration levels of financial industry from 2007 to 2015 were the highest and exceed 1, the values of the manufacturing industry in 2007-2015 were near to 0.85, yet in 2016, 2018 and 2019, the agglomeration levels of the manufacturing industry were greater than the financial agglomeration values; while the average agglomeration levels of leasing and business services were the lowest and were around 0.62.

4.2. Impact of financial and related industries agglomeration on environmental pollution

Bivariate Moran's I was applied to verify the spatial correlation and demonstrated a negative spatial spillover effect between financial agglomeration and industrial wastewater pollution and a significant positive spatial correlation between financial agglomeration and sulfur dioxide and industrial smoke pollution. Moreover, Moran's I value between the agglomeration of finance-related industries and environmental pollution also illustrated obvious spatial correlation.

Further, referred to the framework of Elhorst (2014) to check the applicability of the model, LR and

Wald test were employed in Table 3 to verify the spatial Durbin model could better fit data. Meanwhile, the random effect was rejected with Hausman test at the 1% significance level, so we finally chose the spatial Durbin panel model under the spatial-temporal bidirectional fixed effect. Additionally, we standardized these variables to eliminate dimensions. The main empirical results of the impact of the agglomeration of the financial industry and its related industries on environmental pollution are shown in Table 4, and AG_1 , AG_2 , and AG_3 represent the agglomeration levels of financial industry, leasing and business services, and manufacturing industry, respectively.

Table 3 Spatial econometric models test

Test	Statistics on W_1	Statistics on W_2	Statistics on W_3
LR-lag	54.5831***	55.2941***	62.3917***
LR-err	58.9127***	59.0726***	67.1321***
Wald-lag	59.3913***	59.2735***	67.2716***
Wald-err	85.8647***	115.4312***	113.4232***
Hausman test	70.5321***	68.3918***	60.5222***

Notes: *, ** and *** mean significant at the significance level of 10%, 5% and 1%, respectively.

Further, Table 4 illustrates the spatial lag coefficient ρ of environmental pollution was significantly positive at the 1% statistical level. The coefficients of financial agglomeration (-0.0389) on industrial wastewater pollution at the 1% significance level; yet the agglomeration of leasing and business services with a lower agglomeration level had a significant positive on three pollutant emissions at the 5% significance level. Hypothesis 1 (**H1**) is confirmed, financial industry and leasing and business services are both service industries, and the high industrial

agglomeration level produces a negative impact on environmental pollution. Moreover, the negative spatial lag coefficients (-0.0508, -0.0996) of financial agglomeration on industrial wastewater and smoke emission intensity were significant the 5% statistical level, and the agglomeration of leasing and business services also had a negative spatial spillover effect on industrial smoke pollution. Hypothesis 2 (**H2**) is confirmed. It was worth nothing that the agglomeration of the manufacturing industry showed insignificant direct and spatial effects on environmental pollution.

Table 4 Estimated results of the impact of the agglomeration of financial and its related industries on environmental pollution

Variable	Industrial wastewater emission intensity	Industrial sulfur dioxide emission intensity	Industrial smoke emission intensity
AG_1	-0.0389*** (-2.62)	-0.0116 (-0.61)	-0.0161 (-0.66)
AG_2	0.0596*** (3.62)	0.0460** (2.14)	0.0590** (2.13)
AG_3	-0.0056 (-0.14)	0.0285 (0.55)	0.0677 (1.02)
$\ln GDP$	-0.3897** (-2.59)	-0.9101*** (-4.65)	-0.6107** (-2.51)
$\ln^2 GDP$	0.8786 (1.61)	2.5067*** (3.54)	2.2409** (2.50)
$\ln^3 GDP$	-0.7485** (-1.22)	-2.3769*** (-2.97)	-2.4117** (-2.37)
UR	-0.0390*** (-3.26)	-0.0420*** (-2.69)	-0.0411** (-2.05)
IND	0.0810*** (5.11)	0.1313*** (6.37)	0.1954*** (7.48)
FDI	-0.0105 (-0.95)	-0.0189 (-1.31)	-0.0010 (-0.05)
EI	0.0203 (1.30)	0.0062 (0.30)	0.1281*** (5.01)
TE	-0.0253* (-1.83)	-0.0399** (-2.22)	-0.0142 (-0.63)
ER	-0.0136 (-1.45)	0.0175 (1.44)	-0.0008 (-0.06)
$W*AG_1$	-0.0508** (-2.10)	0.0058 (0.18)	-0.0996** (-2.50)
$W*AG_2$	-0.0046 (-0.16)	0.0427 (1.18)	-0.1183** (-2.54)
$W*AG_3$	-0.0510 (-0.76)	-0.0130 (-0.15)	-0.0102 (0.09)
$W*\ln GDP$	-0.6818*** (-3.12)	-0.5398* (-1.90)	0.1921 (0.62)
$W*\ln^2 GDP$	2.6272*** (3.22)	1.4315 (1.34)	-0.4357 (-0.35)
$W*\ln^3 GDP$	-2.2952** (-2.46)	-0.8519 (-0.70)	0.2972 (0.20)
$W*UR$	0.0038 (0.20)	0.0164 (0.67)	0.0573* (1.95)
$W*IND$	0.0173 (0.73)	0.0208 (0.67)	0.0025 (0.07)
$W*FDI$	0.0042 (0.28)	-0.0228 (-1.15)	-0.0228 (-0.95)
$W*EI$	-0.0364 (-1.54)	-0.0188 (-0.61)	-0.0533 (-1.42)
$W*TE$	0.0379* (1.87)	-0.0622** (-2.35)	-0.0965*** (-3.22)
$W*ER$	-0.0708*** (-4.46)	-0.0663*** (-3.21)	-0.0189 (-1.27)
ρ	0.1736*** (9.78)	0.1559*** (8.70)	0.2868*** (16.85)
σ^2	0.0031*** (42.99)	0.0053*** (43.02)	0.0089*** (42.77)
observations	3718	3718	3718

Notes: *, ** and *** mean significant at the significance level of 10%, 5% and 1%, respectively; the values in parentheses are the t-statistic.

Table 5 Robustness test results

Variables	W_2			W_3		
	Wastewater	Sulfur dioxide	Smoke	Wastewater	Sulfur dioxide	Smoke
AG_1	-0.0056*** (-2.69)	-0.0228 (-1.20)	-0.0221 (-0.95)	-0.0048*** (-2.77)	-0.0254 (-1.35)	-0.0299 (-1.28)
AG_2	0.0575*** (3.48)	0.0494** (2.32)	0.0693*** (2.66)	0.0560*** (3.38)	0.0512** (2.41)	0.0694*** (2.65)
AG_3	-0.0074 (-0.18)	0.0475 (0.91)	0.0262 (0.41)	0.0086 (0.21)	0.0467 (0.90)	0.0222 (0.35)
$W*AG_1$	-0.1257*** (-2.80)	0.0274 (0.48)	-0.1679** (-2.38)	-0.1158*** (-3.14)	0.0883* (1.87)	-0.0556 (-0.96)
$W*AG_2$	-0.0423 (-0.83)	-0.0666 (-1.02)	-0.3651*** (-4.57)	-0.0466 (-1.07)	-0.0796 (-1.43)	-0.2722*** (-3.97)
$W*AG_3$	-0.0617 (-0.73)	-0.0538 (-0.50)	-0.2928** (-2.21)	0.0072 (0.10)	-0.0569 (-0.61)	-0.2138* (-1.86)
ρ	0.1858*** (5.73)	0.2997*** (8.83)	0.3352*** (10.80)	0.1537*** (4.42)	0.3211*** (9.04)	0.3271 (9.86)
σ^2	0.0032*** (43.05)	0.0053*** (42.94)	0.0079*** (42.93)	0.0032*** (43.05)	0.0053*** (42.90)	0.0080*** (42.88)
observations	3718	3718	3718	3718	3718	3718

Notes: *, ** and *** mean significant at the significance level of 10%, 5% and 1%, respectively; the values in parentheses are the t-statistic.

Moreover, the estimated coefficients of UR on three pollutant emission intensity were significantly negative, which verified that the high urbanization development level can help reduce pollution. There was positive relationship between IND and environmental pollution, the increasing proportion of the secondary was not beneficial to environmental protection. The improvement of technological innovation level suppressed the emission of industrial sulfur dioxide and effectively improved the local and surrounding environmental status. Government's environmental regulation showed obvious spatial spillover effects on the industrial wastewater and sulfur dioxide emission intensity at a significance level of 1%, and the pollution reduction function of environmental regulation measures was unbalanced among regions.

Finally, the robustness test was conducted on the comparison the estimated results for the geographical

distance weight matrix W_2 and economic distance weight matrix W_3 with the model under the spatial adjacent weight matrix W_1 in Table 5, we found the estimations under different spatial weight matrices still supported the basic conclusions above, and the signs and significance of the estimate coefficient of related variables had not changed significantly. Therefore, the estimated results of the impact of the agglomeration of financial and its related industries on environmental pollution are robust.

4.3. Decomposition of spatial effect

In spatial Durbin model, not only the direct effects of explanatory variables on the explained variables are expressed, the spatial correlation between different regions also exerts an indirect effect on the explained variables (Elhorst, 2014), and the decomposition results of spatial effect for main variables on environmental pollution are shown in Table 6.

Table 6 Decomposition results of spatial effect

Variable	Industrial wastewater		Industrial sulfur dioxide		Industrial smoke	
	Direct effect	Indirect effect	Direct effect	Indirect effect	Direct effect	Indirect effect
AG_1	-0.0269* (-1.78)	-0.1699*** (-6.00)	-0.0115 (-0.61)	0.0016 (0.05)	-0.0269 (-1.14)	-0.1040** (-2.58)
AG_2	0.0584*** (4.25)	0.0104 (0.35)	0.0461** (2.58)	0.0616 (1.61)	0.0555** (2.49)	-0.0786* (-1.67)
AG_3	0.0004 (-0.01)	0.0556 (0.66)	0.0318 (0.55)	-0.0129 (0.12)	-0.0058 (-0.08)	-0.2328 (-1.77)

Notes: the decomposition results of other variables are not presented due to space limitations; *, ** and *** mean significant at the significance level of 10%, 5% and 1%, respectively; the values in parentheses are the t-statistic.

(1) The influence of financial agglomeration on industrial wastewater emission intensity had significant direct and indirect effect, and the indirect effect was dominant. The increase of 1 unit in the financial agglomeration level reduced the emission intensity of industrial wastewater by 0.0389 units in Table 4, of which the direct and indirect effect accounted for 0.0053 units and 0.0336 units, respectively. The contribution rate derived from indirect effect in the total effect was 86.33%. Moreover, the difference between the higher estimated coefficient -0.0269 and the regression estimated value -0.0389 was 0.0027, indicating there was a positive feedback effect, financial agglomeration had a direct impact on the surrounding areas' environment, which in turn affected the local area. The indirect effect of financial agglomeration on industrial smoke intensity was significantly negative, the improvement of the financial agglomeration level reduced the local environmental pollution and aggravated the pollution in neighboring areas.

(2) The direct effects of leasing and business services agglomeration on three pollutant intensity both were positive and significant at the 5% statistical level, and the total effect coefficient -0.0231 on industrial smoke emission intensity included the direct effect of 0.0555 and the indirect effect of -0.0786, and the spatial spillover was dominant. Consistent with the regression results in Table 4, manufacturing agglomeration had

insignificant direct and indirect effects on environmental pollution.

4.4. Regional heterogeneity of environmental effect of financial agglomeration under industrial correlation

This part aims to explore the regional heterogeneity environmental effects of financial agglomeration. According to the city's geographic location and economic development level, 286 cities are divided into the eastern, central and western economic belts, and numbers of cities in the eastern, central, and western economic belts are 101, 109, and 76, respectively. Table 7 shows the estimated results of the regional samples under the spatial panel Durbin model from 2007 to 2019.

Table 7 Regional heterogeneity of the agglomeration of financial and its related industries on environmental pollution

Variable	Industrial wastewater			Industrial sulfur dioxide			Industrial smoke		
	Eastern	Central	Western	Eastern	Central	Western	Eastern	Central	Western
AG_1	0.0098** (2.05)	-0.0036 (-0.77)	-0.0123 (-0.90)	0.0042 (1.01)	-0.0090 (-1.19)	-0.0075 (-0.44)	0.0047 (0.69)	-0.0168 (-1.48)	-0.0058 (-0.32)
AG_2	0.0052 (1.41)	0.0037 (1.01)	0.0326*** (3.04)	-0.0008 (-0.25)	0.0135** (2.24)	0.0253* (1.86)	0.0052 (1.00)	0.0242*** (2.68)	0.0057 (0.40)
AG_3	-0.0013 (-0.70)	0.0028 (1.10)	0.0002 (0.02)	-0.0016 (0.96)	-0.0015 (-0.36)	-0.0119 (-0.96)	-0.0041 (-1.56)	-0.0006 (-0.09)	0.0065 (0.51)
$W*AG_1$	-0.0041** (-2.08)	0.0150* (1.76)	0.0124 (0.56)	-0.0061 (-0.98)	0.0054 (0.38)	-0.0355 (-1.27)	0.0289*** (2.85)	-0.0912*** (-4.37)	-0.0394 (-1.37)
$W*AG_2$	0.0004 (0.07)	-0.0008 (-0.11)	-0.0041 (-0.28)	-0.0073 (-1.41)	0.0159 (1.37)	0.0217 (1.16)	-0.0048 (-0.56)	-0.0091 (-0.53)	-0.0359* (-1.88)
$W*AG_3$	0.0002 (0.07)	-0.0019 (-0.41)	-0.0130 (-0.76)	-0.0009 (-0.38)	-0.0045 (-0.59)	-0.0340 (-1.56)	-0.0062 (-1.59)	-0.0204* (-1.77)	-0.0470** (-2.10)
ρ	0.2111*** (6.27)	0.1295*** (3.40)	0.1377*** (4.52)	0.3321*** (10.69)	0.2349*** (7.02)	0.0535* (1.69)	-0.0102 (-0.30)	0.1541*** (4.69)	-0.0125 (-0.37)
σ^2	0.0015*** (25.42)	0.0014*** (26.56)	0.0072*** (22.16)	0.0012*** (25.15)	0.0038*** (26.47)	0.0116*** (22.22)	0.0031*** (25.62)	0.0085*** (26.56)	0.0123 (22.23)
Obs.	1313	1417	988	1313	1417	988	1313	1417	988

Notes: the estimated results of $\ln GDP$, $\ln^2 GDP$, $\ln^3 GDP$, UR , IND , FDI , EI , TE and ER are not presented due to space limitations; *, ** and *** mean significant at the significance level of 10%, 5% and 1%, respectively; the values in parentheses are the t-statistic.

(1) The impact of AG_1 on industrial wastewater pollution is positive at 5% significance level in the eastern economic belts, whereas the negative effects on the environmental pollution in the central and western economic belts were not significant. Corresponding, eastern financial agglomeration had a more obvious crowding effect than reduction effect on industrial wastewater pollution. Here, crowding effect is the situation of the environmental deterioration with the growing level of industrial agglomeration. Theoretically, scale advantages such as resource sharing and knowledge spillover accompanied by industrial agglomeration will help reduce environmental pollution, while unplanned and chaotic agglomeration of industries will result in greater energy consumption.

(2) The rising level of leasing and business services agglomeration significantly increased industrial sulfur dioxide and smoke pollution in the

central economic belt and wastewater emission intensity in the western economic belt. The combined effect of leasing and business services in the central and eastern regions was less than the crowding effect. Otherwise, there was an insignificant pollution reduction effect of manufacturing agglomeration in the eastern region.

(3) From the spatial lag coefficients of the explained variables, the industrial wastewater pollution of the eastern, central and western economic belt all had a positive spatial correlation at 1% significance level, yet there was a negative spatial effect on industrial smoke pollution in the eastern and western economic belt.

5. Discussion

To explore the influence of financial agglomeration on environmental pollution, we conduct comprehensive research on three aspects from the identification of closely related industries, the analysis

of the direct and spatial spillover effects and the exploration of regional heterogeneity using the data of 286 prefecture-level cities in China over the period 2007 to 2019.

Firstly, the overall agglomeration levels of financial industry and its related industries are different, and the order is financial industry > manufacturing industry > leasing and business services in Fig. 3. Observing the environmental effects of various industrial agglomeration at the 5% significance level, the results reveal the negative impact of financial agglomeration on industrial wastewater pollution and the positive impact of the agglomeration of upstream related industries-leasing and business services.

Evidently, high industrial agglomeration level tended to show greater contribution to reduce pollution emissions. Similarly, Yuan et al. (2019) verified the impact of financial agglomeration on green development was affected by the city scale. Centralized production method of financial activities had a more significant emission reduction effect than decentralized model, and the ideal situation of economic level increasing and environmental protection might be realized under the impetus of agglomeration effect. Therefore, various sectors in the same industry should integrate and share resources to attain scale economies and reduce energy consumption and pollution emissions.

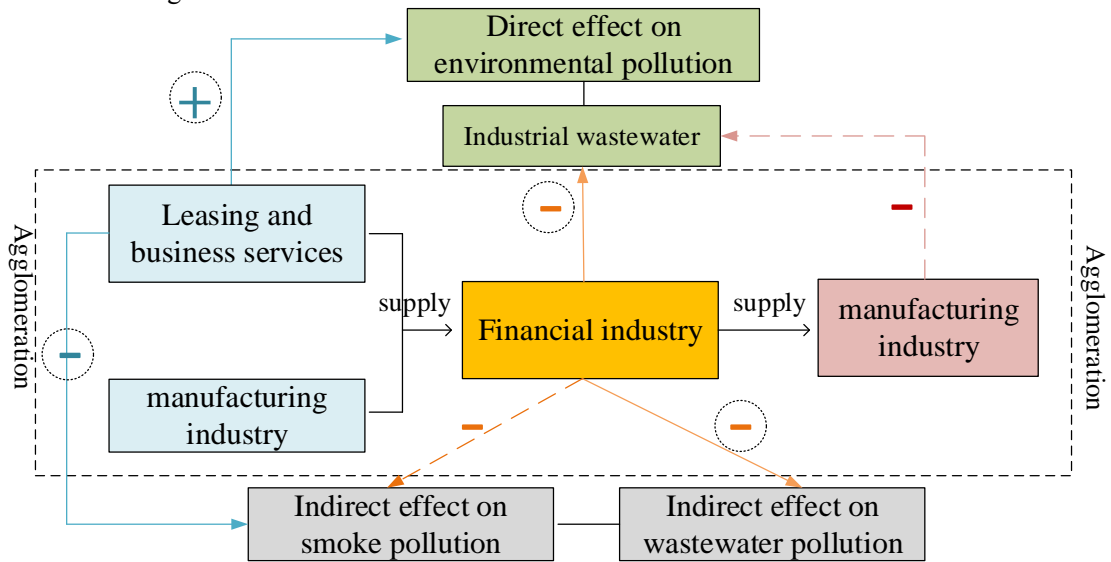


Fig. 4. Diagrammatic presentation of the main empirical results.

Then, we integrate the main conclusions obtained in Section 4.1 and 4.2 as show in Fig. 4. As we all know, finance is the set of activities dealing with the collection and use of funds. Fig 4 illustrates a large number of deposits in the financial industry originate from the leasing and business services and the manufacturing industry, whereas financial loans are chiefly invested in the manufacturing industry. Furthermore, we can also obtain that financial agglomeration is beneficial to reduce industrial wastewater pollution, which is consistent with the research by Yuan et al. (2021). However, the growing agglomeration level of upstream industries-leasing and business services will increase environmental pollution, yet the pollution reduction effect of manufacturing agglomeration is insignificant. Correspondingly, the sustainable capital rationing is likely to reduce large-scale industry deposits and investments on the service and manufacturing enterprises with ineffective agglomeration or heavy pollution and to increase the financial correlation for light polluting companies, which contributes to play the role of financial guidance and supervision for the green development of real economy. It is worth noting that not all spatial agglomeration of different industries possesses an effective pollution reduction, financial industries should avoid the phenomenon of forming multiple agglomeration centers within a small-scale region when absorbing deposits from the leasing and business services based on the negative spatial spillover effect on industrial smoke pollution. The reason may be attributed to scale effect of funds dispersed by multiple agglomeration centers in the local and surrounding areas, failing to achieve centralized control of environmental pollution.

Thirdly, the estimated results indicate the spatial effects of financial agglomeration under different pollutants are different: increasing financial

agglomeration in the surrounding regions is conducive to the decrease of industrial wastewater emissions and smoke pollution for local cities, yet shows a positive spillover effect and aggravates the local sulfur dioxide emissions. The environment was linked in geographic space, and the aggravation of sulfur dioxide pollution in some cities caused the pollution transfer through air flow and other factors (Zhang, 2018), which adds the neglect and difficulty of sulfur dioxide treatment compared with wastewater pollution.

Finally, the environmental effects of financial agglomeration under different economic belts are different: financial agglomeration has a positive effect on industrial wastewater pollution in the eastern region, while it has a negative effect in the central and western regions. The first reason may be that the financial level in the central and western regions is relatively low and the energy resources consumed are correspondingly small, and most of environmental factors are controllable and manageable, while the eastern financial development level is high and the positive external advantages of agglomeration are not fully reflected, which leads to more pollution emissions with the increase of financial level. Second, although most of industries transferring from economically developed coastal cities to underdeveloped central and western cities are pollution-intensive industries in China (Wu et al., 2021), the industrial agglomeration phenomenon in the central and western regions generally occurs after the eastern coastal regions. Gradually mature production decontamination technologies, plus learning from the experience and lessons of the development in the eastern region, more attention is paid for environmental management in the central and western regions when planning the industrial development models and pursuing a green and sustainable industrial development.

6. Conclusions and implications

Based on the data of 286 prefecture-level cities in China from 2007 to 2019, this study systematically verifies the environmental effects of financial agglomeration from the perspective of industrial and spatial correlation. The conclusions demonstrate that the development of financial industry had an obvious demand pulling effect on the leasing and business services, yet showed a demand and supply driving function on the manufacturing industry. Further, the estimation results illustrate that financial agglomeration was conducive to suppressing wastewater pollution, while the agglomeration of leasing and business services showed a positive impact on environmental pollution. Moreover, financial agglomeration presented a negative spatial spillover effect on industrial wastewater and smoke pollution. Similarly, the agglomeration of leasing and business services also showed a negative spatial spillover effect on industrial smoke pollution. Finally, regional heterogeneity analysis depicts the pollution reduction effect of financial agglomeration in the central and western economic belts and a growing industrial wastewater emission intensity in the eastern economic belt. Contrary, the agglomeration of leasing and business services had a positive impact on sulfur dioxide and smoke pollution in the central and western regions.

Corresponding to the findings, we conclude some implications: (1) improve the concentration of economic activities and promote the development of financial cluster centers; (2) emphasis the coordination of environmental regulation between different regions and industries, and the spatial correlation between neighboring or closely economic exchanges and the inter-industrial coordination should be taken into full consideration in formulatibng environmental governance policies; (3) consider the special attention to the environmental prevention and control of

industrial development in the central and western cities; (4) promote economies of scale and leading role of manufacturing agglomeration in the process of environmental protection. The empirical results of the manufacturing industry failed to achieve pollution reduction as the largest part of the financial-related business suggest that it is necessary to strengthen manufacturing management and orderly planning to achieve green development.

In general, our study explores the roughly spatial effects of financial and related industrial agglomeration on environmental pollution at the macro-city level, yet fails to conduct complicated analysis on the ecological effects of the specific business, products, and capital accompanied by the expand of financial agglomeration. Also, our study suffers some limitations on the further deduction in terms of the green development for industrial co-agglomeration rather than single industry. So, we will keen on the influence and mechanism of detail financial business and funding activities, and industrial co-agglomeration between finance and other relevant industries on environmental sustainability.

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我国碳排放权交易机制的减排效果评估——基于多因素分解的比较分析

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摘要：为了适应低碳绿色城市建设的发展趋势，中国从 2010 年开始在 7 个地区实施碳排放权交易计划（ETS），ETS 是一种实现降低二氧化碳排放的有效市场手段，最早是在欧洲国家开始实施，一些研究已经证实了该方法的有效性。然而，关于碳排放交易对碳强度降低的效果和影响渠道的研究并不完整。为了探讨这些问题，本研究进行了实证分析，使用对数平均 Divisia 指数（LMDI）将 2006 年至 2019 年七个试点地区的工业二氧化碳（CO₂）排放量分解为经济规模、经济结构、能源效率和能源结构四个效应。然后，用差分模型（DID）评估 ETS 对这四种效应的影响，最后，用中介效应模型验证影响碳减排的具体途径。研究结果显示：ETS 主要是通过经济水平，经济结构和能源强度三种途径来实现碳强度的减少的。

关键词：LMDI 碳排放权交易机制 差分模型 工业二氧化碳排放 中介效应模型

Evaluation of emission reduction effect of China's carbon emission trading mechanism -- a comparative analysis based on multi factor decomposition

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Abstract : In order to meet the development trend of low-carbon green city construction, China has implemented a carbon emission trading scheme (ETS) in seven regions since 2010. ETS is an effective market instrument to achieve CO₂ emission reduction, which was first started in European countries, and some studies have confirmed the effectiveness of the method. However, research on the effects and impact channels of carbon trading on carbon intensity reduction is incomplete. To explore these issues, this study conducts an empirical analysis using the log-averaged Divisia index (LMDI) to decompose industrial carbon dioxide (CO₂) emissions in seven pilot regions from 2006 to 2019 into four effects: economic size, economic structure, energy efficiency, and energy mix. Then, a difference-in-difference (DID) model is used to assess the impact of ETS on these four effects, and finally, a mediating effects model is used to verify the specific pathways affecting carbon emission reduction. The results of the study show that ETS achieves carbon intensity reduction mainly through three pathways: economic level, economic structure, and energy intensity.

Keywords: LMDI, carbon emission trading mechanism, differential model, industrial CO₂ emissions, mediating effect model

一、引言

随着经济的快速发展以及城镇化的扩张,人们对于能源消耗的需求日益增长,而消耗这些能源所产生的二氧化碳对我们的生活产生了威胁。全球碳市场在过去十几年保持稳定增长,碳交易总量由建立之初的不到 25 亿吨二氧化碳当量增长至 2019 年的 50 亿吨二氧化碳当量,整个世界都将目光焦距在生态文明建设上,各个国家都实施了控制二氧化碳排放量的政策。中国作为最大的发展中国家,同时也是世界经济的主要贡献者,在 2015 年 12 月 12 日参与了《巴黎协定》并承诺在 2030 年左右达到碳排放峰值;单位国内生产总值碳排放强度相较于 2005 年下降 60 到 65 个百分点等约定。并在十九大强调,必须增强危机意识,树立绿色低碳发展理念,将中国经济从高速增长阶段转型为高质量发展。为了达到这些目标,中国采取了一系列减排措施。在十四五规划中,为应对气候变化和实现节能减排制定了明确的目标和任务。

世界上有代表性的气候政策是排放交易计划(ETS)和提交碳税。其中,碳排放权交易政策是一种以市场为导向的政策手段,其作用机制是:政府对排放主体产生的二氧化碳排放量设定一个限制,并分配与该限制大致相等的配额。许可证可以在排放主体间进行交易。目前全球共有 20 个碳排放权交易体系投入运行,6 个国家和地区正在建设碳排放权交易体系,12 个国家和地区正在策划实施碳排放权交易机制。全球碳市场共覆盖了温室气体排放总量的 8% 左右,覆盖范围涉及电力、工业、民航、建筑、交通等多个行业。

我国的碳排放市场建设经历了大致两个阶段:第一阶段(2011 年-2021 年 6 月)为地方试点阶段,分别在深圳、上海、北京、广东、天津、湖北、重庆和福建八个省市进行了碳排放权交易试点;第二阶段(2021 年 7 月至今)为全国运行阶段,这一时期全国统一碳排放权交易市场正式启动。我国碳市场具体的推行脉络如下:2011 年 3 月 16 日,《国民经济和社会发展十二五规划纲要》公布,明确提出逐步建立碳排放交易市场。2011 年 10 月 29 日,

国家发改委办公厅发出《关于开展碳排放权交易试点工作的通知》,同意北京、上海、天津、重庆、湖北、广东、深圳等七省市开展碳排放权交易试点。2013 年年底,深圳、北京、天津、上海、广东等地相继开展了碳排放权试点交易,2014 年 4 月湖北试点交易启动,6 月重庆试点交易启动,2016 年 9 月福建试点交易启动。2021 年 7 月 16 日,全国碳市场上线交易正式启动。

减排的最终目的是为了让企业通过技术创新,使减排具有可持续性。一些研究已经研究了碳市场是否可以减排,但没有深入分析碳市场主要是通过什么路径去实现减排的,既定的减排目标是怎样完成的,本文从分解和中介两个角度分析碳市场影响企业减排的路径,从而为完善碳市场的路径,促进绿色转型提供有效建议。

二、国内外文献综述

许多研究表明,碳排放交易政策对二氧化碳的减少是有效的,Bao (2020),Wang (2020) 和 chen (2020) 研究了近年来碳交易市场的发展状况以及市场特点,总结了碳交易市场存在的问题并提出了相关建议。随着 ETS 在中国的逐步推广,学者们近年来集中研究了 ETS 的影响。这些研究包括企业产品价格和减排行为(Zhang, 2015),对碳强度、二氧化碳排放、国内生产总值(GDP)和部门的影响,国内生产总值(GDP)和部门产出的影响(Li and Jia, 2016),对风力发电投资的影响(Li and Jia, 2016)。对风力发电投资的影响(Mo et al, 2016)。以及对不同行业二氧化碳排放的影响(Li et al, 2017; Lin, 2018),对碳价格的影响(Yang, 2018),对企业行为的影响(Deng, 2018)。

国内外有多种评价 ETS 政策效果的研究方法,Zhang 等(2020)系统地总结了这些研究中使用的方法。其中,差额法(DID)是政策效果评价领域的经典方法,被广泛用于 ETS 政策效果评价的各个领域。这些研究包括 ETS 对碳排放和经济增长的影响(Zhang, 2020)。对绿色发展效率的影响(Zhou 和 Zhang, 2020)。对节能减排的影响(Hu, 2020)。对碳强度的影响(Zhou, 2019; Zhang, 2017; Yi, 2020)。

尽管之前的研究对试点碳市场的实施效果进行了有益的探索,但这些研究也存在一些不足之处。他们一般关注政策和碳排放之间的关系,没有分析政策的作用方式,没有考虑区域间的异质性和具体的影响途径。ETS 如何促进碳排放的减少?该政策是否通过多种途径影响排放?这实际上是衡量政策绩效时必须注意的问题。为了填补这些空白,我们结合差分法模型和 LMDI 探讨了中国试点的 ETS 是如何影响区域层面的碳减排的。此外,我们从区域角度研究了 ETS 效应的异质性,并探讨了中介因素。

本文在以下方面做出了贡献:

对二氧化碳进行了分解,从经济水平,经济结构,能源强度,能源结构四个方面来分析 ETS 是通过影响哪种因素来实现减排作用的。在证实碳交易市场发挥减排作用的同时,研究了政策发挥作用的具体途径。这样可以“对症下药”,为了更高效率的达到减排目标,可以通过加大对有效影响因素的优化调整来实现。

(2) 考虑了地区间的异质性,由于不同试点地区的化石能源结构和经济发展情况不同,所以 ETS 对不同试点地区的影响存在差异。为了调整这些差异,是各个地区的碳排放量达到均衡,本文分别研究了 ETS 对 7 个试点地区的作用途径,根据地方产业和能源特色来调整不同地区的政策。这为接下来开展碳市场全国化提供了宝贵的参考意见。

三、数据和模型

1、LMDI 模型

分解模型最早是由 Ang, B.W 在 2008 年提出,他提出了两种 LMDI 方法,即乘法和加法 LMDI 模型。本文选用的是加法 LMDI 模型来分析在 ETS 的作用下影响 7 个试点地区工业二氧化碳排放的主要因素。根据分析二氧化碳排放量的变化主要受到经济和能源两大因素的影响所以本文将二氧化碳排放量分解为经济水平,经济结构,能源强度,能源结构四个部分。

参考 Yang(2020)的效应分解模型,本文将碳排放分解为以下四个因素,如公式 1:

$$C = \sum_i C_i = \sum_i G * \frac{G_{in}}{G} * \frac{E}{G_{in}} * \frac{C_i}{E} = \sum_i G * EP * EE * ES_i \quad (1)$$

其中, C 表示工业二氧化碳排放量,下标 i 表示不同的能源类别, C_i 表示由第 i 类化石能源的消费所产生的工业二氧化碳排放量,二氧化碳排放量计算公式如公式 7。 G 和 G_{in} 分别为国内生产总值和工业增加值。 E 表示工业化石能源消费导致的二氧化碳排放。 EP 代表工业增加值在 GDP 中的比例在 GDP 中的比例。 EE 代表每个工业增加值的工业化石能源消耗。 ES_i 代表工业化石能源消费结构;它是第 i 类化石能源的 CO_2 排放系数与第 i 类化石能源的比例的乘积。

公式 2 详细分解了从 $t-1$ 年到 t 年,工业二氧化碳排放的变化分为四个方面影响,产生于:经济规模、经济结构、能源效率和能源结构效率和能源结构。 $\Delta C_G^{t,t-1}$ 代表经济规模效应, $\Delta C_{EP}^{t,t-1}$ 是经济结构效应, $\Delta C_{EE}^{t,t-1}$ 是能源效率效应, $\Delta C_{ES}^{t,t-1}$ 标志着能源结构效应。公式 3—公式 6 为四种效应的计算公式:

$$\Delta C^{t,t-1} = \Delta C_G^{t,t-1} + \Delta C_{EP}^{t,t-1} + \Delta C_{EE}^{t,t-1} + \Delta C_{ES}^{t,t-1} \quad (2)$$

$$\Delta C_G^{t,t-1} = \sum_i \frac{C_i^t - C_i^{t-1}}{\ln C_i^t - \ln C_i^{t-1}} * \ln \frac{G^t}{G^{t-1}} \quad (3)$$

$$\Delta C_{EP}^{t,t-1} = \sum_i \frac{C_i^t - C_i^{t-1}}{\ln C_i^t - \ln C_i^{t-1}} * \ln \frac{EP^t}{EP^{t-1}} \quad (4)$$

$$\Delta C_{EE}^{t,t-1} = \sum_i \frac{C_i^t - C_i^{t-1}}{\ln C_i^t - \ln C_i^{t-1}} * \ln \frac{EE^t}{EE^{t-1}} \quad (5)$$

$$\Delta C_{ES}^{t,t-1} = \sum_i \frac{C_i^t - C_i^{t-1}}{\ln C_i^t - \ln C_i^{t-1}} * \ln \frac{ES^t}{ES^{t-1}} \quad (6)$$

2、DID 模型

首先,我们先研究 ETS 政策对试点地区的实施效果,建立以下模型:

$$CO2_{it} = \beta_0 + \beta_1 \cdot treated_i + \beta_2 \cdot time_t + \beta_3 \cdot treated * time_t + \delta_j \cdot X_{it} + \varepsilon_{it} \quad (7)$$

其中, $CO2_{it}$ 表示 i 地区 t 年工业部门的碳排放水平; $time_t$ 表示碳排放权交易政策冲击发生时间的虚拟变量,如果在 2013 年及以前, $time_t$ 为 0,如果在 2013 年及以后, $time_t$ 为 1; $treated_i$ 表示地区 i 是否是受到碳排放权交易政策冲击的虚拟变量,如果地区 i 是碳排放权交易的试点地区, $treated_i$ 取值为 1,表示处理组,否则 $treated_i$ 取值为 0,设定为控制组;交互项 $time_t \times treated_i$ 是政策冲击时间虚

拟变量与政策冲击个体虚拟变量的乘积,其系数 β_3 在实证结果中用 DID 表示。 X_{it} 为其他可能影响就业水平的控制变量, ε_{it} 为误差项。 $\beta_0, \beta_1, \beta_2, \beta_3, \delta_j$ 为待估系数。

为了研究 ETS 是否对四种中介变量也产生了影响,建立以下四种模型:

$$G = \beta_0 + \beta_1 \cdot treated_i + \beta_2 \cdot time_t + \beta_3 \cdot treated * time_i + \delta_j \cdot X_{it} + \varepsilon_{it} \quad (8)$$

$$IS = \beta_0 + \beta_1 \cdot treated_i + \beta_2 \cdot time_t + \beta_3 \cdot treated * time_i + \delta_j \cdot X_{it} + \varepsilon_{it} \quad (9)$$

$$EE = \beta_0 + \beta_1 \cdot treated_i + \beta_2 \cdot time_t + \beta_3 \cdot treated * time_i + \delta_j \cdot X_{it} + \varepsilon_{it} \quad (10)$$

$$ES = \beta_0 + \beta_1 \cdot treated_i + \beta_2 \cdot time_t + \beta_3 \cdot treated * time_i + \delta_j \cdot X_{it} + \varepsilon_{it} \quad (11)$$

公式 8—11 分别代表经济水平,经济结构,能源强度,能源结构四种效应受到 ETS 的影响情况,其结果由表 7—10 表示。

3、多重中介模型

在解释变量 X 对被解释变量 Y 产生影响的过程中, X 可能会通过某个中间变量 M 对 Y 产生影响,则称 M 为中介变量。中介效应也可称之为 X 对 Y 的间接效应,是指 X 通过 M 对 Y 的影响程度。若同时存在多个中介变量 M_i ,则称该效应为多重中介效应。对中介效应的研究能够更为全面的解释自变量对因变量的影响机制,可用如下方程说明中介效应变量间的关系。

多重中介模型的优势在于。1.可以得到总的中介效应;2.在控制其他变量的情况下,可以研究每个变量的具体中介效应;3.可以比较各种中介变量产生的效应,以确定哪个效应更大,即确定哪个中介变量的效应更大。根据中介变量之间是否存在关系,多重中介分为平行多重中介和连锁多重中介,本文采用平行多重中介模型进行机制分析

$$Y = cX + e_1 \quad (12)$$

$$M = aX + e_2 \quad (13)$$

$$Y = C'X + bM_i + e_3 \quad (14)$$

公式(12)中 c 为自变量 X 对因变量 Y 的总效应估计系数;公式(13)中 a 为自变量 X 对中介变量 M 的估计系数;公式(14)中系数 b 为控制 X 的影响后 M 对 Y 的效应,系数 c' 则是在控制 M 的影响后 X 对 Y 的直接效应; $e_1, e_2,$

e_3 分别为公式(12)、(13)、(14)的残差项。在上述模型中,中介效应(也即间接效应)为系数 a、b 的乘积,其与总效应和直接效应的关系用下式表述:

$$C = C' + ab \quad (15)$$

在本文中,将分解的四种种效应当作四种中介变量,通过五种路径分别计算出 ETS 政策对这些效应所带来的影响。这五种路径分别为:1.did-中介变量: ETS 政策对中介变量的影响 a; 2.中介变量- CO_2 : 中介变量对碳排放量的影响 b; did-中介变量- CO_2 (Direct): 控制住中介变量以后, ETS 对碳排放量的直接影响 C' ; did-中介变量- CO_2 (Indirect): 加入中介变量后, ETS 对碳排放量的间接影响 $a*b$; did- CO_2 : 整体的总效应 C。本文将四种效应的中介模型的结果作为一个机制分析,来验证与之前几种 DID 模型的结果是否一致。

4、被解释变量说明及数据来源

据政府间气候变化委员会(IPCC)评估报告显示,全球碳排放量通常采用实际能源消耗量和与之对应的碳排放系数乘积进行测度。本文的二氧化碳排放量的计算公式如公式 16:

$$C = \sum_i CC_i * \rho_i * \alpha_i \quad (16)$$

其中 C 为碳排放量, CC_i 为 i 种能源的消耗量,各种能源消耗量来自《中国能源统计年鉴》中分地区能源消耗平衡表中工业部门的能源消耗量,主要研究八种主要的化石能源即:原煤、焦炭、原油、汽油、煤油、柴油、燃料油以及天然气。 ρ_i 为各类能源对应的标准煤折算系数(如表 1 所示); α_i 为各类能源对应的碳排放系数(如表 1 所示)。

表 1. 各类能源折标准煤参考系数和碳排放系数

能源种类	折标准煤参考系数	碳排放系数
原煤	0.7143	0.7559
焦炭	0.9714	0.855
原油	1.4286	0.5857
汽油	1.4714	0.5538
煤油	1.4714	0.5714
柴油	1.4571	0.5921
燃料油	1.4286	0.6185
天然气	1.33	0.4483

5、中介变量

基于 LMDI 的分解,本文的中介变量为: 1.经

济水平(G): 衡量一个地区经济水平最直观也最权威的就是该地区的国内生产总值 GDP。2.经济结构(IS): 由于本文研究的是工业部门使用化石能源产生的二氧化碳排放量, 所以用工业部门的地区生产总值与地区整体的生产总值的比例来衡量该地区的经济结构。3.能源消耗(EE): 用一个地区化石能源的使用量来衡量该地区的能源消耗是最直观的。4.能源结构(ES): 用工业部门使用的本文研究的能源的消耗量与整个工业部门使用的能源消耗量的比值来衡量一个地区的能源结构。

6、控制变量

为了使实证结果更加可行, 本文采用了政策实施前后的 6 年的数据, 从 2006 年—2019 年。本文的数据来源于《中国能源统计年鉴》,《中国城市统计年鉴》,《中国环境统计年鉴》和《中国科技统计年鉴》。

本文引入了以下控制变量:

(1) 产业深化程度(IE): 判断一个地区的产业是否先进, 主要是看其第三产业水平, 本文用一个地区的第三产业产值与总产值的比例来衡量该地区的产业深化程度。

(2) 城镇化率(UR): 一个地区的主要经济来源和经济产出主要来源于城镇, 所以城镇的覆盖程度能够反应该地区的经济水平, 本文用一个地区的城镇人口数与总人口的占比来衡量该地区的城镇

化率。

(3) 人均经济水平(PG): 除了地区的整体生产总值之外, 最能反应该地区经济水平的就是人均生产总值了。

(4) 工资水平(W): 本文在控制通货膨胀以后的地区人均年工资来衡量该地区的工资水平。

创新水平(IN): 一个地区的创新水平可以除了可以反应该地区的经济水平外, 还可以反应该地区的资源利用情况, 本文用地区专利申请数量来衡量该地区的创新水平。

(5) 环境治理投资(EI): 一个地区在环境治理上的投资反映了该地区对与绿色生态建设的重视程度, 本文用地区对工业废气治理设施运行的费用与地区生产总值的比例来衡量该地区的环境治理投资。

(6) 外商投资(FDI): 反映对外开放程度。

(7) 物价水平(P): 反映该地区消费水平。

(8) 人均收入(IC): 反映该地区产出能力和经济发展水平。

(9) 公共预算支出(EX): 一个地区的支出可以侧面的反映该地区的资源使用投入水平。

(10) 科技投资(SC): 科技上的投资包含对能源设施的投资, 本文用科技投资与公共预算总支出的比例来衡量。

变量的描述性统计见表 2。

表 2.描述性分析

变量	样本数	处理组				样本数	控制组			
		均值	标准差	最小值	最大值		均值	标准差	最小值	最大值
G	84	10.14	0.83	8.15	12.03	336	9.68	1.058	6.464	11.961
IS	84	0.41	0.10	0.16	0.60	336	0.46	0.076	0.207	0.615
EE	84	0.36	0.32	-0.24	1.18	336	0.69	0.502	-0.406	2.086
ES	84	9.59	0.51	8.44	12.68	336	9.74	0.681	6.759	10.893
IE	84	0.53	0.13	0.36	0.83	336	0.41	0.064	0.286	0.589
UR	84	4.25	0.21	3.78	4.49	336	3.90	0.19	3.313	4.257
PG	84	2.06	0.68	0.21	3.25	336	1.48	0.691	-0.499	5.124
W	84	11.18	0.68	9.47	12.51	336	10.87	0.628	9.525	11.967
IN	84	9.64	1.11	6.97	12.51	336	8.28	1.656	3.611	12.078
EI	84	-6.50	0.65	-8.44	-5.00	336	-5.945	0.573	-7.506	-3.726
FDI	84	-0.52	0.71	-1.80	0.55	336	-1.535	0.761	-3.033	1.766
P	84	4.621	0.019	4.573	4.667	336	4.627	0.02	4.581	4.706
IC	84	8.08	0.931	5.761	9.898	336	7.313	1.083	3.743	9.535
EX	84	8.435	0.867	6.297	10.21	336	8.163	0.922	5.162	9.891
SC	84	4.845	1.456	0.304	8.994	336	3.822	1.315	-0.547	7.378

四、实证结果

1、 ETS 对整体的影响

由于政策对于实施主体来说往往是外生的，为了避免逆向因果问题，本文采用双重差分法来进行政策评估。根据公式 7，我们得到 ETS 对整

体的影响，结果如表 3 显示。不难看出，在控制地区效应和个体固定效应的前提下，模型中的交互项的系数 did 是显著的，且为负数。这说明，碳排放交易机制的实施是有利于二氧化碳的减少的。

表 3.ETS 对整体的影响

	(1)	(2)	(3)	(4)	(5)
	CO_2	CO_2	CO_2	CO_2	CO_2
did	4.525*** (0.325)	1.343*** (0.277)	1.447*** (0.247)	0.834*** (0.250)	0.686*** (0.242)
UR	32.035*** (0.730)	7.973*** (1.287)	11.045*** (1.189)	7.095*** (1.264)	5.498*** (1.246)
PE		4.944*** (0.243)	5.572*** (0.225)	5.996*** (0.222)	3.905*** (0.418)
EI			3.227*** (0.319)	2.267*** (0.333)	2.317*** (0.320)
FDI				1.156*** (0.168)	1.481*** (0.171)
EX					2.076*** (0.357)
_cons	-2.733*** (1.069)	3.074*** (0.547)	-2.934*** (1.047)	9.709*** (0.012)	5.731*** (1.300)
N	434	434	434	434	434

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

本文对实验组和对照组的二氧化碳排放量的平行趋势进行了检验。如图 1 和图 2 所示，在政策实施前一年，即 2013 年以前处理组和对照组的二氧化碳排放量增长趋势基本一致。在政策实施后，即 2013 年以后，处理组的排放量明显呈下降趋势，对照组仍然是上升状态。满足双重差分模型的假

设条件。为了排除其他政策对试点地区二氧化碳排放量的影响，证明 ETS 的真实有效性，本文将政策实施时间分别提前改为 2010 年，推迟改为 2016 年，来验证 ETS 发生作用与政策实施时间有关系。即没有受到其他政策的影响。结果如表 4 和图 3 显示，结果表明改变政策实施时间后，ETS 没有发挥作用。

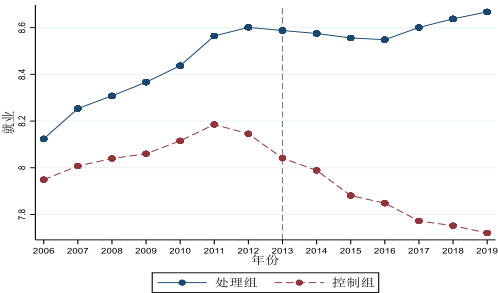


图 2.平行趋势检验结果

表 4.改变政策实施时间的安慰剂检验

变量	CO_2	
	year 2010	year 2016
time	-0.040 (0.055)	0.507** (0.009)
treated	0.429** (0.208)	0.407 (0.170)
time * treated	0.026 (0.048)	-0.017 (0.264)
控制变量	yes	yes
时间固定	yes	yes
个体固定	yes	yes
观测值	150	150

2、 ETS 对四种效应的影响

为了判断 ETS 的实施是否真的对四种效应产生了影响，根据公式 8-11，本文分别对四种效应进行了回归，结果如表 5-8 所示。对于经济水平，经济结构，能源强度效应，无论是否添加控制变量，

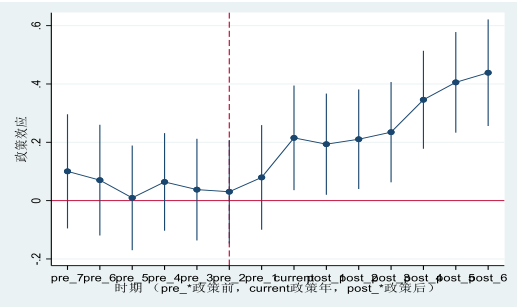


图 1.平行趋势检验

加几个控制变量，DID 的 P 值均显著，表明 ETS 的 无论是否加控制变量，DID 的 P 值都不显著，是大实施对这三种效应产生了影响。而能源结构的系数， 于 0.1 的，这说明 ETS 没有对能源结构产生影响。

表 6.ETS 对经济结构的影响

	(1)	(2)	(3)	(4)	(5)
	IS	IS	IS	IS	IS
did	0.020 (0.046)	-0.029*** (0.009)	-0.033*** (0.008)	-0.013*** (0.004)	-0.009** (0.004)
expend		-0.033*** (0.003)	-0.247*** (0.023)	-0.025* (0.013)	-0.030** (0.013)
income			0.223*** (0.024)	0.040*** (0.013)	0.038*** (0.013)
service				-0.899*** (0.026)	-0.911*** (0.026)
UR					0.057*** (0.021)
_cons	9.709*** (0.012)	0.726*** (0.025)	0.822*** (0.025)	0.758*** (0.012)	0.596*** (0.061)
N	420	420	420	420	420

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

表 7.ETS 对能源强度的影响

	(1)	(2)	(3)	(4)	(5)
	EE	EE	EE	EE	EE
did	-0.421*** (0.050)	-0.424*** (0.051)	-0.435*** (0.051)	-0.115*** (0.034)	-0.082*** (0.031)
environmen t		-0.015 (0.037)	0.015 (0.038)	0.098*** (0.024)	0.120*** (0.022)
FDI			0.113*** (0.036)	0.083*** (0.023)	0.059*** (0.021)
science				-0.193*** (0.008)	-0.090*** (0.013)
patent					-0.145*** (0.015)
_cons	0.680*** (0.076)	0.589** (0.232)	0.923*** (0.251)	2.125*** (0.168)	3.045*** (0.179)
N	420	420	420	420	420

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

表 8.ETS 对能源结构的影响

	(1)	(2)	(3)	(4)	(5)
	ES	ES	ES	ES	ES
did	0.020 (0.046)	0.029 (0.050)	0.028 (0.050)	0.029 (0.050)	0.031 (0.050)
wage		-0.009 (0.021)	-0.010 (0.031)	0.008 (0.050)	-0.014 (0.061)
service			0.018 (0.310)	-0.013 (0.318)	0.017 (0.321)
science				-0.010 (0.022)	-0.015 (0.023)
patent					0.021 (0.032)
_cons	9.709*** (0.012)	9.801*** (0.227)	9.808*** (0.253)	9.663*** (0.403)	9.742*** (0.422)
N	420	420	420	420	420

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

3、不同试点地区的异质性分析

由于各个试点地区的经济水平和工业化程度不同,能源分布和能源消耗量不一样,所以 ETS 在发挥减排作用的时候不同试点地区间会存在异质性。为了更好的研究 ETS 对各个试点地区的影响途径,本研究专门整理了 ETS 对四种效应产生的影响。解释了不同试点地区受到的影响途径不同,这样可以针对不同地区对症下药,通过调整各自的影响途径来达到更好的减排效果。

表 9-12 显示了 ETS 通过四种效应对七个试点地区的影响。结果显示(1)由于本省的经济水平效应受到 ETS 的影响从而使得二氧化碳排放量减少的试点地区有 5 个,分别是:北京,上海,湖北,

广东,重庆,深圳。(2)由于本省的经济结构效应受到 ETS 的影响从而使得二氧化碳排放量减少的试点地区有 5 个,分别是:北京,天津,上海,湖北,重庆。其中,对北京的影响不大,显著水平不太高。(3)每个试点地区都受到了由 ETS 影响能源强度而带来的二氧化碳排放量减少这一结果,这表明能源强度是最主要的传导途径。(4)由于本省的经济水平效应受到 ETS 的影响从而使得二氧化碳排放量减少的试点地区只有北京和湖北 2 个地区,且显著性水平不太高,这表明能源结构这一影响路径作用不大。

表 9.通过经济水平对试点地区产生的影响

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Beijing	Tianjin	Shanghai	Hubei	Guangdong	Chongqing	Shenzhen
did	0,067** (2.23)	0,069 (1.41)	0,236*** (3.57)	-0,094*** (-2.99)	0,058*** (3.94)	0,230** (2.34)	0,213*** (7.57)
FDI	-0,007 (-0.24)	-0,007 (-0.23)	-0,001 (-0.03)	-0,002 (-0.05)	0,004 (0.15)	-0,005 (-0.18)	0,007 (0.22)
P	-2,971** (-2.35)	-2,931** (-2.41)	-2,839** (-2.30)	-2,885** (-2.44)	-2,763** (-2.31)	-2,876** (-2.37)	-2,741** (-2.31)
PE	0,468* (1.86)	0,454* (1.83)	0,474* (1.88)	0,452* (1.82)	0,468* (1.86)	0,464* (1.85)	0,462* (1.86)
SC	0,284** (2.32)	0,294** (2.41)	0,281** (2.29)	0,295** (2.40)	0,285** (2.30)	0,288** (2.33)	0,292** (2.41)
_cons	21,612*** (3.77)	21,409*** (3.86)	21,014*** (3.74)	21,242*** (3.96)	20,717*** (3.82)	21,184*** (3.84)	20,609*** (3.83)
N	350	350	350	350	350	350	350
R ²	0.927	0.930	0.926	0.931	0.927	0.930	0.924

表 10.通过经济结构对试点地区产生的影响

	(1) Beijing	(2) Tianjin	(3) Shanghai	(4) Hubei	(5) Guangdong	(7) Chongqing	(7) Shenzhen
did	0,017* (1.89)	-0,073*** (-8.83)	-0,067*** (-9.85)	0,033*** (3.97)	-0,008 (-1.10)	-0,032*** (-3.38)	-0,006 (-0.76)
W	-0,098*** (-3.18)	-0,099*** (-3.26)	-0,099*** (-3.22)	-0,099*** (-3.19)	-0,099*** (-3.16)	0,104 (1.61)	-0,102*** (-3.07)
IC	0,037 (1.47)	0,036 (1.44)	0,037 (1.47)	0,037 (1.46)	0,038 (1.47)	-0,007*** (-3.02)	0,046 (1.65)
IN	0,001 (0.05)	0,002 (0.21)	0,001 (0.10)	0,002 (0.16)	0,001 (0.08)	0,004 (0.28)	-0,003 (-0.31)
FDI	-0,043*** (-2.97)	-0,044*** (-3.02)	-0,044*** (-2.96)	-0,045*** (-2.98)	-0,043*** (-3.03)	-0,115* (-1.84)	-0,043*** (-2.79)
_cons	1,179*** (6.86)	1,202*** (7.04)	1,195*** (7.01)	1,178*** (6.88)	1,187*** (6.93)	0,380** (2.19)	1,194*** (6.58)
N	350	350	350	350	350	350	350
R ²	0.521	0.539	0.543	0.508	0.524	0.283	0.504

t statistics in parentheses

* p < 0.1, ** p < 0.05, *** p < 0.01

表 11.通过能源强度对试点地区产生的影响

	(1) Beijing	(2) Tianjin	(3) Shanghai	(4) Hubei	(5) Guangdong	(6) Chongqing	(7) Shenzhen
did	-0,200*** (-3.13)	0.149** (0.072)	-0,084** (-2.19)	-0,253*** (-6.42)	-0,188*** (-4.65)	-0,334*** (-8.09)	0,684*** (10.75)
IN	-0,065* (-1.86)	-0,433*** (0.106)	-0,065* (-1.81)	-0,061* (-1.72)	-0,056** (-2.07)	-0,064* (-1.74)	-0,056 (-1.56)
UR	-0,775** (-2.17)	0.199 (0.531)	-0,804** (-2.19)	-0,777** (-2.08)	-1,652*** (-5.23)	-0,792** (-2.09)	-0,922** (-2.28)
SC	-0,080*** (-3.24)	0.013 (0.019)	-0,075*** (-2.88)	-0,084*** (-3.09)	-0,070*** (-3.35)	-0,079*** (-3.00)	-0,067** (-2.26)
EI	0,047 (1.12)	0.082 (0.051)	0,044 (0.99)	0,042 (0.98)	2,143*** (8.01)	0,047 (1.11)	0,038 (0.84)
_cons	4,874*** (4.02)	4,552*** (1.122)	4,937*** (4.04)	4,807*** (3.92)	6,985*** (7.20)	4,898*** (3.96)	5,587*** (4.26)
N	350	350	350	350	350	350	350
R ²	0.730	0.149**	0.719	0.743	0.823	0.741	0.707

t statistics in parentheses

* p < 0.1, ** p < 0.05, *** p < 0.01

表 12.通过能源结构对试点地区产生的影响

	(1) Beijing	(2) Tianjin	(3) Shanghai	(4) Hubei	(5) Guangdong	(6) Chongqing	(7) Shenzhen
did	-0,591** (-12.65)	0,022 (0.80)	0,126 (1.10)	0,096* (2.98)	-0,101 (-1.09)	0,074 (1.38)	-0,067 (-0.53)
W	0,011 (0.08)	0,011 (0.08)	0,007 (0.05)	0,002 (0.01)	0,020 (0.13)	0,010 (0.07)	-0,061 (-0.36)
IE	0,039 (0.07)	0,014 (0.03)	-0,097 (-0.23)	0,005 (0.01)	-0,013 (-0.03)	0,007 (0.02)	0,107 (0.27)
SC	-0,011 (-0.48)	-0,008 (-0.35)	-0,016 (-0.63)	-0,014 (-0.60)	-0,007 (-0.32)	0,005 (0.21)	0,017 (0.80)
IN	0,010 (0.25)	0,013 (0.31)	0,211 (0.31)	0,022 (0.53)	0,056 (0.08)	-0,040 (-0.06)	0,280 (0.30)
_cons	9,541*** (10.03)	9,546*** (9.77)	8,923*** (6.72)	9,575*** (10.12)	9,340*** (7.35)	9,758*** (7.23)	9,028*** (3.75)
N	350	350	350	350	350	350	350
R ²	0.129	0.006	0.011	0.009	0.008	0.018	0.014

t statistics in parentheses

* p < 0.1, ** p < 0.05, *** p < 0.01

五、机制分析

为了验证之前 DID 的回归结果,证明 ETS 真的是通过经济水平,经济结构和能源强度三种效应对二氧化碳排放量产生了影响,本文用多重中介模型进行了一个机制分析,来验证前面 DID 的结果。并对中介模型的结果进行检验。

四种效应中介效应的系数与检验的结果如表 13-16 所示,表 13 表示从经济水平的中介传导机制,路径一的回归系数是显著的,则可以看出 ETS 的实施(这里用 did 表示)对经济水平的提高具有促进作用。途径三表示在控制住经济水平的情况下,ETS 的实施对 CO_2 的直接影响,该系数显著为负,说明在不考虑经济水平这个中介变量的情况下,ETS 对 CO_2 是有显著抑制作用的。途径四的系数显著且是的正值,说明在以经济水平为中介变量的模型中,公式 13 和公式 14 中对应的 a 和 b 的乘积为正值,表明经济水平作为中介变量对被解释变量 CO_2 的影响是显著的,也意味着 ETS 政策通过促进经济水平的提高来对碳排放量产生显著的促进作用。途径五为总效应,该系数显著为负,说明虽然 ETS 通过经济水平对二氧化碳排放量产生了促进作用,但该作

用并不大,小于 ETS 对碳排放量直接产生的抑制作用。

表 14 中的途径四的系数显著且是的负值,表明 ETS 政策通过促进经济水平的提高来对碳排放量产生显著的抑制作用。途径五系数显著为-0.108,说明虽然 ETS 通过经济结构对二氧化碳排放量产生了抑制作用,该作用大于在控制中介变量后政策对碳排放量的直接影响。

表 15 中的途径四系数为-0.088 且是显著的,这说明 ETS 政策通过抑制能源强度的提高来对碳排放量产生显著的抑制作用,该值小于途径三的系数,说明通过降低能源强度从而减少碳排放量产生的作用不大。途径五系数显著为负,则说明在加入能源强度这个中介以后,ETS 对 CO_2 有显著的抑制作用。

表 16 表示以能源结构为中介的传导机制,路径一系数为负,但 95%的置信区间中包含 0,说明结果不显著。且途径四系数很小,则途径五的总体效应都是 ETS 对碳排放量产生的直接影响,能源结构并没有在抑制碳排放上起到中介传导的作用。

表 13.以经济水平为中介 ETS 的作用路径

效应	路径	影响	影响系数	95%置信区间	
				下限	上限
经济水平	did-G	-	1.005***	0.229	0.397
	G-CO2	-	0.611***	0.641	0.759
	did-G-CO2	Direct	-0.916***	-0.397	-0.256
	did-G-CO2	Indirect	0.614***	0.152	0.286
	did-CO2	Total	-0.107**	-0.202	-0.013

表 14.以经济结构为中介 ETS 的作用路径

效应	路径	影响	影响系数	95%置信区间	
				下限	上限
经济结构	did-IS	-	-0.265***	-0.352	-0.178
	IS-CO2	-	0.502***	0.426	0.577
	did-IS-CO2	Direct	0.025	-0.061	0.111
	did-IS-CO2	Indirect	-0.133***	-0.182	-0.084
	did-CO2	Total	-0.108**	-0.202	-0.013

表 15.以能源强度为中介 ETS 的作用路径

效应	路径	影响	影响系数	95%置信区间	
				下限	上限
能源强度	did-EE	-	-0.304***	-0.388	-0.219
	EE-CO2	-	-0.289***	-0.381	-0.197
	did-EE-CO2	Direct	-0.109***	-0.289	-0.102
	did-EE-CO2	Indirect	-0.088***	0.049	0.126
	did-CO2	Total	-0.197**	-0.202	-0.013

表 16.以能源结构为中介 ETS 的作用路径

效应	路径	影响	影响系数	95%置信区间	
				下限	上限
能源结构	did-ES	-	-0.003	-0.099	0.092
	ES-CO2	-	0.336***	0.252	0.420
	did-ES-CO2	Direct	-0.106**	-0.195	-0.018
	did-ES-CO2	Indirect	-0.001	-0.033	0.031
	did-CO2	Total	-0.108**	-0.202	-0.013

六、总结和建议

利用 2006-2019 年 30 个省的面板数据,采用 LMDI 方法,试点地区的工业二氧化碳排放的主要影响因素分解为经济水平、经济结构、能源强度和能源结构四个效应。LMDI 分解的结果表明:经济水平和能源强度效应对工业二氧化碳减排的贡献率较高,表明排放量的变化主要是通过影响 GDP 增长和化石能源消耗强度来对二氧化碳排放量产生作用的。根据 DID 和中介模型的结果可知:经济结构也对对减排的产生了贡献,但作用很小;经济增长对碳排放减少产生的促进作用受 ETS 的影响有所下降;ETS 在通过降低能源强度来对碳排放的减少产生促进作用;能源结构对碳排放的减少几乎没有任何贡献。根据研究结果,本文提出以下建议:

(1) 降低化石能源使用率。结果表明 ETS 主要是通过抑制能源强度来抑制二氧化碳的排放的,所以降低化石能源的消耗是实现碳减排,完成绿色生态文明城市建设的关键一步,本文主要研究的能源是原煤,焦炭、原油、汽油、煤油、柴油、燃料油以及天然气八类能源。这些能源也是产生有害气体,造成污染的关键。所以,推动全国省份减少化石能源的消耗量,开放新能源是必不可少的。

(2) 认真对待经济与绿色之间的关系。改变需要牺牲绿色生态来促进经济增长的状态,要让经济和生态共存,加快低碳经济的建设。让绿色生态助力经济发展,而不是让经济的增长消耗绿色生态。可以通过提高技术创新,制度创新来提高经济水平,实现经济社会发展与生态环境保护双赢。

(3) 优化产业结构。降低工业产值在 GDP 中的占比,推动第三产业的发展;对工业化程度高的城市进行惩罚机制,让大家意识到城市过度工业化对人民带来的危害;激励企业产业转型,优化资源配置,携手企业一起打赢生态环保攻坚战。

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Digital finance, environmental regulation and carbon emissions in China's manufacturing sector: dynamic spatio-temporal correlation and moderation effects analysis

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Abstract: Emerging digital finance is impacting on the economic and environmental system on various aspects, and the emission reduction effects of government environmental regulation and free market competition are becoming increasingly important. However, the relationship between digital finance, environmental regulation and manufacturing carbon emissions has apparently been neglected in surveys, and the moderating effect of competition among financial institutions has rarely been investigated. Based on provincial-level data from 2011-2018, an extended STIRPAT-DSDM model and a dynamic systems GMM model are applied to examine, allowing for temporal correlation, spatial dependence, covering regulatory effects, and overcoming endogeneity issues. The study provides ample evidence of a strong link of digital finance, environmental regulation and manufacturing carbon emissions. Specifically, digital finance reduces carbon emissions in the local region and increases carbon emissions in neighboring regions, with the total effect being an increase in carbon emissions. Nevertheless, the overall emissions reduction effect gradually emerges over time. Notably, financial institution competition provides a valuable impetus to the emission reduction effects of digital finance. In addition, environmental regulation mitigates carbon emissions in both the short-term and long-term, and has a more positive abatement effect in the long-term, with the overall abatement effect featuring a marginal incremental increase. More importantly, our research supports the full integration of free markets and active government, and the need for strong and effective environmental regulation alongside increased competition among financial institutions, which could help achieve the 'double carbon' target sooner rather than later.

Key Words: Digital finance; Environmental regulation; Manufacturing carbon emissions; Dynamic spatial panel Durbin model

1. Introduction

Environmental degradation and global warming increasingly serious, developing a low-carbon economy and controlling temperature rise has reached a global consensus with the effects of greenhouse gas emissions generating a lively debate in academic and political circles (Lin and Jia, 2019; Leitao et al., 2022; Zhao et al., 2020). The 2021 International Energy Agency (IEA) report “Net Zero by 2050, A Roadmap for the Global Energy Sector” reveals that while global CO₂ emissions decline in 2020 due to the Corona Virus Disease 2019 (COVID-19), those emissions have begun to rebound strongly as the economy recovers. China accounts for about 29% of global carbon emissions, more than the US and EU combined (Cao et al., 2021). Manufacturing holds a major portion of labor, energy consumption and total production (Lin and Chen, 2020) and is responsible for more than 50% of China's total CO₂ emissions (Xu and Lin, 2016b). The rapid development of China's manufacturing industry is also accompanied by huge energy consumption and environmental damage (Yuan et al., 2017), resulting in enormous carbon emissions. How to effectively reduce carbon emissions in the manufacturing sector is crucial to achieving China's “carbon peak and neutrality” and the global “Net Zero by 2050” targets.

An enormous attention has been devoted to the impacts of economic growth, industrialization, energy efficiency and economic policy uncertainty on energy efficiency and emission reduction in manufacturing (Xu and Lin, 2016a; Xu and Lin, 2017; Yu et al., 2021). More recent studies are gradually confirming the positive effects of financial development on energy saving and emission reduction of manufacturing industries (Maji et al., 2017). However, as digital technologies, internet technologies and financial elements converge, innovative digital financial patterns supported by information technology are emerging as

an essential part of China's financial system (Li et al., 2020). The emerging financial landscape of digital finance is shocking traditional finance in terms of access avenues, transaction approaches and customer acquisition patterns. Rapid digital technologies are now being used to deliver financial services, considerably reducing costs, thereby increasing financial inclusion and allowing for large-scale increases in economic productivity (Chen et al., 2021). Latest research focuses more attention on the relationship between emerging digital finance patterns and energy and environmental performance (Cao et al., 2021), but rarely has the literature explored the impact of digital finance on carbon emissions in manufacturing. In addition, environmental regulation is also critical for carbon reduction. Recent literature has examined the spatial spillover effects of environmental regulation on carbon emissions (Jiang and Ma, 2021). As “mandatory emission reductions” exist, environmental regulations significantly reduce carbon emissions (Nam and Jin, 2021). Conversely studies suggest that environmental regulation may also increase carbon emissions, generating a “green paradox” (Sinn, 2008). However, given the combined effect of “mandatory emissions” and the “green paradox”, the impact of environmental regulations on carbon emissions from energy-intensive industries is still uncertain (Pei et al., 2019). Therefore, further evaluation of the mitigation effects of environmental regulations is essential for the implementation of mitigation policies.

Whether time-and-space matters as much as it did in the era of traditional finance? Will digital finance be effective in reducing emissions based on the traditional financial development? Can digital finance and environmental regulation simultaneously contribute to carbon emission reduction in manufacturing? When introducing the dynamic properties of spatial and temporal time and the moderating effect of financial

institution competition, does the impact changes? This paper strives to examine the relationship of digital finance, environmental regulation and carbon emissions from the perspective of spatio-temporal dynamic correlation, suggesting new directions for the formulation of specific emission reduction policies.

The paper contributes to the existing literature in three ways. First, it extends the scope of the analytical framework and drivers of carbon emission reduction in manufacturing. Based on Xu and Lin's (2017) study, the STIRPAT model is further extended by introducing digital financial variables, along with environmental regulatory variables. To our best knowledge, this may be the first study to discuss the relationship for digital finance, environmental regulation and carbon emissions within the same framework. Second, it reveals the dynamic spatial-temporal correlation effects of each driver of carbon emissions, expanding the static and geographic dimension analysis into a dynamic spatial-temporal correlation one, and mitigating the interference of endogeneity issues on the findings. Although the geographically weighted regression model is able to capture the non-stationary spatial effects of each driver of carbon emissions (Xu et al., 2017), it only captures the effects of geographical factors and cannot measure the dynamic spatial-temporal correlation effects. This paper utilizes a dynamic spatial panel Durbin model to effectively extend the existing research horizon. To eliminate possible endogeneity issues, a dynamic systems GMM approach is re-estimated in this paper. Third, the paper innovatively assesses the moderating effect of financial institution competition in the impact of digital finance on carbon emissions reduction, and verifies the institutional advantages of the co-existence of "free market" and "responsive government".

The remainder of the paper is as follows: Section two reviews the literature, and section three conducts a

theoretical analysis and formulates the research hypothesis. Section four constructs the models as well as describing the data sources. Section five presents the empirical results with stability and endogeneity tests and discusses the findings. Section six contains the conclusions and implications.

2. Literature review

2.1 Digital finance and carbon emissions

Financial development provides the blood of economic development and a driving force to ensure the stable operation of the economy and promote expansion. Additionally, the financial sector generates the necessary credit and investment funds for innovation and technological improvements (Chauvet and Jacolin, 2017), further advancing the development of abatement technologies and enhancing technological efficiency. There is growing evidence that digitalization is affecting traditional financial development models and performance in many ways (Burlacu et al., 2021). Digital finance provides a financial service through a card connected to a mobile phone, computer, internet or digital payment system (Ozili, 2018). It includes numerous new financial products, financial services, financial-related software and innovative customer communication and interaction modes (Gomber et al., 2017). By relying more on internet channels and information technology, digital finance permits banks and fintech providers to reduce the cost of financial intermediation (Ozili, 2018) and mitigate information asymmetries. There is a powerful link between digital finance and the economy and society. Digital finance can enhance the availability of financial services, promote household consumption and optimise the allocation of resources in financial markets (Li et al., 2020).

For manufacturing industries, early studies examined the relationship between environmental performance and economic performance of Japanese

manufacturing firms (Fujii et al., 2013). Subsequent research has investigated carbon emissions in the manufacturing sector using nonparametric additive regression models and vector autoregressive models in a sample from China (Xu and Lin, 2016a; (Xu and Lin, 2016b). Lee (2021) explores the carbon performance of the manufacturing sector in Korea via the Metafrontier Malmquist-Luenberger (MML) index. As digital finance continues to penetrate traditional manufacturing, green and digital innovation waves inevitably emerge and the green manufacturing process continues to advance (Chang et al., 2022). Chen and Zhang (2021) apply ordinary least squares and high-dimensional fixed effects models to find that digital finance has a positive impact on the servitization of manufacturing in China. Cao et al. (2021) demonstrate that digital finance can significantly improve energy and environmental performance by employing data envelopment analysis and Benchmark model. Digital finance is also capable of indirectly promoting the development of a green economy through the agglomeration of producer services and achieving industrial structure optimization and upgrading (Li et al., 2021). However, rarely has the literature investigated the relationship between digital finance and manufacturing carbon emissions and assessed their spatial and temporal dynamic correlation using spatial measures.

2.2 Environmental regulation and carbon emissions

Environmental regulation can both directly reduce carbon emissions (Pei et al., 2019; Zhao et al., 2020) and yield the Porter effect (Nie et al., 2021), the technology effect and the carbon haven effect (Zhao et al., 2020), influencing corporate investment behavior (Xie et al., 2021) and industrial shift movements, thus indirectly affect carbon emissions. Empirical examinations of the BRICS countries (Brazil, Russia,

India, China and South Africa) reveal that environmental regulations have a positive effect in reducing carbon emissions (Danish et al., 2020). An empirical investigation across 109 countries also find that energy efficiency regulations contribute to carbon emission reductions with an elasticity of 0.003% (Nam and Jin, 2021). Similarly, the carbon reduction effect of environmental regulation is confirmed in China, and is significant in both the short and long term (Khan et al., 2019). Another analysis combining data from Organization for Economic Co-operation and Development (OECD) countries with social network analysis indicates a U-shaped relationship between environmental regulation and carbon emission networks (Jiang and Ma, 2021). In addition, additional surveys conclude the opposite. Sinn's (2008) study confirms the positive impact of environmental regulation on carbon emissions. The "green paradox" evidently arises, whereby green policies may not only result in the acceleration of fossil fuel extraction but also in the accumulation of carbon emissions (Ritter and Schopf, 2014). Further research reveals that the "green paradox" and the "emissions reduction effect" vary according to the intensity of environmental regulation. As environmental regulation strengthens, its impact changes from a "green paradox" effect to a "back-forced reduction" effect (Guo and Chen, 2018). On a sector-specific basis, environmental regulations have the ability to curb carbon emissions from tourism (Chen et al., 2021). For energy-intensive industries, studies conducted by the double-threshold models suggest that the carbon reduction effect of environmental regulations increases with technological efficiency (Pei et al., 2019). Evidence from manufacturing and the Full Modified Ordinary Least Square (FMOLS) model indicates that the higher the intensity of environmental regulation, the lower the carbon emissions of the manufacturing sub-sector and

the greater the agglomeration economy (Wang et al., 2018).

Although the literature on digital finance, environmental regulation and carbon emissions is progressively expanding, there are still some limitations. Firstly, the existing literature examines environmental issues separately on digital finance or environmental regulation dimensions, and systematically studies that integrate digital finance, environmental regulation and carbon emissions within the same framework are absent. Secondly, existing studies have mainly concentrated on the national scale, whereas evidence from manufacturing is comparatively limited. Thirdly, prior research neglects spatial correlation and mostly focuses on nonparametric additive regression models, high-dimensional fixed effects, the double-threshold models, social network analysis methods, Full Modified Ordinary Least Square (FMOLS); few studies utilize spatial econometric models. Fourthly, most of the previous investigations are static, and the dynamic correlation effects of variables in time are not adequately regarded, and the endogeneity problems arising from bidirectional causality between variables cannot be effectively addressed. In contrast, the temporal difference effect should be considered when discussing carbon emission reduction in China's manufacturing industry (Xu and Lin, 2016a). Therefore, in this paper, we construct a dynamic spatial panel Durbin model based on data collected at the provincial level and the manufacturing level in China from 2011-2018 to synthesize the impact of digital finance, environmental regulation on carbon emissions in the manufacturing sector. In contrast, the temporal difference effect should be considered when discussing carbon emission reduction in China's manufacturing industry (Xu and Lin, 2016a). Therefore, in this paper, we construct a dynamic spatial panel Durbin model

based on data collected at the provincial level and the manufacturing level in China from 2011-2018 to synthesize the impact of digital finance, environmental regulation on carbon emissions in the manufacturing sector. More importantly, we utilize a dynamic spatial panel Durbin model with a dynamic system GMM model to validly examine the spatially correlated effects and dynamic variation characteristics of manufacturing carbon emissions, and effectively address the potential endogeneity issue.

3. Theoretical analysis and research hypothesis

The development and spread of digital finance are conducive to corporate innovation, lower transaction costs and the upgrading of industrial structures, thereby reducing carbon emissions. First, digital finance contributes to enterprise innovation and improves the performance of the energy environment (Cao et al., 2021). Digital finance enables individuals, companies and start-ups to access the necessary funding via the internet, rather than being limited to traditional banks, venture capital or financial resource providers (Gomber et al., 2017), largely supporting entrepreneurial innovation. The Internet simplifies the process of gathering together those seeking funding and those willing to provide it (Zhang and Liu, 2012), and the availability, timeliness and accessibility of credit resources are enhanced. Mitigating financial constraints and increasing investment in R&D are the primary channels through which digital finance drives corporate green innovation (Liu et al., 2022). Second, the development of digital finance promotes a reduction in transaction costs and a more efficient utilization of funds. Digital finance enables individuals and enterprises to access payment, savings and credit facilities via the Internet without having to visit a bank branch or deal directly with a financial service provider. With the prevalence of digital finance and the rising

cooperation between banks and enterprises, the traditional offline credit business is gradually moving online, whereby the Internet has reduced transaction costs and transaction time (Zhang and Liu, 2012). The spread and intensification of digital finance allows for easier and faster daily processing of business and a more efficient utilization of funds, whether for large or small and medium-sized enterprises. Additionally, digital finance is capable of reducing the cost of financial mediation for banks and fintech providers (Ozili, 2018), thus boosting carbon reduction. Third, digital finance facilitates the upgrading of industrial structures, thereby reducing carbon emissions. The expansion of digital finance drives the upgrading of manufacturing industries (Chen and Zhang, 2021). Fourth, financial development can breed competition (Rajan and Zingales, 2003). And bank competition has been demonstrated to have an impact on the economic and environmental effects unleashed by financial development (Chauvet and Jacolin, 2017). Competition among financial institutions has a moderating effect, releasing and promoting the formation of energy-saving and emission reduction mechanisms in firms, thus mitigating carbon emissions and improving environmental quality. Therefore, the impact of digital finance on carbon emissions in manufacturing may be mediated by competition among financial institutions.

Hypothesis 1: Digital finance affects manufacturing carbon emissions, and such effects suffer from both temporal and spatial impacts, combined with shocks from financial institution competition.

The mechanism of the impact of environmental regulation on carbon emissions focuses on three levels. First, the technological and Porterian effects of environmental regulation can promote corporate investment in technology and innovation, which in turn improves technological efficiency and thereby reduces

carbon emissions. Specifically, environmental regulation triggers the Porter effect whereby firms innovate (Nie et al., 2021), impacting industrial energy-environmental performance through technological innovation (Wu and Lin, 2022). Environmental regulation can also promote R&D investment, particularly in instrumentation, effectively contributing to technological efficiency and technological progress (Zhou and Tang, 2021), thereby indirectly reducing carbon emissions through technological efficiency (Pei et al., 2019). Second, the crowding-out effect of environmental regulation on enterprise production affects the comparative advantage of enterprises in different industries and sectors, which in turn causes carbon migration. By affecting the comparative advantage of carbon-intensive industries, environmental regulation leads to a shift in carbon emissions, which has a carbon safe haven effect (Zhao et al., 2020). Third, environmental regulation improves the structure of energy consumption and exerts a pro-reducing effect. Environmental regulation policies tend to reduce the coal consumption and coal intensity of enterprises (Zhou et al., 2022) and influence the structure of national and regional energy consumption (Xia et al., 2021), resulting in a carbon emission reduction effect, where energy-intensive industries and state-owned enterprises have a heavier energy-saving responsibility. In addition, the shock of financial institution competition undermines the effectiveness of environmental regulation in reducing emissions.

Hypothesis 2: The impact of environmental regulation on carbon emissions tends to vary over time and region, having spatial spillover effects and marginal laws.

Hypothesis 3: The convergence of market competition (financial institution competition) and government regulation (environmental regulation) yields more effective emission reductions.

4. Model construction and data

4.1. Constructing the extended STIRPAT model

The Impact = Population^a· Affluence^b· Technology^c (IPAT) framework is broadly applied in environmental assessment fields (Xu and Lin, 2015). However, the IPAT model implies that the elasticities of all the independent variables are equal to one, which is manifestly incompatible with the Environmental Kuznets Curve (EKC) hypothesis (Timmer et al., 2016; Xu and Lin, 2017). In response to the IPAT model's limitations, Dietz and Rosa (1997) extended IPAT to a stochastic form, i.e., STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model, which dates as Eq. (1).

$$I_{it} = a \cdot P_{it}^b \cdot A_{it}^c \cdot T_{it}^d \cdot e_{it} \quad (1)$$

where I_{it} denotes environmental impact, and P , A , and T represent population, wealth, and technology, respectively. i refers to observational data, t to time; a means the intercept, and b , c , and d denote the elasticity of each variable to environmental effects; e indicates the error term. Many scholars have investigated the impacts of the various factors of carbon emissions in this framework (Huang et al., 2021; Liu et al., 2021; Shuai et al., 2017), normally in the logarithmic form of Eq. (1). Emerging financial and environmental regulation is crucial to the functioning of the energy and environmental sectors (Cao et al., 2021). Digital finance and environmental regulation are incorporated into the STIRPAT framework to examine the drivers of carbon emissions from the manufacturing industry in an extended STIRPAT model, as shown in Eq. (2).

In Eq. (2), e is the same as Eq. (1), i and t present province and time, respectively. MC denotes carbon emissions from the manufacturing industry, concerning Shan et al. (2020). DF presents digital finance and is calculated as Guo et al. (2020). ER refers to

environmental regulation, as assessed by the ratio of investment in wastewater and exhaust gas treatment to industrial value-added. Energy consumption (EN), population density (PO), and economic growth (GN) are adopted to measure the impact of technological, population, and wealth factors (Alshehry and Belloumi, 2015; Song et al., 2020), as the same of Eq. (1). Then a sequence of other control variables is introduced at the same time to account for the probable effect of potential factors. Industrialization level (IL) variously affects manufacturing carbon emissions, using the share of industrial value-added in GDP to calculate industrialization (Xu and Lin, 2017). Additionally, the change of industrial structure (ST) has an impact on manufacturing carbon emissions. Referring to Lin and Chen (2018), applying the ratio of GDP in the secondary industry for measuring industrial structure. To control the impact of conventional financial development on carbon emissions, the year-end loan balance to built-up area ratio, i.e. financial density (FS), is used to weigh conventional financial development. Considering technological progress influences manufacturing carbon productivity (Fang et al., 2021), the model additionally accounts for the impact of technological innovation (TI), as assessed by patents granted per capita.

4.2. Combining the extended STIRPAT model to construct a dynamic spatial panel Durbin model

Carbon emissions exhibit high spatial autocorrelation (Li et al., 2019; Liu and song, 2020; Zhang et al., 2021), and disregarding this correlation is likely to result in biased conclusions. The Wald test in Table 1 shows that the spatial Durbin model is more appropriate compared to the spatial lag and spatial error models. Additionally, the time-lagged effects of carbon emissions suggest that their dynamics must be taken into account (Yan et al., 2022). Fixed effects models are more appropriate and robust in most situations than

random-effects models (Lee and Yu, 2010), and the Hausman test in Table 1 indicates that the fixed effects form ought to be preferred. Accordingly, combining the above analysis and Eq. (2), we construct a dynamic

$$LnMC_{it} = \beta_0 + \beta_1 LnDF_{it} + \beta_2 LnER_{it} + \beta_3 LnEN_{it} + \beta_4 LnPO_{it} + \beta_5 LnGN_{it} + \beta_6 LnIL_{it} + \beta_7 LnST_{it} + \beta_8 LnFS_{it} + \beta_9 LnTI_{it} + e_{it}$$

$$\begin{aligned} LnMC_{it} = & \delta_0 + \delta_1 LnMC_{i,t-1} + \delta_2 \sum_{j=1}^n W_{ij} LnMC_{j,t-1} + \delta_3 LnDF_{it} + \delta_4 LnER_{it} + \delta_5 LnEN_{it} + \delta_6 \sum_{j=1}^n W_{ij} LnDF_{jt} + \delta_7 \sum_{j=1}^n W_{ij} LnER_{jt} \\ & + \delta_8 \sum_{j=1}^n W_{ij} LnEN_{jt} + \delta_9 \sum_{j=1}^n LnX_{jt} + \mu_i + \varepsilon_{it} \end{aligned}$$

As we primarily focus on the impact of digital finance, environmental regulation, and energy consumption on carbon emissions, other influential variables in Eq. (2) are shown in control variables (X). Specifically, $i = 1, 2, \dots, n$ and $t = 2011, 2012, \dots, 2018$; MC , DF , ER and control variables (X) are all the same with Eq. (2). $MC_{i,t-1}$ indicates carbon emissions from the Manufacturing industry of province i in year $t-1$ to examine the time lag effect of carbon emissions; δ denotes the parameter to be estimated; W refers to the spatial weight matrices, adopting a binary spatial weight matrix ($W=1$ when two regions are geographically contiguous, otherwise $W=0$); μ and ε represent fixed effects and random disturbance terms, respectively.

4.3. Data

The data evaluated in this paper is gathered from 30 provinces in China covering the period 2011–2018. The original data is obtained from the China Statistical Yearbook, China Energy Statistical Yearbook, and the official website of the China Statistics Bureau (except for Hong Kong, Macao, Taiwan, and Tibet). Carbon emissions data for manufacturing are obtained from Carbon Emission Accounts & Datasets for emerging economies (CEADs). Digital finance data is obtained

spatial panel Durbin model with fixed effects in the framework of the extended STARPAT model, presented in Eq. (3).

from the Peking University Digital Financial Inclusion Index, which refers to the total digital finance index calculated by Guo et al (2020). All data involving prices are adjusted to constant prices with 2011 as the base period. Then all variables are taken as natural logarithms for empirical analysis, except DF , in light of its index. Table 2 presents the descriptive statistics of the variables.

5. Results, robustness and endogeneity tests, and discussion

5.1 Results

5.1.1 Spatial correlation test of digital finance, environmental regulation and carbon emissions

This paper examines the spatial correlation by calculating the Moran's I of dependent and core independent variables. Table 3 presents the Moran's I of China's carbon emissions, digital finance, and environmental regulation level based on the 0-1 matrix during 2011 to 2018. As can be seen in Table 3, carbon emissions, digital finance and environmental regulation all have significant positive Moran's I value. Therefore, all of them have significant positive spatial autocorrelation and spatial clustering characteristics. This also justifies the necessity of applying spatial econometric models.

Table 1

Wald and Hausman test for the spatial panel model.

	Testing	0-1 weight matrix	P-values
Wald test	Spatial lag	62.05***	0.0000
	Spatial error	38.43***	0.0000
Hausman test		185.46***	0.0000

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 2

Descriptive statistics of variables.

Variable category	Variables	Symbols	Mean	Std.	Min	Max	Unit
Dependent variables	Carbon emissions	<i>MC</i>	259.37	178.27	22.70	802.55	Million tons
Core independent variables	Digital finance	<i>DF</i>	188.19	84.98	18.33	377.73	\
	Environmental regulation	<i>ER</i>	33.48	35.35	0.52	284.46	\
Moderating variables	Financial institution competition	<i>PT</i>	0.25	0.22	0.02	1.04	\
Control variables	Energy consumption	<i>EN</i>	14803	8796	1601	40581	Ton of standard coal
	Industrialization	<i>IL</i>	32.96	8.53	11.84	55.63	\
	Economic growth	<i>GN</i>	8.68	2.37	0.50	16.40	\
	Industrial structure	<i>ST</i>	44.69	8.46	18.60	59.05	\
	Population density	<i>PO</i>	2.90	1.02	1.28	6.95	million people / sq.km
	Financial density	<i>FS</i>	6.56	3.88	2.64	24.04	billion yuan / sq.km
	Technological innovation	<i>TI</i>	9.74	11.28	0.87	57.33	Pieces / million people

Table 3

The Moran's I value for manufacturing carbon emissions and digital finance.

Year	MC		DF		ER	
	Moran's I	Z(I) value	Moran's I	Z(I) value	Moran's I	Z(I) value
2011	0.163**	1.826	0.324***	3.250	0.378***	3.703
2012	0.146**	1.660	0.325***	3.298	0.115*	1.347
2013	0.143*	1.628	0.318***	3.251	0.253***	2.669
2014	0.144*	1.636	0.315***	3.219	0.343***	3.434
2015	0.154**	1.723	0.284***	2.943	0.163**	1.781
2016	0.151**	1.689	0.295***	3.044	0.349***	3.518
2017	0.133*	1.536	0.361***	3.665	0.380***	3.745
2018	0.159**	1.774	0.413***	4.108	0.183**	2.027

Note: ***, **, and * indicate significant at the 1%, 5%, and 10% levels, respectively.

5.1.2 Impact of digital finance, environmental regulation on carbon emissions

Model (4) in Table 4 presents the estimation results for the dynamic spatial panel Durbin model with fixed effects. Both the ordinary least squares estimation model, the fixed effects model and the static spatial panel Durbin model are reported in this paper. The impact of digital finance and environmental regulation on carbon emissions changes when the spatial spillover effects of the variables and the time-correlated effects of carbon emissions are taken into account. This also confirms that failure to capture temporal and spatial correlation effects in carbon emission models is probably resulting in biased estimation results. In the following analysis, the model (4) prevails.

As shown in model (4) of Table 4, carbon emissions from the manufacturing sector have both a significant time-lagged effect and a spatial spillover effect. The time-lagged term of carbon emissions is noticeably positive at the 1% level, indicating that a higher carbon emission in the previous period is associated with a higher carbon emission in the current period. In terms of the temporal dimension, manufacturing carbon emissions possess a strong path-dependent characteristic. Simultaneously, the spatial lag term of carbon emissions is significantly negative at the 1% level, indicating that the higher the carbon emissions of the neighboring regions in the previous period, the lower the carbon emissions of the local region in the current period. In terms of the spatial dimension, manufacturing carbon emissions present a more obvious spatial shift characteristic. This is primarily due to the fact that the rapid development of manufacturing industries in neighboring regions tends to attract more factors and generate large amounts of carbon emissions. This siphoning effect reduces the production factors available in the manufacturing industry of the local region, and forces the manufacturing industry in the neighboring regions to transform by reducing factors and improving efficiency,

thereby revealing the spatial transfer characteristics.

The estimated coefficient of digital finance is significantly negative at the 10% level, and that of the spatial term is significantly positive at the 1% level. As a result, the development of digital finance in the local region promotes the reduction of carbon emissions from the manufacturing industry of the local region, whereas that of neighboring regions promotes the increase of carbon emissions of the local manufacturing industry. Developing digital finance is able to improve the efficiency of manufacturing companies' usage of capital, reduce transaction costs and access to capital for timely technology exploration and process upgrading, thereby reducing carbon emissions for the local region. Concurrently, regions with high levels of digital finance development are more economically developed and have higher ecological and environmental requirements, increasing the transfer and diffusion of high energy-consuming and high-emission manufacturing to surrounding regions, resulting in an increase of carbon emissions in neighboring regions. Therefore, Hypothesis 1 is validated to some extent. The estimated coefficient of environmental regulation is negative but insignificant, and that of its spatial term is negative and significant. It implies that environmental regulation in either the local region or the neighboring region can mitigate carbon emissions in the local region. Consequently, Hypothesis 2 is verified partially.

For the control variables, the estimates results reveal that the energy consumption term is significantly positive at the 5% level and its spatial term is significantly negative. This suggests that energy consumption of the local region has a pro-increasing effect on carbon emissions of the local region, while that of the neighboring region has a pro-decreasing effect on carbon emissions of the local region. The industrialization level, industrial structure and

population density are significantly positive at the 1%, 5% and 10% levels respectively, reflecting that all three of them contribute considerably to manufacturing carbon emissions. The coefficients of economic growth and financial intensity are both positive and insignificant, implying that both are not adequately driving carbon emissions in the manufacturing sector currently. The negative but insignificant coefficient for technological innovation indicates that its impact on manufacturing emissions reduction is relatively minor.

5.1.3 Decomposition of short- and long-term

Table 4

Results of digital finance, environmental regulation impacting manufacturing carbon emissions.

Variables	OLS (1)	FE (2)	SDM (3)	DSDM (4)
<i>DF</i>	0.0006* (0.05)	0.0003* (0.09)	-0.0038*** (0.00)	-0.0013* (0.08)
<i>ER</i>	0.0690*** (0.01)	0.0158* (0.10)	0.0157 (0.11)	-0.0014 (0.89)
<i>EN</i>	0.7433*** (0.00)	0.9468*** (0.00)	0.8482*** (0.00)	0.2840** (0.02)
<i>IL</i>	0.8064*** (0.00)	0.3544*** (0.00)	0.3450*** (0.00)	0.1801*** (0.00)
<i>GN</i>	-0.0586 (0.33)	-0.0102 (0.73)	0.0114 (0.68)	0.0140 (0.34)
<i>ST</i>	0.1854 (0.29)	0.0590 (0.61)	0.0921 (0.40)	0.1829** (0.03)
<i>PO</i>	-0.3119*** (0.00)	-0.2104** (0.04)	-0.2321** (0.02)	0.1810* (0.09)
<i>FS</i>	-0.3751*** (0.00)	0.0072 (0.93)	0.0716 (0.40)	0.0518 (0.50)
<i>TI</i>	-0.0688* (0.09)	-0.1057*** (0.00)	-0.0701** (0.02)	-0.0233 (0.24)
<i>WDF</i>			0.0042*** (0.00)	0.0020*** (0.00)
<i>WER</i>			-0.0225 (0.14)	-0.0318** (0.02)
<i>WEN</i>			-0.3582*** (0.00)	-0.2597** (0.03)
<i>L.MC</i>				0.7250*** (0.00)
<i>L.WMC</i>				-0.3957*** (0.00)
Observations	240	240	240	210
R-squared	0.998	0.869	0.870	0.923

Note: () denote p-value; ***, **, and * indicate significant at the 1%, 5%, and 10% levels, respectively.

spatial effects of digital finance and environmental regulation impacting carbon emissions

As the spatial Durbin panel model includes a spatially lagged element of the dependent variable, the estimates are only valid at the directional and significance levels and fail to account for the marginal effects of the independent factors on the dependent variable (Liu and Song, 2020). Consequently, the paper further presents the decomposition results of the short- and long-term spatial effects of the core explanatory variables, as shown in Table 5.

Table 5

Results of the short- and long-term spatial effects decomposition.

Variables	SR			LR		
	Direct	Indirect	Total	Direct	Indirect	Total
DF	-0.0010 (0.12)	0.0023*** (0.00)	0.0012*** (0.00)	-0.0044* (0.10)	0.0072*** (0.00)	0.0027*** (0.00)
ER	-0.0048 (0.61)	-0.0498*** (0.01)	-0.0546*** (0.00)	-0.0037 (0.92)	-0.1169** (0.05)	-0.1206** (0.01)

Note: () denote p-value; ***, **, and * indicate significant at the 1%, 5%, and 10% levels, respectively.

(1) Decomposition results of the short-term spatial effects. The short-term spatial direct effects indicate that a 1% increase in digital finance and environmental regulations results in -0.1% and -0.48% of manufacturing carbon emissions in the local region, respectively. The short-term indirect spatial effects reveal that a 1% increase in digital finance and environmental regulations leads to 0.23% and -4.98% of manufacturing emissions in neighboring regions respectively. The total short-term spatial effect suggests that a 1% increase in digital finance and environmental regulation causes 0.12% and -5.46% of manufacturing carbon emissions respectively.

(2) Decomposition results of the long-term spatial effects. The long-term spatial direct effects of a 1% improvement in digital finance and environmental regulations contribute to -0.44% and -0.37% of manufacturing carbon emissions in the local region, respectively. The long-term spatial indirect effect shows that 1% rise in digital finance and environmental regulations respectively leads to 0.72% and -11.69% of manufacturing emissions in the neighboring regions. The total long-term spatial effect reveals that a 1% expansion in digital finance and an increase in environmental regulations result in 0.27% and -12.06% of manufacturing carbon emissions respectively.

(3) Comparative assessment of the decomposition results of the short-term and long-term spatial effects. Comparing the three short-term spatial effects of digital

finance with the three long-term spatial effects separately, it is observed that (in terms of the increase in the magnitude of the impact of the variables): the pro-decreasing effect of digital finance development on carbon emissions in the region is increased by 340% in the long term compared to the short term, and the effect turns from insignificant to significant; the pro-increasing effect of digital finance development on carbon emissions in neighboring regions is increased by 213% in the long term compared to the short term; the overall effect is that the incremental effect of digital financial development on carbon emissions increases by 125% in the long term compared to the short term. In the long term, digital financial development is expected to contribute more to the reduction of carbon emissions in the local region than to the increase of carbon emissions in neighboring regions. Additionally, the three short-term spatial effects of environmental regulation are compared with the long-term spatial effects: environmental regulation's mitigating effect on carbon emissions in the local region is 23% lower in the long term than in the short term; the mitigating effect of environmental regulation on carbon emissions in neighboring regions is 135% higher in the long term than in the short term; the overall effect is that the mitigating effect of such regulation on carbon emissions is 121% higher in the long term than in the short term. Combined, hypotheses 1 and 2 are validated.

5.1.4. Moderating effects of financial institution competition

An interaction term of digital finance and financial institution competition is introduced in equation (3) in section 4.2 to measure the moderating effect of financial institution competition on digital finance and environmental regulation affecting manufacturing carbon emissions, as shown in equation (4). The estimation method remains with the dynamic spatial panel Durbin model. Financial institution competition dividing the total assets of provincial financial institution outlets by the number of national financial institutions, and it measures the level of competition in the financial industry among provinces.

Table 6 presents the results of the decomposition on the spatial effects of the dynamic spatial panel Durbin model. It is observed that the $DF \times PT$ term reduces manufacturing carbon emissions in both the short and long term, domestically, in the neighboring regions and in general. Although the reduction effect is presently noticeable only in the local region, the longer-term mitigation effect is appreciably enhanced compared to the short-term. It indicates that financial institution competition can contribute to the abatement

effect of digital finance on manufacturing, and that it will have a greater abatement effect over time. Hypothesis 1 is partially validated. The coefficients on both the long- and short-term spatial effects of the ER term are considerably higher than those without the introduction of financial institution competition. It suggests that financial institution competition has driven environmental regulation to be more effective in reducing emissions. This further confirms Hypothesis 3, that the combination of market competition and government regulation tends to generate more effective emission reductions.

5.2 Robustness tests

5.2.1 Shock effects of developing inclusive finance policies in 2013 for robustness analysis

In 2013, the Third Plenary Session of the 18th Party Central Committee specifically proposed to develop inclusive finance, which probably affects the results of the study; consequently, to ensure the robustness of the findings, we introduce a dummy variable for the shock of this policy on the results, see model (1) of Table 6. The results indicate that our findings remain robust to developing inclusive finance policy shocks, and the model maintains stability.

$$LnMC_{it} = \delta_0 + \delta_1 LnMC_{i,t-1} + \delta_2 \sum_{j=1}^n W_{ij} LnMC_{j,t-1} + \delta_3 LnDF_{it} + \delta_4 Ln(DF_{it} \times PT_{it}) + \delta_5 LnER_{it} + \delta_6 LnEN_{it} + \delta_7 \sum_{j=1}^n W_{ij} LnDF_{jt} + \delta_8 \sum_{j=1}^n W_{ij} Ln(DF_{it} \times PT_{it}) + \delta_9 \sum_{j=1}^n W_{ij} LnER_{jt} + \delta_{10} \sum_{j=1}^n W_{ij} LnEN_{jt} + \delta_{11} \sum_{i=1}^n LnX_{it} + \mu_{it} + \varepsilon_{it} \quad (4)$$

Table 6

Results of the moderating effect of financial institution competition.

Variables	SR			LR		
	Direct	Indirect	Total	Direct	Indirect	Total
$DF \times PT$	-0.0004** (0.04)	-0.0003 (0.44)	-0.0006 (0.15)	-0.0012** (0.04)	-0.0004 (0.73)	-0.0016 (0.24)
ER	-0.0045 (0.49)	-0.0583*** (0.00)	-0.0628*** (0.00)	-0.0046 (0.83)	-0.1409** (0.03)	-0.1455** (0.03)
All other controls	Yes					

Note: () denote p-value; ***, **, and * indicate significant at the 1%, 5%, and 10% levels, respectively.

5.2.2 Substitution of carbon emission variable for robustness analysis

To ensure the robustness of the study, we compute carbon emissions per capita (*MCR*) instead of *MC* for robust testing (*MC*→*MCR*). Model (2) in Table 6 provides the results of the corresponding tests. When *MC* is substituted for *MCR*, the conclusion is consistent with Model (4) of Table 4.

5.2.3 Substitution of 0-1 spatial weight matrix for robustness analysis

Furthermore, for robustness testing, we employ a geographical distance matrix as proxy matrix for the original 0-1 spatial weight matrix. Table 7's Model (3) presents the results of the corresponding tests. When the 0-1 spatial weight matrix is substituted by a geographical distance matrix, the conclusions are generally consistent with Model (4) of Table 4.

5.3 Endogeneity tests

Although the dynamic SDM model can tackle explanatory variable endogeneity concerns for space-lagged terms, time-lagged terms, space-time lag term, and omitted factors, it cannot handle associative endogeneity caused by the interaction of dependent and independent variables. Referencing Han et al. (2018), the dynamic system GMM technique is used to estimate the dynamic SDM model, taking into account the probable associative endogeneity between carbon emissions and digital finance.

Under the loosened assumptions of the dynamic

systems GMM approach, using the lagged terms of the dependent and endogenous variables allows the endogeneity problem to be addressed to some extent. As a result, as instrumental variables for estimation, lagged four-period variables of the dependent variable and its spatially lagged term, as well as lagged four-period variables of digital finance and its spatially lagged term, are utilized. The results of the re-estimation with lagged terms of the dependent and endogenous variables as instrumental variables and applying the GMM approach are presented in model (1) in Table 8. Moreover, on the basis of the lagged variables as instrumental variables, we further employ the policy of “developing inclusive finance” as an exogenous instrumental variable in the Third Plenary Session of the 18th Central Committee in 2013 for re-estimation through the systematic GMM approach, as shown in Model (2) in Table 8.

In Table 8, the p-value for AR (1) is less than 0.1 and the p-value for AR (2) is more than 0.1, indicating that no second-order autocorrelation exists. The Hansen tests presents that both p-values are more than 0.1, thereby verifying that the instrumental variable is validate. Therefore, the estimates in Table 4 are robust. The estimation results for models (1) and (2) in Table 8 are consistent with model (4) of Table 4, thereby indicating that the model setup is appropriate and the conclusions are robust.

Table 7

Results of robustness tests.

Variables	DSDM (1) Policy shocks	DSDM (2) $MC \rightarrow MCR$	DSDM (3) Geographical distance matrix
DF	-0.0012 (0.12)	-0.0013* (0.09)	-0.0013 (0.19)
ER	-0.0004 (0.97)	-0.0014 (0.88)	-0.0014 (0.83)
WDF	0.0020*** (0.00)	0.0020*** (0.01)	0.0020** (0.04)
WER	-0.0280* (0.06)	-0.0328** (0.01)	-0.0318*** (0.01)
L.MC	0.7211*** (0.00)	0.7163*** (0.00)	0.7250*** (0.00)
L.WMC	-0.3917*** (0.00)	-0.3429*** (0.00)	-0.3957*** (0.00)
R-squared	0.927	0.697	0.923
All other controls	Yes	Yes	Yes

Note: () denote p-value; ***, **, and * indicate significant at the 1%, 5%, and 10% levels, respectively.

Table 8

Re-estimation by applying the dynamic system GMM approach for endogeneity problem.

Variables	SYS-GMM (1) Lagged variables as instrumental variables	SYS-GMM (2) Lagged variables and exogeneity indicators simultaneously as instrumental variables
DF	-0.0026* (0.06)	-0.0026* (0.06)
ER	-0.0352*** (0.00)	-0.0341*** (0.00)
WDF	0.0030** (0.03)	0.0031** (0.03)
WER	-0.0293** (0.03)	-0.0196* (0.07)
L.MC	0.9520*** (0.00)	0.9441*** (0.00)
L.WMC	-0.0090 (0.75)	0.0037 (0.93)
AR(1)	0.001	0.001
AR(2)	0.138	0.193
Hansen test	0.456	0.529
All other controls	Yes	Yes

Note: () denote p-value; ***, **, and * indicate significant at the 1%, 5%, and 10% levels, respectively.

5.4. Discussion

The progressive upgrading of information technology and the flattening of the world economy are accelerating the development of digital finance, which is a powerful driver of changes in traditional finance and results in a range of environmental and economic effects. However, there is still a paucity of research on digital finance and the environment, energy and carbon emissions, particularly the impact on manufacturing carbon emissions. Our study addresses these gaps by revealing that the impact of digital finance on manufacturing carbon emissions is characterized by remarkable spatial and temporal correlations and spatial spillover effects, with the aggregate mitigating effect of digital finance gradually emerging over time. This partly confirms Cao et al.'s (2021) study, which argues that digital finance can improve energy and environmental performance. In particular, developing digital finance tends to converge across regions over time, reducing the 'carbon paradise' effect caused by heterogeneity in its development and tending to release low-carbon, green environmental economic effects.

Financial institution competition contributes to the mitigating effect of digital finance on manufacturing carbon emissions, and it is expected to have a larger mitigating effect over time. Evidently, in line with Kim et al. (2021) and Kim et al. (2020), a more competitive banking and finance system is conducive to improving environmental quality and reducing carbon emissions. A more concentrated and less competitive banking and finance system increases carbon emissions and energy usage by providing more loans to households and discouraging the development of green technologies (Kim et al., 2021). Conversely, a more competitive and less concentrated banking and finance system is conducive to improving environmental quality (Kim et al., 2020).

Additionally, the study confirms that

environmental regulation has an abatement effect, both in the local region and its neighbors, and is more effective in reducing emissions in the long term. This differs from Sinn's (2008) study, but largely consistent with Zhang et al.'s (2020) study, which suggests that the positive effect of environmental regulation in reducing carbon emissions becomes more pronounced as environmental regulation completes. The higher the regional investment in environmental governance, the stricter the environmental regulation by the local government and the higher the environmental requirements for the manufacturing industry. In order to comply with regulatory standards, companies have to seek new processes and technologies, thereby promoting the development and application of energy-saving and emission reduction technologies to reduce carbon emissions. Local environmental regulation is less effective in reducing emissions than that of neighboring regions, possibly attributed to the pollution haven effect of carbon emissions. The more stringent environmental regulations in the local area, the more incentive for high-carbon industries to move to neighboring areas with less stringent regulations. These findings also partially support Zhao et al.'s (2020) study, who concluded that varying the intensity of environmental regulation across regions indeed results in intra-regional migration of carbon emissions.

Simultaneously, energy consumption exhibits a pro-increase effect on carbon emissions from manufacturing in the local region, mainly due to the fact that manufacturing comprises a major energy consumer, accounting for more than 50% of China's total carbon emissions (Xu and Lin, 2016). It substantiates the work of Waheed et al. (2019) that energy consumption remains an important source of carbon emissions in both developing and developed countries. Rising industrialization, restructuring industries (higher share of secondary industries) and

increasing population density all substantially drive-up manufacturing carbon emissions. These findings corroborate Lin and Chen's (2020) study, who suggest that economic growth and industrial structure have a significant impact on China's energy and environmental efficiency. The industrial sector (including manufacturing) is the primary generator of carbon emissions in China, and there is a collective relationship between manufacturing carbon emissions and its output and structure. Population density encourages daily energy usage and consumption by the residents, resulting in additional production in the manufacturing sector, which in turn drives up carbon emissions. Furthermore, the boosting effect of economic growth and financial density on manufacturing sector remains insignificant, in contrast to the study by Xu et al. (2017), who found that such boosting effect of economic growth is positive, probably due to the difference in research methodology. With the orientation towards high-quality economic and financial development in China, the traditional development paradigm of pursuing speed, expanding scale and increasing emissions is being replaced, thereby resulting in a non-significant boost to carbon emissions. The impact of technological innovation on manufacturing emissions reduction is minor at this stage, contrary to Lin and Chen's (2020) study. It is probably related to the fact that the emission reduction effect from technological innovation at this stage is not sufficient to offset the incremental emission effect caused by other factors.

6. Conclusions and implications

The issue of carbon emissions reduction has received increasing attention in the context of quality development and the promotion of dual carbon targets. The existing literature focuses solely on the impact of traditional finance on the environment and carbon emissions, and fails to simultaneously assess the impact

of environmental regulation. Recently, the emergence of digital finance is challenging the impact of traditional finance in various domains, and environmental regulation is gaining attention; however, few studies have examined the relationship between digital finance, environmental regulation and carbon emissions from manufacturing, and the moderating effect of financial institution competition has been neglected.

Based on the existing literature, hypothesis of the study is developed and an extended STIRPAT-DSDM model and a dynamic systems GMM model are implemented to investigate the abatement effects of digital finance and environmental regulation, combined with the moderating effects of financial institution competition. Present investigation enables temporal correlation, spatial dependence, covers regulatory effects and overcomes endogeneity concerns. The study provides new empirical evidences and sufficient grounds to reveal a tight connection of digital finance, environmental regulation and manufacturing carbon emissions. First, manufacturing carbon emissions possess powerful path-dependent characteristics and spatial shifting properties, with noticeable spatial and temporal correlation effects. Regarding digital finance, the results depict that it is capable of reducing carbon emissions in the local region and increasing carbon emissions in neighboring regions, whether in the short or long term, whereas the total effect tends to increase carbon emissions. Nevertheless, digital finance's mitigation effect on carbon emissions in the local region tends to outpace its promotion effect in neighboring regions in the long run, gradually revealing an overall carbon reduction effect. Notably, financial institution competition provides a powerful incentive for digital finance to reduce carbon emissions. In addition, environmental regulation alleviates carbon emissions in both the short and long term, whether in

the local or neighboring regions, with an even more positive emission reduction effect in the long term. Furthermore, the overall mitigation effect of environmental regulation is expected to be marginal increasing. More critically, an adequate combination of free markets and active government is found to be a more effective mechanism for reducing emissions in our study.

As regards implications, in light of the empirical evidence of this study, targeted management and guidance measures should be developed to address the path-dependent nature and spatial transfer of carbon emissions from the manufacturing sector. In terms of carbon emission permit issuance and trading conditions, the scale of carbon emissions in the inventory and the overall regional distribution should be taken into account, with the aim of maximizing the formation of a clean development mechanism in the carbon market. As far as the financial sector is concerned, available research supports the active promotion of digital finance on the basis of the development of traditional finance. Designing carbon finance products and improving risk management systems. Simultaneously, promoting competition among financial institutions and leveraging the “invisible hand” can gradually unleash the carbon reduction effects of digital finance. Regarding the impact of policies, according to the findings of the current study, policymakers should strengthen the implementation of environmental regulatory policies and highlight the spatial spillover effects and the marginal incremental law of environmental regulatory policy implementation. It requires regional coordination to achieve regulatory integration and to tackle the “pollution sanctuary” and “carbon paradise” effects.

Although this study constitutes a useful addition to the existing literature, filling in the gaps in digital finance, environmental regulation in influencing

carbon emission reduction in manufacturing and examining the dual correlation between temporal and spatial properties, some limitations nonetheless persist. The research sample is only representative of developing countries and cannot adequately explain similar phenomena in developed countries. Economies of different stages of development differ considerably in terms of development goals, resource endowments, etc., and the impacts induced by digital finance may be varied. In addition, this paper can only observe the impact of digital finance on carbon emissions reduction in the manufacturing sector, and cannot explore its possible impact on other industries or enterprises. Further research might approach these dimensions.

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环境污染群体性事件利益相关者行为策略的演化博弈分析： 媒体干预的效果

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摘要：环境污染群体性事件的有效解决是保障群众利益和社会稳定的关键。考虑制度性救济——政府监管与非制度性救济——媒体曝光并存的现实情况，本文构建政府-周边群众-污染企业-媒体四方演化博弈模型分别讨论各博弈主体策略选择的稳定性，并基于 Lyapunov 第一法则对系统中可能存在的均衡点进行稳定性分析，利用 MATLAB 数值模拟了关键要素对系统演化结果的影响。研究发现，媒体曝光会在制度性救济失灵时发挥作用，且舆论发酵程度的增强会增加政府监管和污染企业整改的策略倾向。整改负担是影响污染企业策略选择的关键因素，随着污染企业整改成本负担的减轻，污染企业会倾向于整改策略。周边群众集体抗争策略选择的动力来自事件“闹大”收益的增加，在集体抗争争取到的收益减少情况下，周边群众的策略会倾向于妥协。

关键词：环境污染群体性事件；媒体曝光；四方演化博弈；数值分析

Evolutionary game analysis of stakeholder behavior strategies in mass incidents of environmental pollution: The effects of media intervention

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Abstract: Effective settlement of mass incidents of environmental pollution is the key to guarantee the interests of the masses and social stability. Consider institutional relief - the government regulatory and institutional relief that the media exposure of the reality, the paper builds the government - surroundings - polluting enterprises - media square evolutionary game model respectively to discuss the stability of the main each game strategy choice, and the first law based on Lyapunov stability analysis was carried out on the possible equilibrium in the system. MATLAB is used to simulate the influence of key elements on the system evolution results. The study found that media exposure would play a role in the failure of institutional relief, and the enhancement of public opinion fermentation would increase the strategic tendency of government supervision and rectification of polluting enterprises. The burden of rectification is the key factor affecting the choice of the strategy of polluting enterprises. With the reduction of the burden of rectification cost of polluting enterprises, polluting enterprises tend to adopt the rectification strategy. The motivation for the surrounding people to choose the strategy of collective protest comes from the increase of the benefits of "making a big scene". When the benefits obtained by collective protest decrease, the surrounding people tend to compromise.

Key Words: Mass incidents of environmental pollution; Media exposure; Quadrilateral evolutionary game;

一 引言

近年来我国工业发展迅速，但与此同时也产生了诸多环境问题。当污染的负外部性对周边群众生产生活造成不良影响时，周边群众会对污染设施的正常运行进行抗议甚至爆发大规模群体性突发事件^[1]。由于政府环境监管的不足，污染企业反复违规排污，而公民的环境意识却在不断增强，这样就导致环境污染群体性事件的频繁爆发。这不仅会造成严重的社会不良影响，还可能使政府陷入“塔西佗陷阱”^[2]。所谓塔西佗陷阱就是指当一个部门失去公信力时，无论说真话还是假话，做好事还是坏事，都会被认为是说假话、做坏事。这一定律在近年发生的一系列环境类群体事件中有充分的体现。如果集体抗争最终使政府让步而实现其利益诉求，那么这会在客观上助长了非法的抗争方式，反而不利于社会秩序的稳定。因此，环境污染群体性事件处置的研究具有一定的价值与意义。

民众采取集体抗争等非制度性抗争方式的一个重要原因是当前各种制度性权利救济渠道缺失或失效^[3]。比如，公民熟知并普遍采用的信访制度，给公民诉苦的权利，却无法给予解决问题的明确承诺，导致信访在实际中变成上访。而上访却耗费大量时间、精力和金钱成本，且问题往往得不到实质性解决^[4]。再如行政复议、行政诉讼等法律救济途径，其进入门槛高，周边群众环境维权过程中需要投入大量精力和物力来收集证据，且程序复杂、旷日费时，这让普通公民尤其是经济拮据、知识匮乏的弱势群体望而却步^[5]。不仅如此，当公民的合法权益直接遭受到政府公权力的侵害或者威胁时，在权势力量干涉下，这些体制内救济途径更易失效。

在媒体社会中，信息传播具有快捷、交互与不受时空限制等特性。而且政府控制媒体、压制不同声音和垄断信息资源变得越来越困难。民众可以便捷的利用电视、报纸、互联网等新闻媒体的“传声筒”角色与议程设置功能，借助社会媒体压力，促使政府采取措施解决问题，从而达到环境维权

的目的^[6]。相对于其他途径，借助媒体的力量是一个成本划算的抗争途径，这就是近年来“媒介化抗争”日益增多的重要原因^[7]。维权公民的目标是要控制环境污染项目，却无法获得制度化的沟通渠道和公共决策的话语权，最终他们只能被迫通过非常规渠道表达利益诉求。在公民可以选择的范围内，网络成为他们能够获得的最有力工具。许多维权公民在环境污染性群体性事件中选择媒体报道这一成本低，获益高的方法与污染企业进行对抗^[8]。

因此，在环境污染群体性事件中，媒体是不可忽视一个重要角色。媒体在此类事件中的作用体现在，媒体的报道可以增加政府监管部门的重视和引起网民对污染企业的共同抵制^[9]。但并非所有的污染事件都能被媒体曝光。面对媒体这种第三方监管机制，污染企业会想办法阻拦，监管部门也因忌惮媒体曝光会影响上级部门对其工作业绩评价，利用各种方式增大媒体曝光的交易成本，从而降低媒体对此类事件曝光的概率^[10]。媒体曝光后舆论的发酵存在不确定性，这体现在舆论发酵程度越高，对政府和污染企业的声誉造成的影响越大。因此，在不同媒体曝光程度下，环境污染群体性事件中利益相关者的行为会有何变化是值得探讨的。

国内外现有文献主要从环境污染群体性事件的发生机理、补偿机理、相关利益主体之间的博弈关系以及舆论与信息传播等方面进行探讨。例如，汪伟全^[2]从风险放大、集体行动和政策博弈角度研究了环境类群体事件的发生机理。沈焱^[11]等提出了经济补偿和部署警力两种处置环境群体事件的优化模型，最后发现两种方式各有优势，经济补偿风险较小。但从长期来看经济补偿容易引发无关群众的侥幸心理，而部署警力在短期能有效控制冲突，但不利于政府的声誉，因此需要权衡利用。刘德海^[12]运用演化博弈理论分析了不同社会结构下群体性突发事件相关利益主体之间的博弈关系和影响各主体策略演化方向的因素。郑君君^[13]等从政府的角度建立了环境群体事件的优化模型，

发现监管部门加大舆情引导有利于污染企业与群众之间的博弈向最优方向演化。

从管理科学的角度分析，环境污染群体性事件需要综合分析媒体、环境监管部门、周边群众以及污染企业之间的利益博弈关系并通过策略及参数的调整使演化状态由集体抗争到实现妥协的帕累托最优状态^[15]。此外还需要通过博弈来分析媒体和政府策略选择对事件演化均衡的影响^[16]。为此，本文在综合考虑政府和媒体因素的基础上综合分析环境污染群体性事件背后涉及的参与主体利益博弈及其演化规律、通过数值模拟参数的调整使演化态势由集体抗争的“囚徒困境”到实现群众妥协、企业整改、政府监管部门积极监管的最优状态。结论表明，博弈系统任何一方主体的演化趋势都与其他三方的策略选择密切相关。媒体曝光对监管部门与污染企业的声誉影响、污染企业整改成本的有效解决以及转变传统的经济补偿解决集体抗争方法是有效解决环境污染群体性事件的关键。

虽然相关学者分析了周边群众与污染企业之间的博弈与优化问题，但把媒体、环境监管部门、污染企业和周边群众四者放在一个框架下进行综合博弈分析的文献较少。为此，本文的贡献体现在利用演化博弈理论分析媒体、政府监管部门、周边群众和污染企业四方利益关系，运用复制动态方程求得均衡解、分析各主体策略演化稳定的条件，最后运用数值仿真分析了使博弈系统达到最优状态并避免周边群众集体抗争的因素，对上级政府有效避免和解决此类事件具有一定的参考价值。

二 模型假设与演化博弈模型构建

2.1 模型假设及问题描述

综合考虑利益相关者理论和环境污染群体性事件的特点，本文对环境污染群体性事件中利益相关者的界定如下。环境污染群体性事件的利益相关者指能够影响环境污染群体性事件发生并受到其影响的所有个人和群体。其中，任何一方的利益变化都会影响环境污染群体性事件的发生机

制。因此，厘清各主体之间的利益关系，平衡各方利益，对环境污染群体性事件的解决产生影响。由于受利益相关者利益诉求强度和取向的不同影响，为简化研究，本研究选取政府、污染企业、周边群众和媒体作为环境污染群体性事件的主要利益相关者。由于四者之间在关注点和利益追求上差异的影响，四方主体未能立刻达成共识，形成长期的利益博弈关系。

不考虑其他外部条件的情况下，环境污染群体性事件的参与主体涉及政府监管部门、媒体、周边群众和污染企业。在环境污染群体性事件中，周边群众妥协的概率为 X ，集体抗争的概率为 $1 - X$ ；污染企业整改的概率为 Y ，不整改的概率为 $1 - Y$ ；政府部门监管概率为 Z ，不监管的概率为 $1 - Z$ ；媒体曝光的概率为 W ，不曝光的概率为 $1 - W$ 。 $X, Y, Z, W \in [0, 1]$ 。扩展到整个社会群体，每个概率可以表示为该博弈主体的整个群体中选择某确定策略的比例。四方均为风险中性，以追求自身利益最大化为目标。本文采用动态演化博弈理论，讨论周边群众环境维权博弈过程。本文建模分析满足以下假设条件：

(1) 对于污染企业和周边群众而言，污染企业造成的环境损失和经济赔偿是二者利益博弈主要关注的内容。环境污染群体性事件中，周边群众和污染企业间的利益博弈会因政府监管部门和媒体的介入而演化到不同的方向。本研究构建关于环境污染群体性事件的博弈模型。媒体可以采取曝光策略记为 d_1 ，还可以采取不曝光策略记为 d_2 ，策略集合为 $l_0 = \{d_1, d_2\}$ 。政府可以采取监管策略记为 c_1 ，或者采取不监管策略记为 c_2 ，策略集合为 $l_1 = \{c_1, c_2\}$ ；周边群众可以采取妥协策略记为 a_1 ，采取集体抗争策略记为 a_2 ，策略集合为 $l_2 = \{a_1, a_2\}$ ；污染企业可以选择的策略同样可以分为整改 b_1 和不整改 b_2 两种，污染企业的策略集合记为 $l_3 = \{b_1, b_2\}$ 。

(2) 在政府和媒体介入的背景下，污染企业和周边群众的谈判结果将面临很大的不确定性。一方面，双方谈判地位处于不平等状态，周边群众

会不断寻找改善自己收益的方式；另一方面，污染企业会因政府和媒体的介入而改变自己的策略。由于周边群众的意愿和预期收益的差异，造成周边群众在策略空间{妥协接受，集体抗争}中采取分散化行动。假设符合演化博弈的大部分参与者“惯例”行为，少部分采取“试错法”的创新行为为基本假设。根据污染企业的不同理念，采取的应对方案包括{整改，不整改}。当博弈双方分别采取不同策略时，他们会获得不同的收益，具体数值为：

①{妥协接受，整改}对应收益为 $(P, G - K)$ 。其中， P 为周边群众的环境获利。 G 为污染企业的声誉收益和政府补贴等， K 为污染企业的整改过程中的支出，包括环保投资，社会公益，对周边群众的赔偿等。

②{妥协接受，不整改}对应收益为 $(-L, B - H)$ 。其中 L 为周边群众的经济和环境损失。 B 为污染企业继续经营获得的收益， H 为污染企业的声誉损失。

③{集体抗争，整改}对应收益为 $(P - C + M, G - K - F)$ 。其中， C 为抗议成本， F 为周边群众集体抗争对污染企业造成的经济损失。

④{集体抗争，不整改}对应收益为 $(P - C + M - L, B - I - F)$ 。其中 M 表示周边群众采取抗议行动争取到的利益， I 为污染企业不整改，周边群

众集体抗争时对周边群众的补偿。

(3) 为保证环境维权的解决，政府会对双方的谈判进行监管，并对不妥协方进行惩罚。政府可采取的策略为监管或者不监管。政府监管会获得声誉收益 R ，政府监管需要付出包括人力、物力、财力在内的监管成本 C ，环境污染群体性事件的解决会带给政府巨大的社会收益 S 。在环境污染群体性事件中，政府的作用体现在对采取集体抗争策略的周边群众和不整改策略的污染企业进行惩罚，分别为 E_1 和 E_2 。发生集体抗争事件时，政府的监管部门会受到上级部门的追责 U 。

(4) 媒体也会权衡曝光环境污染群体性事件的收益和成本在曝光和不曝光策略之间进行选择。媒体的介入会因舆论发酵程度的不同产生差异，在此引入发酵系数 η 。媒体曝光情形下，政府的声誉损失、污染企业的声誉损失和舆论发酵程度相关。媒体曝光成本包括非官方途径调查成本及政府监管部门的行政阻力。媒体不曝光时，会失去大众的信任，即公信力损失为 R_1 。

2.2 演化博弈模型构建

根据以上假设分析，可以得到政府和媒体介入情境下，周边群众与污染企业的博弈支付矩阵，如表 1 所示。

表 1 考虑媒体因素介入情境下双方演化博弈收益矩阵

		政府监管		政府不监管	
		污染企业整改 (b_1)	污染企业不整改 (b_2)	污染企业整改 (b_1)	污染企业不整改 (b_2)
媒体曝光(d_1)	周边群众妥协 (a_1)	$\begin{bmatrix} \eta S - N \\ P \\ \eta G - K \\ \eta B - E_G - E_E \end{bmatrix}$	$\begin{bmatrix} E_1 - N \\ \eta I - P \\ K - \eta I - E_1 \\ \eta B - E_G - E_E \end{bmatrix}$	$\begin{bmatrix} \eta(S - R) \\ P \\ \eta G - K \\ \eta B - E_E \end{bmatrix}$	$\begin{bmatrix} -\eta R \\ \eta I - P \\ K - \eta I \\ \eta B - E_E \end{bmatrix}$
	周边群众集体抗争 (a_2)	$\begin{bmatrix} E_2 - N - \eta U \\ P \\ \eta G - K - F \\ \eta B - E_G - E_E \end{bmatrix}$	$\begin{bmatrix} E_1 + E_2 - N - \eta U \\ -C + \eta M - P - E_2 \\ -F - \eta M - \eta H - E_1 \\ \eta B - E_G - E_E \end{bmatrix}$	$\begin{bmatrix} \eta(-R - U) \\ P - C \\ \eta G - K - F \\ \eta B - E_E \end{bmatrix}$	$\begin{bmatrix} \eta(-R - U) \\ -C + \eta M - P \\ -F - \eta M - \eta H \\ \eta B - E_E \end{bmatrix}$
	媒体不曝光 (d_2)	$\begin{bmatrix} S - N \\ P \\ G - K \\ -R_1 \end{bmatrix}$	$\begin{bmatrix} E_1 - N \\ I - P \\ K - I - E_1 \\ -R_1 \end{bmatrix}$	$\begin{bmatrix} S - R \\ P \\ G - K \\ -R_1 \end{bmatrix}$	$\begin{bmatrix} -R \\ I - P \\ K - I \\ -R_1 \end{bmatrix}$

周边群众 集体抗争 (a_2)	$\begin{bmatrix} E_2 - N - U \\ P - C - E_2 \\ G - K - F \\ -R_1 \end{bmatrix}$	$\begin{bmatrix} E_1 + E_2 - N - U \\ -C + M - P - E_2 \\ -F - M - H - E_1 \\ -R_1 \end{bmatrix}$	$\begin{bmatrix} -R - U \\ P - C \\ G - K - F \\ -R_1 \end{bmatrix}$	$\begin{bmatrix} -R - U \\ -C + M - P \\ -F - M - H \\ -R_1 \end{bmatrix}$
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(1) 媒体的复制动态方程

媒体选择监管曝光和不曝光策略的期望收益及平均收益分别记为 E_W^Y 、 E_W^N 和 $\overline{E_W}$ 。媒体选择曝光策略的期望收益为：

$$E_W^Y = -E_G X + \eta B - E_E$$

(1)

$$F(W) = \frac{dW}{dt} = W(E_W^Y - \overline{E_W}) = W(1-W)(-E_G X + \eta B - E_E + R_1)$$

(4)

(2) 政府的复制动态方程

政府选择监管策略和不监管策略的期望收益及平均收益分别记为 E_X^Y 、 E_X^N 和 $\overline{E_X}$ 。政府选择监管策略的期望收益为：

$$E_X^Y = YZW(\eta S - N) + Y(1-Z)W(E_1 - N) + (1-Y)ZW(E_2 - N - \eta U) + (1-Y)(1-Z)W(E_1 + E_2 - N - \eta U) + YZ(1-W)(S - N) + Y(1-Z)(1-W)(E_1 - N) + (1-Y)Z(1-W)(E_2 - N - U) + (1-Y)(1-Z)(1-W)(E_1 + E_2 - N - U)$$

(5)

$$F(X) = \frac{dX}{dt} = X(E_X^Y - \overline{E_X}) = X(1-X)(E_X^Y - E_X^N) = X(1-X)[W(\eta - 1)R - YE_2 - ZE_1 + (E_1 + E_2 - N + R)]$$

(3) 周边群众的复制动态方程

周边群众选择妥协策略和集体抗争策略的期望收益及平均期望收益分别记为 E_Y^Y 、 E_Y^N 和 $\overline{E_Y}$ 。

周边群众选择妥协策略的期望收益为：

$$E_Y^Y = XZWP + X(1-Z)W(\eta I - P) + (1-X)ZWP + (1-X)(1-Z)W(\eta I - P) + XZ(1-W)P + X(1-Z)(1-W)(I - P) + (1-X)Z(1-W)P + (1-X)(1-Z)(1-W)(I - P)$$

(9)

周边群众选择集体抗争策略的期望收益为：

$$E_Y^N = XZWP + X(1-Z)W(-C + \eta M - P - E_2) +$$

$$F(Y) = \frac{dY}{dt} = Y(E_Y^Y - \overline{E_Y}) = Y(1-Y)[XZW(-C - E_2) + W(1-Z)(\eta I - \eta M - I + M) + XE_2 - Z(I - M) + I + C - M]$$

(4) 污染企业的复制动态方程

污染企业选择整改策略和不整改策略的期望

媒体不曝光策略的期望收益为：

$$E_W^N = -R_1$$

(2)

$$\overline{E_W} = WE_W^Y + (1-W)E_W^N$$

(3)

媒体以 W 和 $1-W$ 概率选择曝光和不曝光策略的期望收益为：

政府选择不监管策略的期望收益为：

$$E_X^N = YZW[\eta(S - R)] + Y(1-Z)W(-\eta R) + (1-Y)ZW[\eta(-R - U)] + (1-Y)(1-Z)W[\eta(-R - U)] + YZ(1-W)(S - R) + Y(1-Z)(1-W)(-R) + (1-Y)Z(1-W)(-R - U) + (1-Y)(1-Z)(1-W)(-R - U)$$

(6)

政府以 X 和 $1-X$ 概率选择监管和不监管策略的期望收益为

$$\overline{E_X} = XE_X^Y + (1-X)E_X^N$$

(7)

政府的复制动态方程为：

$$(1-X)ZW(P - C) + (1-X)(1-Z)W(-C + \eta M - P) + XZ(1-W)(P - C - E_2) + X(1-Z)(1-W)(-C + M - P - E_2) + (1-X)(1-W)Z(P - C) + (1-X)(1-W)(1-Z)(-C + M - P)$$

(10)

周边群众以 Y 和 $1-Y$ 概率选择监管和不监管策略的期望收益为

$$\overline{E_Y} = YE_Y^Y + (1-Y)E_Y^N$$

(11)

周边群众的复制动态方程为：

收益及平均期望收益分别记为 E_Z^Y 、 E_Z^N 和 $\overline{E_Z}$ 。污染企业选择整改策略的期望收益为：

$$E_Z^Y = XYW(\eta G - K) + X(1-Y)W(\eta G - K - F) + XY(1-W)(G - K) + X(1-Y)(1-W)(G - K - F) + (1-X)YW(\eta G - K) + (1-X)(1-Y)W(\eta G - K - F) + (1-X)Y(1-W)(G - K) + (1-X)(1-Y)(1-W)(G - K - F) \quad (13)$$

污染企业选择不整改策略的期望收益为：

$$E_Z^N = XYW(K - \eta I - E_1) + X(1-Y)W(-F - \eta M - \eta H - E_1) + XY(1-W)(K - I - F(Z)) = \frac{dZ}{dt} = Z(1-Z)(E_Z^Y - E_Z^N) = Z(1-Z)[XE_1 + YW(\eta I - \eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H]$$

联立式(4)、(8)、(12)和(16)，得到媒体、政府、周边群众和污染企业选择立项策略组合式

$$\begin{cases} F(X) = X(1-X)[W(\eta-1)R - YE_2 - ZE_1 + (E_1 + E_2 - N + R)] \\ F(Y) = Y(1-Y)[XZW(-C - E_2) + W(1-Z)(\eta I - \eta M - I + M) + XE_2 - Z(I - M) + I + C - M] \\ F(Z) = Z(1-Z)[XE_1 + YW(\eta I - \eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H] \\ F(W) = W(1-W)(-E_G X + \eta B - E_E + R_1) \end{cases} \quad (17)$$

三. 各博弈主体策略稳定性分析

(1) 政府策略稳定性分析

令 $F(X) = \frac{dX}{dt} = X(1-X)[W(\eta-1)R - YE_2 - ZE_1 + (E_1 + E_2 - N + R)] = 0$ ，则可得 $X_1 = 0, X_1 = 1, Y_0 = \frac{W(\eta-1)R - ZE_1 + (E_1 + E_2 - N + R)}{E_2}$ 。其中 $X_1 = 0, X_1 = 1$ 是政府监管部门可能的稳定策略。对 $F(X)$ 求偏导可得：

$$F'(X) = (1-2X)[W(\eta-1)R - YE_2 - ZE_1 + (E_1 + E_2 - N + R)] \quad (18)$$

由微分方程稳定性定理，政府选择监管并处于稳定状态必须满足： $F(X) = 0$ 且 $F'(X) < 0$ 。具体讨论如下：

命题 1 当 $W(\eta-1)R - YE_2 - ZE_1 + (E_1 + E_2 - N + R) = 0$ 时， $F(X) = 0$ 恒成立，对所有 $X \in [0,1]$ 均属于稳定水平，即此时的策略选择比例不随时间的变化而变化。即 $Y_0 = \frac{W(\eta-1)R - ZE_1 + (E_1 + E_2 - N + R)}{E_2}$ 时，无法确定稳定策略。当 $Y > Y_0$ 时，不监管是政府监管部门的演化稳定策略；当 $Y < Y_0$ 时，监管是政府监管部门的演化稳

$$E_1) + X(1-Y)(1-W)(-F - M - H - E_1) + (1-X)YW(K - \eta I) + (1-X)(1-Y)W(-F - \eta M - \eta H) + (1-X)Y(1-W)(K - I) + (1-X)(1-Y)(1-W)(-F - M - H) \quad (14)$$

污染企业以 Z 和 $1-Z$ 的概率选择整改和不整改策略的期望收益为：

$$\bar{E}_Z = ZE_Z^Y + (1-Z)E_Z^N \quad (15)$$

污染企业的复制动态方程为：

$$\frac{dZ}{dt} = Z(1-Z)(E_Z^Y - E_Z^N) = Z(1-Z)[XE_1 + YW(\eta I - \eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H] \quad (16)$$

的复制动态系统：

定策略。

证明：令 $N_Y = W(\eta-1)R - YE_2 - ZE_1 + (E_1 + E_2 - N + R)$ ， $\frac{\partial N_Y}{\partial Y} < 0$ ，因此， N_Y 是关于 Y 的减函数。当 $Y < Y_0$ 时， $N_Y > 0$ ， $(F(X)|X=1) = 0$ 且 $(F'(X)|X=1) < 0$ ，则 $X=1$ 具有稳定性；当 $Y > Y_0$ 时， $N_Y < 0$ ， $(F(X)|X=0) = 0$ 且 $(F'(X)|X=0) < 0$ ，则 $X=0$ 具有稳定性。当 $Y = Y_0$ 时， $F(X) = 0$ 对 $X \in [0,1]$ 均处于稳定状态，因此无法确定稳定策略。

命题 1 表明：在环境污染群体性事件中，周边群众妥协概率的提升，会使得政府监管部门稳定策略由监管转变为不监管。反之，若周边群众妥协的概率降低，政府监管部门的稳定策略为监管，以维护社会稳定。影响政府监管策略的因素主要是行政成本和声誉。

(2) 周边群众策略稳定性分析

令 $F(Y) = \frac{dY}{dt} = Y(1-Y)[XZW(-C - E_2) + W(1-Z)(\eta I - \eta M - I + M) + XE_2 - Z(I - M) + (I + C - M)] = 0$ ，则可得 $Y_1 = 0, Y_2 = 1, Z_0 = \frac{W(\eta I - \eta M - I + M) + XE_2 + I + C - M}{W(\eta I - \eta M - I + M) + (I - M) - XW(-C - E_2)}$ 。其中 $Y_1 = 0, Y_2 = 1$ 是周边群众可能的稳定策略。对 $F(Y)$ 求偏导可得：

$$F'(Y) = (1 - 2Y)[XZW(-C - E_2) + W(1 - Z)(\eta I - \eta M - I + M) + XE_2 - Z(I - M) + I + C - M] \quad (19)$$

由微分方程稳定性定理，政府选择监管并处于稳定状态必须满足： $F(Y) = 0$ 且 $F'(Y) < 0$ 。具体讨论如下：

命题 2：当 $XZW(-C - E_2) + W(1 - Z)(\eta I - \eta M - I + M) + XE_2 - Z(I - M) + I + C - M = 0$ 时， $F(Y) = 0$ 恒成立，对所有 $Y \in [0, 1]$ 均属于稳定水平，即此时的策略选择比例不随时间的变化而变化。即 $Z_0 = \frac{XE_2 + I + C - M}{W(-C - E_2) + (I - M) - XW(-C - E_2)}$ 时，无法确定稳定策略。当 $Z > Z_0$ 时，妥协是周边群众的演化稳定策略；当 $Z < Z_0$ 时，集体抗争是周边群众的演化稳定策略。

证明：令 $N_Z = XZW(-C - E_2) + W(1 - Z)(\eta I - \eta M - I + M) + XE_2 - Z(I - M) + I + C - M$ ， $\frac{\partial N_Z}{\partial Z} > 0$ 。因此 N_Z 是关于 Z 的增函数。当 $Z < Z_0$ 时， $N_Z < 0$ ， $(F(Y)|Y = 0) = 0$ 且 $(F'(Y)|Y = 0) > 0$ ，则 $Y = 0$ 具有稳定性；当 $Z > Z_0$ 时， $N_Z > 0$ ， $(F(X)|X = 1) = 1$ 且 $(F'(X)|X = 1) < 0$ ，则 $Y = 1$ 具有稳定性。当 $Y = Y_0$ 时， $F(Y) = 0$ 对所有 $Y \in [0, 1]$ 均成立，无法确定稳定策略。

命题 2 表明：在环境污染群体性事件中，污染企业整改概率的提升，会使得周边群众稳定策略由集体抗争转变为妥协；反之，若污染企业整改的概率降低，周边群众的稳定策略为集体抗争，以维护自身的合法权益。妥协收益、集体抗争成本与集体抗争收益是影响周边群众策略选择的主要因素。这也反映了周边群众的策略选择是基于成本收益的理性计算。当面对多种策略选择时，作为理性的公民会对各种选择进行计算，如果集体抗争无利可图，妥协便是他们的上选。

(3) 污染企业策略稳定性分析

令 $F(Z) = \frac{dZ}{dt} = Z(1 - Z)[XE_1 + YW(\eta I - \eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H] = 0$ ，则可得 $Z_1 = 0$ ， $Z_2 = 1$ ， $X_0 = YW(\eta I -$

$\eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H)/(-E_1)$ 。其中 $Z_1 = 0$ ， $Z_2 = 1$ 是周边群众可能的稳定策略。对 $F(Z)$ 求偏导可得：

$$F'(Z) = (1 - 2Z)[XE_1 + YW(\eta I - \eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H] \quad (20)$$

由微分方程稳定性定理，政府选择监管并处于稳定状态必须满足： $F(Z) = 0$ 且 $F'(Z) < 0$ 。具体讨论如下：

命题 3：当 $XE_1 + YW(\eta I - \eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H = 0$ 时， $F(Z) = 0$ 恒成立，对所有 $Z \in [0, 1]$ 均属于稳定水平，即此时的策略选择比例不随时间的变化而变化。即 $X_0 = YW(\eta I - \eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H/(-E_1)$ 时，无法确定稳定策略。当 $X > X_0$ 时，整改是污染企业的演化稳定策略；当 $X < X_0$ 时，不整改是污染企业的演化稳定策略。

证明：令 $N_X = YW(\eta I - \eta M - \eta H + M + H) + W(\eta G + \eta M + \eta H - G - M - H) + Y(-K + I - M - H) + G - K + M + H$ ， $\frac{\partial N_X}{\partial X} > 0$ 。因此 N_X 是关于 X 的增函数。当 $X < X_0$ 时， $N_X < 0$ ， $(F(Z)|Z = 0) = 0$ 且 $(F'(Z)|Z = 0) > 0$ ，则 $Z = 0$ 具有稳定性；当 $X > X_0$ 时， $N_X > 0$ ， $(F(Z)|Z = 1) = 0$ 且 $(F'(Z)|Z = 1) < 0$ ，则 $Z = 1$ 具有稳定性。当 $X = X_0$ 时， $F(Z) = 0$ 对所有均成立，无法确定稳定策略。

命题 3 表明：在环境污染群体性事件中，政府监管概率的提升，会使得污染企业稳定策略由不整改转变为整改；反之，若政府监管的概率降低，污染企业的稳定策略为整改，以避免不必要的惩罚。污染企业进行整改的成本、政府补贴、声誉损失、对周边群众的赔偿、应对周边群众集体抗争的成本和政府的惩罚是影响其策略选择的关键因素。

(4) 媒体策略稳定性分析

令 $F(W) = \frac{dW}{dt} = W(1-W)(-E_G X + \eta B - E_E + R_1) = 0$ ，则可得 $W_1 = 0$ ， $W_2 = 1$ ， $X_0 = \frac{\eta B - E_E + R_1}{E_G}$ 。其中 $W_1 = 0$ ， $W_2 = 1$ 是媒体可能的稳定策略。对 $F(W)$ 求偏导可得：

$$F'(W) = (1-2W)(-E_G X + \eta B - E_E + R_1) \quad (21)$$

由微分方程稳定性定理，政府选择监管并处于稳定状态必须满足： $F(W) = 0$ 且 $F'(W) < 0$ 。具体讨论如下：

命题 4：当 $-E_G X + \eta B - E_E + R_1 = 0$ 时， $F(W) = 0$ 恒成立，对所有 $W \in [0, 1]$ 均属于稳定水平，即此时的策略选择比例不随时间的变化而变化。即 $X_0 = \frac{\eta B - E_E + R_1}{E_G}$ 时，无法确定稳定策略。当 $X > X_0$ 时，不曝光是媒体的演化稳定策略；当 $X < X_0$ 时，曝光是媒体的演化稳定策略。

证明：令 $N_X = -E_G X + \eta B - E_E + R_1$ ， $\frac{\partial N_X}{\partial X} < 0$ 。因此 N_X 是关于 X 的减函数。当 $X < X_0$ 时， $N_X > 0$ ， $(F(Z)|Z=1) = 0$ 且 $(F'(Z)|Z=1) < 0$ ，则 $W = 1$ 具有稳定性；当 $X > X_0$ 时， $N_X < 0$ ， $(F(W)|W=0) = 0$ 且 $(F'(W)|W=0) > 0$ ，则 $W = 0$ 具有稳定性。当 $X = X_0$ 时， $F(W) = 0$ 对所有 $W \in [0, 1]$ 均处于稳定状态，无法确定稳定策略。

命题 4 表明：在环境污染群体性事件中，政府监管概率的提升，会使得媒体稳定策略由曝光转变为不曝光；反之，若政府监管的概率降低，媒体的稳定策略为曝光，以避免政府行政阻力、获取流量成本和避免公信力的丧失。此外，影响媒体策

略选择的因素主要包括政府的行政阻力、企业的阻力、流量收益和媒体形象。

四. 策略组合稳定性分析

在环境污染群体性事件中和，在媒体、政府监管部门、周边群众和污染企业四方博弈的复制动态系统中，四方博弈主体策略组合的稳定性可以根据 Lyapunov 第一法则判断。Ritzberger 等和 Selten 指出，多种群演化博弈中的稳定解为严格纳什均衡。而严格纳什均衡一定是纯策略，因此，本研究将对四方演化博弈中的 16 个纯策略均衡点的稳定性进行分析。根据各博弈主体的复制动态方程，得到复制动态系统的 Jacobian 矩阵为

$$J = \begin{bmatrix} \frac{dF(X)}{dX} & \frac{dF(X)}{dY} & \frac{dF(X)}{dZ} & \frac{dF(X)}{dW} \\ \frac{dF(Y)}{dX} & \frac{dF(Y)}{dY} & \frac{dF(Y)}{dZ} & \frac{dF(Y)}{dW} \\ \frac{dF(Z)}{dX} & \frac{dF(Z)}{dY} & \frac{dF(Z)}{dZ} & \frac{dF(Z)}{dW} \\ \frac{dF(W)}{dX} & \frac{dF(W)}{dY} & \frac{dF(W)}{dZ} & \frac{dF(W)}{dW} \end{bmatrix}$$

4.1 政府不监管策略下策略组合稳定性分析

当政府的稳定策略为不监管时，即满足条件 ① $W(\eta - 1)R - YE_2 - ZE_1 + (E_1 + E_2 - N + R) < 0$ 时，复制动态系统均衡点的渐近稳定性分析见表 2。由表 2 可知，在政府不监管的情况下不存在纯策略稳定均衡点。

表 2 政府不监管复制动态系统均衡点渐进稳定性分析

均衡点	特征值 $\lambda_1, \lambda_2, \lambda_3, \lambda_4$	符号正负	稳定性
$E_1(0,0,0,0)$	$E_1 + E_2 - N + R, I + C - M, G - K + M + H, \eta B - E_E + R_1$	$(-, -, -, +)$	不稳定
$E_2(0,0,0,1)$	$E_1 + E_2 - N + \eta R, \eta I + C - \eta M, \eta G - K + \eta M + \eta H, -(\eta B - E_E + R_1)$	$(-, -, -, -)$	不稳定
$E_3(0,0,1,0)$	$E_2 + R - N, C, -(G - K + M + H), \eta B - E_E + R_1$	$(-, +, -, +)$	不稳定
$E_4(0,1,0,0)$	$E_1 + R - N, -(I + C - M), I + G - 2K, \eta B - E_E + R_1$	$(-, -, -, +)$	不稳定
$E_5(0,0,1,1)$	$E_2 + \eta R - N, C, -(\eta G - K + \eta M + \eta H), -(\eta B - E_E + R_1)$	$(U, +, U, -)$	不稳定
$E_6(0,1,0,1)$	$E_1 + \eta R - N, -(\eta I + C - \eta M), (1 + \eta)I + \eta G - 2K, -(\eta B - E_E + R_1)$	$(U, +, U, -)$	不稳定
$E_7(0,1,1,0)$	$R - N, -C, -(I + G - 2K), \eta B - E_E + R_1$	$(-, -, +, +)$	不稳定
$E_8(0,1,1,1)$	$\eta R - N, -C, -[(1 + \eta)I + \eta G - 2K], -(\eta B - E_E + R_1)$	$(U, -, U, -)$	不稳定

注：U 表示正负符号不确定，下同；ESS 表示演化稳定策略。

4.2 政府监管下策略组合稳定性分析

当政府的稳定策略为监管时，即满足条件② $W(\eta - 1)R - YE_2 - ZE_1 + (E_1 + E_2 - N + R) > 0$ 时，复制动态系统均衡点的渐近稳定性分析见表 3。

由表 3 可知，在整部监管部门监管情况下稳定策略组合维(1,0,0,0)，表示政府监管部门监管，周边群众集体抗争、污染企业不整改和媒体不曝光。然而，ESS 的点并不是所要求的理想状态。具体来说，无论政府是否监管，污染企业整

改的态度总是消极的，周边居民也不会放弃抵制，这反映了政府惩罚机制在环境污染群体性事件中的失灵。因此，环境污染群体性事件中利益相关者博弈的最终进化稳定状态并不理想，事件也将变得更加难以管理。由各博弈主体博弈策略的稳定性分析来看，当政府的监管失灵时，媒体进行曝光的概率增加。同时，媒体曝光概率的增加会影响污染企业整改的概率。因此，本文试图进一步分析媒体在环境污染群体性事件中的作用。

表 3 政府监管复制动态系统均衡点渐进稳定性分析

均衡点	特征值 $\lambda_1, \lambda_2, \lambda_3, \lambda_4$	符号正负	稳定性
$E_1(1,0,0,0)$	$-(E_1 + E_2 + R - N), E_2 + I + C - M, E_1 + G - K + M + H, -E_G + \eta B - E_E + R_1$	$(-, -, -, -)$	ESS
$E_2(1,0,0,1)$	$-(E_1 + E_2 - N + \eta R), E_2 + I + C - M, E_1 + \eta G - K + \eta M + \eta H, -(-E_G + \eta B - E_E + R_1)$	$(-, -, U, +)$	不稳定
$E_3(1,0,1,0)$	$-(E_2 + R - N), E_2 + C, -(E_1 + G - K + M + H), -E_G + \eta B - E_E + R_1$	$(-, +, +, -)$	不稳定
$E_4(1,1,0,0)$	$-(E_1 + R - N), -(E_2 + I + C - M), E_1 + I + G - 2K, -E_G + \eta B - E_E + R_1$	$(-, +, -, -)$	不稳定
$E_5(1,0,1,1)$	$-(E_2 + \eta R - N), 0, -(E_1 + \eta G - K + M + H), -(-E_G X + \eta B - E_E + R_1)$	$(-, 0, U, +)$	不稳定
$E_6(1,1,0,1)$	$-(E_1 + \eta R - N), -(E_2 + \eta I + C - \eta M), E_1 + (1 + \eta)I + \eta G - 2K, -(-E_G X + \eta B - E_E + R_1)$	$(-, +, U, +)$	不稳定
$E_7(1,1,1,0)$	$-(R - N), -(E_2 + C), -(E_1 + I + G - 2K), -E_G + \eta B - E_E + R_1$	$(-, -, +, -)$	不稳定
$E_8(1,1,1,1)$	$-(\eta R - N), 0, -[E_1 + (1 + \eta)I + \eta G - 2K], -(-E_G X + \eta B - E_E + R_1)$	$(-, 0, U, +)$	不稳定

五 考虑政府监管的环境维权三方演化稳定性数值仿真

为更深入、直观地展开复制动态系统中关键要素对多方博弈演化过程及演化结果的影响，下面运用 MATLAB 对各博弈方的演化轨迹进行数值仿真。

环境污染群体性事件中，政府可以选择进行监管，存在监管成本 $N = 4$ ，对不整改企业处罚 $E_1 = 2$ ，进行集体抗争的周边群众处罚 $E_2 = 0.5$ ；也可以选择不监管，但会有声誉损失 $R = 1$ 。环境维权事件解决会给政府带来巨大的社会收益 $S = 1$ ，在集体抗争爆发时，监管部门会受到上级政府

的追责 $U = 4$ 。媒体可以选择曝光企业的污染行为，存在包括政府行政阻力在内的曝光成本 $E_G = 10$ 和污染企业的阻碍成本 $E_E = 2$ 。媒体将企业的污染信息曝光后会获得流量收益 $B = 2$ ，流量收益会随舆论热度的大小发生变化，初始状态设 $\eta = 4$ 。媒体对污染企业污染行为的忽视会使媒体丧失公信力 $R_1 = 3$ 。周边群众可以选择妥协或集体抗争，收益会因污染企业策略选择的不同发生变化。污染企业不整改情况下，周边群众妥协时，周边群众会获得经济补偿 $I = 2$ 。而当周边群众集体抗争，需要付出抗争成本 $C = 1$ ，集体抗争会带给污染企

业经济损失 $F = 2$ ，周边群众会因集体抗争获得经济赔偿 $M = 4$ ，与此同时，不整改的污染企业会存在声誉损失 $H = 1$ 。污染企业选择整改时会存在整改成本 $K = 5$ ，政府会对整改的企业进行补贴 $G = 2$ ，周边群众会获得环境收益为 $P = 5$ 。

5.1 政府监管机制的影响

为验证周边群众性事件中，政府监管部门对事件监管的有效性，通过设置 $X = 0$ 和 $X = 0.9$ 来分别政府监管部门不进行监管和进行监管两种状态，在三维空间对污染企业、周边群众和媒体三方不同初始策略的演化过程进行仿真分析，仿真结果如图1所示。由图1-a可知，当 $X = 0$ 时，即政府监管部门对环境污染群体性事件不予监管的情况下，系统不存在稳定点。由于行政阻力下降的影响，媒体策略选择倾向于选择进行曝光。由于声誉损失风险和赔偿金额等多种因素的影响，污染企业策略会出现整改和不整改的周期性波动，而周边群众在污染企业整改策略周期性波动下也会出现妥协和集体抗争的周期性波动。由图1-b可知，当 $X = 1$ 时，即政府监管部门对污染企业的污染行为进行处置，由于政府行政阻力，媒体倾向于选择不曝光。对于污染企业，其进行整改的成本远远大于政府对其惩罚、收到的补贴与对周边群众赔偿之和，因此污染企业倾向于选择不整改。周边群众会因政府监管失灵而倾向于集体抗争。

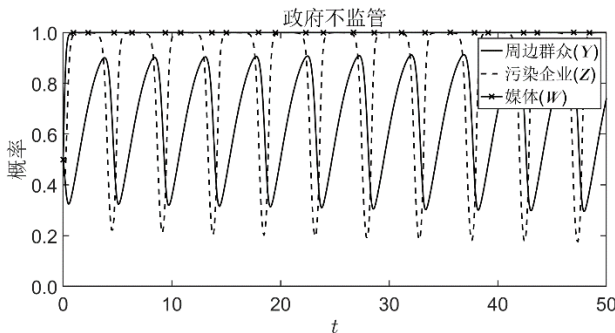


图 1-a $X = 0$

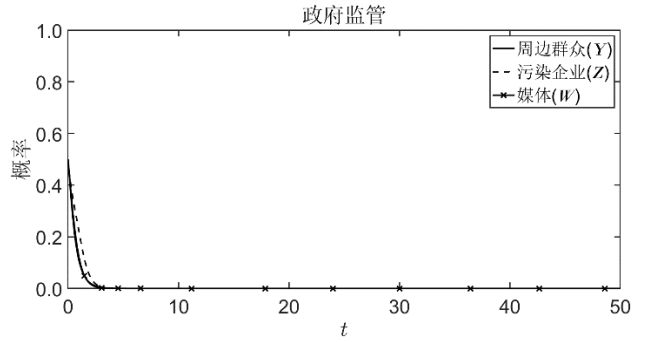


图 1-b $X = 1$

图 1 政府监管机制对各方策略演化的影响

5.2 舆论发酵程度的影响

为检验舆论发酵程度对系统演化的影响，设 $\eta = \{3, 6, 9, 12\}$ ，四方博弈主体策略演化过程及结果如图2所示。

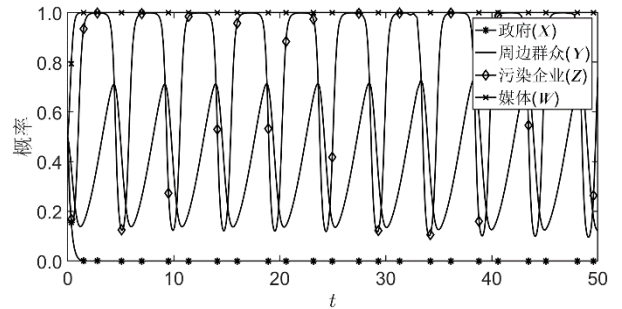


图 2-a $\eta = 3$

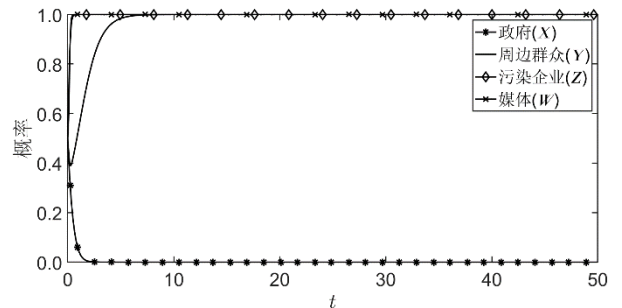


图 2-b $\eta = 6$

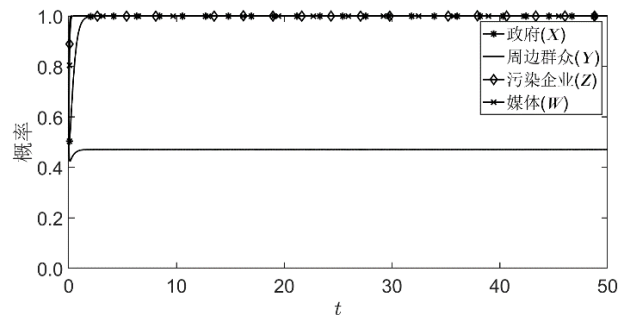


图 2-a $\eta = 9$

图 2 舆论发酵程度对各方策略演化的影响

由图 2 可知，舆论强度的变化对四方主体策略演化趋势都有影响。舆论发酵程度的增加，政府不监管和污染企业不整改声誉损失随之增加，使得政府的策略选择逐渐倾向于进行监管，污染企业倾向于进行整改。对于媒体而言，舆论发酵程度越高，其获得流量收益随之增加，因此媒体倾向于曝光。周边群众集体抗争的收益和妥协时的收益都会随着舆论的发酵而增加，周边群众策略也逐渐倾向于妥协。但当舆论的发酵大到一定程度时，周边群众的策略趋向于中性，有一半的概率选择集体抗争或者妥协。

5.3 企业整改负担的影响

设 $\{K, G\} = \{13, 2\}$ ，四方博弈主体策略演化过程及结果见表 3。

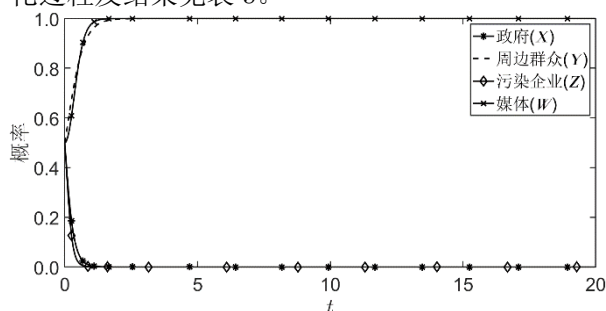


图 3-a $\{K, G\} = \{13, 2\}$

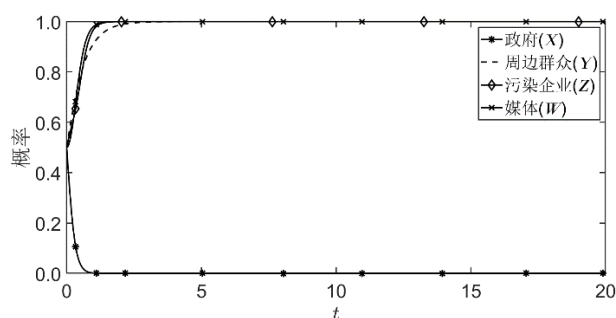


图 3-b $\{K, G\} = \{9, 4\}$

图 3 污染企业整改负担对污染企业策略演化的影响

由图 3 可知，随着污染企业整改负担的减轻，污染企业的策略选择会由不整改向整改转变。这说明环境污染群体性事件的有效解决一方面依赖于污染处理技术的进步降低企业整改成本，另一方面依赖于政府的扶持，依靠政府扶持解决整改初期的资金问题。

5.4 集体抗争收益的影响

未检验周边群众集体抗争收益对博弈系统演化结果的影响，设 $M = \{0, 6, 12\}$ ，四方博弈主体策略演化过程及结果见图 4。

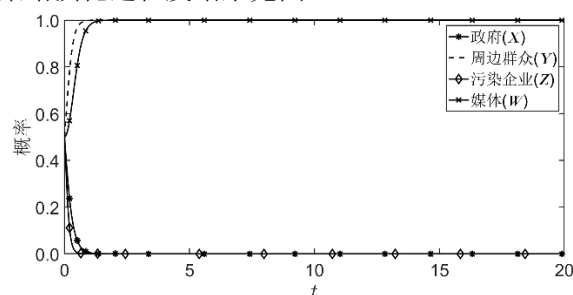


图 4-a $M = 0$

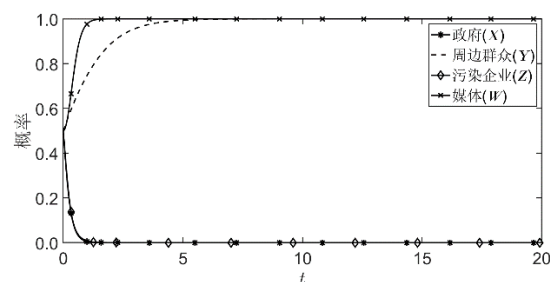


图 4-b $M = 6$

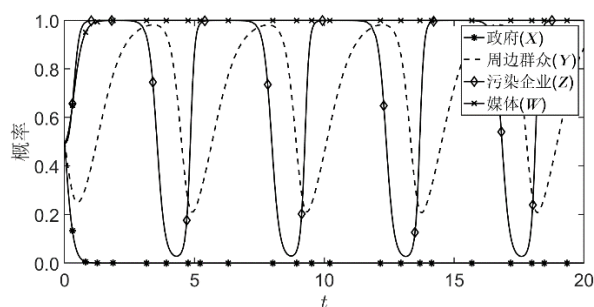


图 4-c $M = 12$

图 4 集体抗争收益对周边群众策略演化的影响

由图 4 可知，随着集体抗争收益的增加，周边群众选择妥协策略的概率逐渐降低，当集体抗争的收益无限增加到一定程度时，周边群众策略选择呈现在妥协与集体抗争间的周期性变动。当 $M = 0$ 时，即集体抗争无利可图，周边群众倾向于妥协。随着集体抗争收益的增加，周边群众付出少量的集体行动成本就可以获得更多的收益，因此会有更多的人愿意参与到集体抗争中。同时，污染企业对集体抗争群众的赔偿增加，污染企业倾向于整改时，周边群众也会随之选择妥协。因此周边群众和污染企业的策略分别在妥协与集体抗争、整改与不整改之间周期性变动。

六 结语

本研究针对污染企业环境污染引起的周边群众维护自身环境权益而发生的环境污染群体性事件，在政府监管部门的监管机制与媒体的曝光机制并存的情况下研究周边群众和污染企业的策略选择以及影响其策略演化的因素，得出以下主要结论。

(1) 在环境污染群体性事件中，影响政府监管部门策略选择的主要因素是声誉损失，也就是政府形象，和包括 GDP 损失在内的行政成本。此外，出现政府监管部门惩罚机制失灵现象。一方面，政府监管部门不能有效减少污染企业进行环境整改的负担，另一方面，政府监管部门缓和周边群众集体抗争的方法局限于经济补偿，使得周边群众形成了“不闹不解决，小闹小解决，大闹大解决”

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的思考逻辑。

(2) 舆论发酵程度是影响环境污染群体性事件中四方主体策略演化的关键因素。舆论发酵通过影响政府公信力和污染企业的声誉来影响其策略选择，使政府策略向监管演变，污染企业策略向整改演变。此外，舆论的发酵通过增加周边群众补偿收益，使其策略向妥协演化。

(3) 促使污染企业进行整改的关键因素是减轻其整改负担。从企业自身来说，通过技术创新可以减少其绿色整改成本。从政府职能角度来，政府应当制定扶持污染企业绿色转型的应对政策，包括税收的减少和绿色补贴。集体抗争收益的增加会使得周边群众选择集体抗争策略的概率增加。这种博弈还体现为周边群众“闹大”心态。周边群众意图通过“闹大”获得更多的补偿。

The transmission mechanism of the manufacturing industry production activities to carbon emissions from the input-output subsystem perspective: A case of China

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Abstract: Manufacturing is the industrial sector with the largest energy consumption and the most prominent carbon emission in China, of which emission reduction effect largely determines the process of achieving carbon peaking and carbon neutrality. This study compares the direct carbon emissions of China's manufacturing sector and the carbon emissions caused by final demand in 2018, and uses the input-output model to decompose the carbon emissions caused by final demand into indirect own internal component, feed-back, indirect spillover, direct own internal component, direct spillover, scale component. Moreover, this paper studies the carbon emission path to meet the final demand of the manufacturing sector for the spillover components, and applies sensitivity analysis and scenario analysis to analyze the influencing factors and the future development trend until 2060 of China's manufacturing carbon emissions. The results show that in 2018, the direct carbon emissions of China's manufacturing industry and the carbon emissions caused by final demand were about 4.61 billion tons and 3.50 billion tons, respectively. Indirect spillovers and direct spillovers account for 62.1% and 23.1% of the carbon emissions of the final demand of the manufacturing industry respectively, accounting for the largest proportion of the carbon emissions caused by the final demand. The self-spillover of manufacturing industry accounts for 37.6% of the carbon emissions generated by the final demand of manufacturing industry, and the spillover of power, heat, natural gas and water production and supply industries accounts for 33.6% of the carbon emissions. Based on the carbon emission transfer path map caused by the final demand of the manufacturing industry, the direction and amount of carbon emission transfer of a certain energy can be accurately located. For every 5% decrease in energy efficiency, final demand and total energy consumption, the carbon emissions generated by the final demand of the manufacturing industry will be reduced by about 190 million tons. The CR scenario shows that the manufacturing industry will reach the peak of carbon from 2025 to 2030, with the corresponding peak between 4.02-4.06 billion tons, which will drop to 2.1 billion tons in 2060, reducing carbon emissions by 40% compared with 2018. Finally, this paper puts forward targeted policy recommendations based on the carbon emission characteristics of different sectors of the manufacturing industry.

Key Words: Manufacturing industry; Input-output subsystem analysis; Transmission mechanism; Carbon emission structure

1 Introduction

Global warming has caused a significant impact on social development and the environment. Since the signing of the Paris Agreement, the contribution of countries to carbon emissions has been widely valued^[1]. Controlling and reducing greenhouse gas emissions is the main way to deal with climate change, but the current international carbon emission reduction situation is not optimistic^[2]. The International Energy Agency (IEA) issued a communique that with the lifting of epidemic prevention and control measures and economic recovery, global carbon emissions in 2021 were about 33 billion tons, an increase of 4.8% year-on-year, mainly due to the strong rebound in coal demand in the power industry^[3]. Unless governments around the world act quickly, mankind will face an even worse situation in 2022. China is a major carbon emitter in the world, accounting for about 30% of global carbon emissions^[4]. As the world's largest carbon emitter, China is actively undertaking the responsibility of emission reduction. China will adopt more effective policies and measures, strive to reach the peak of carbon dioxide emissions by 2030, and strive to achieve carbon neutrality by 2060^[5]. This is the first time that China has clearly put forward the task of carbon emission reduction to the world, which indicates that carbon emission reduction and low-carbon development will be an important theme of China's environmental governance during the 14th Five Year Plan period and for a long time in the future. Since 2000, most of China's carbon emissions have been caused by industrial energy consumption, and manufacturing energy consumption accounts for more than 80% of the industry's and shows an upward trend year by year^[6]. While maintaining high-quality economic development, the emission reduction effect of manufacturing industry largely determines the realization of carbon peak and carbon neutralization goals.

At present, scholars have done a lot of research work around the carbon emission of manufacturing industry. The research content mainly involves the current situation and evolution trend of carbon emission of manufacturing industry, the analysis of influencing factors and the path of carbon emission reduction. For the current situation and evolution trend of manufacturing carbon emissions, most of the literature is limited to a country or region. Zhang et al. analyzed the current situation and problems of manufacturing carbon emissions in Beijing Tianjin Hebei region of China, and put forward corresponding countermeasures and suggestions^[7]. Hang et al. used Tapio decoupling index to explore the decoupling between China's manufacturing added value and carbon dioxide emissions from 1995 to 2015^[8]. Wang et al. analyzed the temporal and spatial evolution of carbon emissions from China's high-carbon manufacturing industry from 2006 to 2015, and found that there are significant path dependence and spatial spillover effects on carbon emissions from high-carbon manufacturing industry^[9]. Most scholars have found that policy, technology and energy consumption are the main factors driving the change of carbon emissions in manufacturing. Morgenstern et al. examined the short-term impact of carbon reduction policies on U.S. manufacturing and found that only a small number of industries bear the disproportionate short-term burden caused by carbon taxes or similar policies^[10]. Ding et al. used the STIRPAT model to quantitatively analyze the impact of technological factors on the carbon emissions of China's manufacturing industry, and believed that technological factors had a negative effect on the carbon emissions of manufacturing industries^[11]. Xu and Lin used a vector autoregressive model to analyze the influencing factors of China's manufacturing carbon dioxide emissions, and the study found that energy efficiency played a leading role in

reducing carbon dioxide emissions^[12]. Su et al. examined the impact of energy mismatch on the carbon emission efficiency of the manufacturing industry, and believed that improving energy allocation can significantly improve the carbon emission efficiency of the manufacturing industry^[13]. The research on carbon emission reduction path of manufacturing industry mainly focuses on carbon emission reduction action planning and responsibility allocation. Wang et al. analyzed the dynamic evolution process and driving effect of China's manufacturing carbon emissions from 1995 to 2016, and made a trend analysis of manufacturing carbon emissions during the "14th Five-Year Plan" period based on government policy planning^[14]. The outward transfer of high energy consuming manufacturing industry can effectively alleviate the pressure of China's carbon emission^[15]. Zhang and Cheng calculated the carbon emission reduction responsibilities of various departments of China's manufacturing industry from 2020 to 2030 based on China's carbon emission reduction target to 2030^[16].

Many scholars have decomposed the driving factors of manufacturing carbon emissions, including generalized Dirichlet exponential decomposition (GDIM) and logarithmic mean Dirichlet decomposition (LMDI). Jin and Han used the GDIM model to decompose the influencing factors of China's manufacturing carbon emissions from 1995 to 2018 into industrial added value, energy consumption, fixed asset investment, carbon productivity, energy structure, energy intensity, investment carbon intensity and investment efficiency, and believes that fixed asset investment is the main driving force of carbon emissions^[17]. Shi et al. established an inter-sectoral LMDI model to explore the main drivers of changes in China's manufacturing CO₂ emissions from 2000 to 2015, arguing that energy intensity was the main factor

responsible for the differences in CO₂ emissions between sectors^[18]. Moreover, some scholars have analyzed the carbon emissions of the manufacturing industry based on the input-output method. Lenzen's research shows that the energy consumption of the manufacturing industry is second only to the primary energy production sector, and its high dependence on energy leads to higher carbon emissions, and also points out that the carbon emissions caused by intermediate inputs are also considerable^[19]. Tunc et al. used the input-output model to study the carbon emissions and emission reduction responsibilities of various industries in Turkey, and found that the manufacturing industry ranks first in Turkey's carbon emissions and should undertake important emission reduction tasks^[20]. Xu and Hu used the input-output model to decompose the carbon emissions caused by final demand, and found that the manufacturing industry has a greater demand for carbon emissions from the energy industry and service industry^[21]. Tian et al. applied the Structural Path Decomposition (SPD) method based on the environmental input-output model to find the key supply chain paths driving the carbon dioxide life cycle changes in China's manufacturing industry, and found that higher-order paths lead to a large increase in carbon emissions^[22].

Summarizing the existing literature, it can be found that the current research on the driving factors of manufacturing industry mainly focuses on the impact of factors such as energy intensity and fixed asset investment on carbon dioxide emissions. However, there are few studies on the related driving factors within the manufacturing industry and between the manufacturing industry and other industries, which is not conducive to the formulation of industrial emission reduction policies. Moreover, when decomposing carbon emissions, the decomposing method used causes the factors not to be completely decomposed.

Therefore, this paper studies the direct and indirect carbon emissions of China's manufacturing sector based on input-output analysis and structural decomposition, and further decomposes the manufacturing carbon emissions into 6 parts, revealing the manufacturing sector's transmission mechanism on carbon emissions which can provide a reference for the formulation of China's manufacturing carbon emission reduction policies. Moreover, we analyze each sector as a separate object and consider its relationship with other sectors, so as to determine the most suitable emission reduction policy for each sector. The rest of this paper is structured as follows. The second part describes the method and explains the data used in detail. The third part introduces the results, sensitivity analysis and scenario prediction. The fourth part discusses and summarizes, and points out some policy implications.

2 Material and methods

2.1 Methodology

The input-output model can calculate the direct and indirect carbon dioxide emissions of various sectors of the national economy, and then evaluate the impact of changes in the final demand of a certain sector on other sectors or total emissions^[23]. Based on the input-output model, this research establishes a carbon emission decomposition model for China's manufacturing sector, which can be used to analyze the carbon emissions of various industries in the manufacturing industry and the links with other sectors of the economic system. Firstly, this study makes a simple calculation of the carbon emissions per unit output value of various sectors of the national economy^[24]. The specific formula is shown below.

$$c_i = \frac{\sum E_k f_k}{x_i} \quad (1)$$

In the formula, c_i represents the carbon emission per unit output value of industry i , E_k represents the consumption of k types of energy in a certain industry,

f_k represents the carbon emission coefficient of k types of energy, and x_i represents the total output value of industry i .

In this paper, we need to obtain data from China's non-competitive input-output table. The total carbon emissions caused by final demand in the manufacturing sector can be calculated by the following formula^[25].

$$TEMI = \sum_{j=12}^{99} \sum_{i=1}^{153} c_i b_{ij} y_j \quad (2)$$

In the formula, $TEMI$ represents the total carbon emissions generated to meet the final demand of the manufacturing industry. b_{ij} represents the elements in row i and column j of the complete consumption coefficient matrix, which means the sum of the value of the i -th sector directly and indirectly consumed by the production unit value of the j -th sector. y_j represents the final demand of department j .

The proposed concept of input-output subsystem improves and supplements the traditional input-output analysis, obtains the detailed characteristics of carbon emission of a department and its subsystems, and may be of progressive significance to put forward the carbon emission reduction scheme in the production process of a department^[26]. Next, we propose to decompose the emissions related to economic activities into different components, and the method is improved on the basis of Francisco and Vicent^[27]. From the perspective of final demand, the total carbon emission of the whole manufacturing industry is composed of the intermediate input generated by all other sectors required by the economic sector and the emission generated by each economic sector, that is, the emission generated to obtain productive input and the emission generated to obtain final demand^[25]. For the intermediate input required for production, we distinguish between direct components and indirect components according to the definition of complete consumption coefficient^[28]. Therefore, we use the concept of input-output subsystem to decompose the carbon emissions of each sector into two categories:

Indirect component, *Direct component*, and 6 subsystems: *Indirect own internal component*, *Feed-back*, *Indirect spillover*, *Direct own internal component*,

$$TES_j = \underbrace{c_j[(1 - a_{jj})^{-1} - a_{jj} - 1]y_j}_{\text{Indirect own internal component}} + \underbrace{c_j(1 - a_{jj})^{-1} \sum_{i \neq j} a_{ji} b_{ij} y_j}_{\text{Feed-back}} + \underbrace{\sum_{i \neq j} c_i (b_{ij} - a_{ij}) y_j}_{\text{Indirect spillover}} + \underbrace{c_j a_{jj} y_j}_{\text{Direct own internal component}} + \underbrace{\sum_{i \neq j} c_i a_{ij} y_j}_{\text{Direct spillover}} + \underbrace{c_j y_j}_{\text{Scale component}} \quad (3)$$

Direct component

In the formula, TES_j and c_j respectively represents the total carbon emissions and unit output carbon emissions of sector j , and a_{jj} , a_{ji} , and a_{ij} respectively represents the corresponding elements in the direct consumption coefficient matrix.

Combined with figure A1, we can clearly understand the basis and economic meaning of subsystem Division: *Indirect own internal component* represents the indirect internal demand of department j for its own production in order to obtain the final demand; *Feed-back component* represents department j 's self-production by satisfying the input needs of other departments; *Indirect spillover* refers to the emissions generated by other departments in the production process of indirect flow to department j , which means to meet the final demand of department j through investment in other departments; *Direct own internal component* represents the direct internal demand of department j for its own production in order to obtain the final demand; *Direct spillover* refers to the emissions generated by other departments in the production process of direct flow to department j ; *Scale component* indicates the emissions directly related with the magnitude of the final demand. The decomposition model of this study defines the internal components in detail, and involves the carbon emission transmission relationship between each sector and other sectors, allowing the determination of carbon emission reduction policies that are more in line with different sectors^[29].

Direct spillover, *Scale component*. The decomposition method is derived in detail in Appendix A, and the decomposition results are shown in formula (3).

2.2 Data sources

In this study, we need to obtain data from the input-output table compiled by China's statistics department and *China Energy Statistics Yearbook*. The complete consumption coefficient matrix and direct consumption coefficient matrix used are calculated from the 2018 China Input-Output Table^[30]. Due to data limitations, this study only measures the carbon emissions from energy consumption, and ignores the carbon emissions from the production process and the carbon inflow of raw materials, but this does not affect the analysis results of this study^[2, 31]. The carbon emissions in national economic production mainly come from the consumption of three traditional energy sources: raw coal (coal, coke), petroleum (gasoline, diesel, kerosene, fuel oil) and natural gas^[32]. The consumption data of various energy sources are obtained from the *2018 China energy statistical yearbook*^[33]. The carbon emission factors for each energy are shown in table B1 of Appendix B^[34]. In order to get a more intuitive result, we adjusted the complete consumption coefficient matrix by merging 153 departments into 45 departments in the input-output table according to the division of departments of the national bureau of statistics of China, as shown in table B2^[35].

3 Results

3.1 Overall analysis of carbon emissions in manufacturing industry

The carbon emissions per unit output value of each industry in China in 2018 are calculated by formula (1),

as shown in Table B3. In the non-manufacturing sector, Production and Supply of Electric Power and Heat Power and Mining and Washing of Coal have the highest carbon emissions per unit output, which are 5.79 tons/10000 yuan and 1.99 tons/10000 yuan respectively, mainly due to the high emissions of coal mining and power generation^[36]. In the manufacturing sector, the major carbon emissions per unit output value are heavy industry sectors, such as Processing of Petroleum, Coking and Processing of Nuclear Fuel and Smelting and Pressing of Ferrous Metals, which are 2.25 tons/10000 yuan and 2.42 tons/10000 yuan respectively, but, the carbon emissions per unit output value of light industries such as equipment manufacturing rank lower in the manufacturing industry. When formulating manufacturing carbon emission reduction policies, focusing only on heavy industry and ignoring light industry, and vigorously developing equipment manufacturing and other high-tech industries in the current state of my country's technological performance, can effective carbon emission reduction be achieved? In order to have an intuitive understanding of the carbon emission status of the manufacturing industry and internal departments, this part calculates the direct carbon emission of each department of the manufacturing industry and the carbon emission caused by the final demand respectively, and analyzes the contribution of different departments to carbon emission from the difference between the two data.

Direct carbon emissions refer to the total emissions of the sector, while emissions due to final demand refer to the emissions of various productive sectors to meet the final needs of the sector^[37]. Table 1 shows the direct carbon emissions from the production of various sectors and the carbon emissions caused by final demand of China's manufacturing industry in 2018. We calculated that the carbon emissions of all

production sectors in China in 2018 were approximately 10.04 billion tons. On the whole, the direct carbon emissions of the manufacturing sector accounted for 45.9% of the carbon emissions of the production sector in my country, while the carbon emissions caused by the final demand accounted for 34.8%. This shows that only considering the direct carbon emissions of various sectors and ignoring the correlation effect between sectors (leading to the carbon emissions of this sector by providing intermediate products for other sectors) is likely to lead to wrong judgment on the contribution of some sectors to carbon emissions, resulting in policy mistakes. Moreover, this also shows that other industries have a relatively large demand for manufacturing products, resulting in the direct carbon emissions of the manufacturing industry being greater than the carbon emissions caused by the final demand. In terms of specific sectors of manufacturing industry, the proportion of carbon emissions in the Processing of Petroleum, Coking and Processing of Nuclear Fuel decreased from 22% of direct emissions to 5.5% of emissions caused by final demand, and the Smelting and Pressing of Ferrous Metals decreased from 35.5% to 4.7%. This shows that such sectors have a greater demand for energy in the production process and a smaller demand for products from other sectors, while other sectors have a greater demand for products from such sectors, resulting in direct carbon emissions greater than those caused by final demand. The proportion of carbon emissions in the Manufacture of Automobiles increased from 0.2% of direct emissions to 9.8% of emissions caused by final demand, the Manufacture of Electrical Machinery and Apparatus from 0.1% to 8.2%, and the Manufacture of Computers, Communication and Other Electronic Equipment from 0.2% to 9.3%. Although these sectors have little demand for energy in the production process, resulting

in small direct carbon emissions, they have a strong industrial correlation effect, and the final demand has a strong pulling effect on the carbon emissions of other sectors, resulting in a large demand for the carbon emissions of other sectors.

Table 1: Manufacturing energy consumption carbon emissions.

	Sector	Direct carbon emissions		Carbon emissions caused by final demand	
		Kt	%	Kt	%
S8	Processing of Food from Agricultural Products	43917.8	1.0%	169749.2	4.9%
S9	Manufacture of Foods	34346.7	0.7%	128169.4	3.7%
S10	Manufacture of Liquor, Beverages and Refined Tea	15808.4	0.3%	52400.7	1.5%
S11	Manufacture of Tobacco	521.0	0.01%	6678.9	0.2%
S12	Manufacture of Textile	24527.9	0.5%	77501.1	2.2%
S13	Manufacture of Textile, Wearing Apparel and Accessories	2404.5	0.1%	118527.2	3.4%
S14	Manufacture of Leather, Fur, Feather and Related Products and Footwear	1124.7	0.02%	66724.9	1.9%
S15	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	2808.5	0.1%	9705.0	0.3%
S16	Manufacture of Furniture	585.7	0.01%	71489.4	2.0%
S17	Manufacture of Paper and Paper Products	85963.2	1.9%	15044.2	0.4%
S18	Printing and Reproduction of Recording Media	2224.5	0.05%	3693.0	0.1%
S19	Manufacture of Articles for Culture, Education, Arts and Crafts, Sport and Entertainment Activities	2570.9	0.1%	90605.1	2.6%
S20	Processing of Petroleum, Coking and Processing of Nuclear Fuel	1014743.2	22.0%	193669.1	5.5%
S21	Manufacture of Raw Chemical Materials and Chemical Products	624059.2	13.5%	206262.9	5.9%
S22	Manufacture of Medicines	19733.2	0.4%	58914.6	1.7%
S23	Manufacture of Chemical Fibers	27618.6	0.6%	13540.7	0.4%
S24	Manufacture of Rubber and Plastics Products	13221.5	0.3%	68334.6	2.0%
S25	Manufacture of Non-metallic Mineral Products	525148.3	11.4%	85316.2	2.4%
S26	Smelting and Pressing of Ferrous Metals	1638482.5	35.5%	164048.8	4.7%
S27	Smelting and Pressing of Non-ferrous Metals	438077.9	9.5%	49752.5	1.4%
S28	Manufacture of Metal Products	28508.6	0.6%	176568.1	5.1%
S29	Manufacture of General Purpose Machinery	15595.3	0.3%	295350.9	8.4%
S30	Manufacture of Special Purpose Machinery	4788.6	0.1%	242926.7	6.9%
S31	Manufacture of Automobiles	9783.2	0.2%	341037.9	9.8%
S32	Manufacture of Railway, Ship, Aerospace and Other Transport Equipments	17006.6	0.4%	125826.0	3.6%
S33	Manufacture of Electrical Machinery and Apparatus	3691.6	0.1%	286867.2	8.2%
S34	Manufacture of Computers, Communication and Other Electronic Equipment	8745.2	0.2%	326572.1	9.3%
S35	Manufacture of Measuring Instruments and Machinery	428.7	0.01%	28040.0	0.8%

The transmission mechanism of the manufacturing industry production activities to carbon emissions from the input-output subsystem perspective: A case of China

S36	Other Manufacture	775.9	0.02%	15785.4	0.5%
S37	Utilization of Waste Resources	3852.1	0.1%	97.3	0.003%
S38	Repair Service of Metal Products, Machinery and Equipment	357.7	0.01%	7120.0	0.2%
	Total	4611421.6	100%	3496319.3	100%

Figure 1 shows the energy structure of direct carbon emissions from China's manufacturing industry and carbon emissions caused by final demand in 2018. On the whole, the proportion of carbon emissions from coal in manufacturing industry has increased from 66.4% of direct emissions to 74.8% of emissions caused by final demand and the proportion of carbon emissions from coke has decreased from 26.9% to 13.0%. This is because the correlation effect between the manufacturing industry and other industries is considered when calculating the carbon emission caused by the final demand, for example, the increase in the proportion of coal carbon emission is caused From the perspective of specific sectors of manufacturing industry, from direct carbon emission to

carbon emission caused by final demand, the change of energy carbon emission structure of high energy consuming industries such as energy and chemical industry is not large, while the change of low energy consuming industries such as equipment manufacturing and food processing is relatively large. Through the research on the energy carbon emission structure of the manufacturing sector, the correlation effect between various sectors in the manufacturing industry and other sectors is further verified, which also shows that the analysis of the transmission mechanism of carbon emission from the perspective of final demand has some enlightenment for China's manufacturing industry to formulate carbon emission reduction policies.

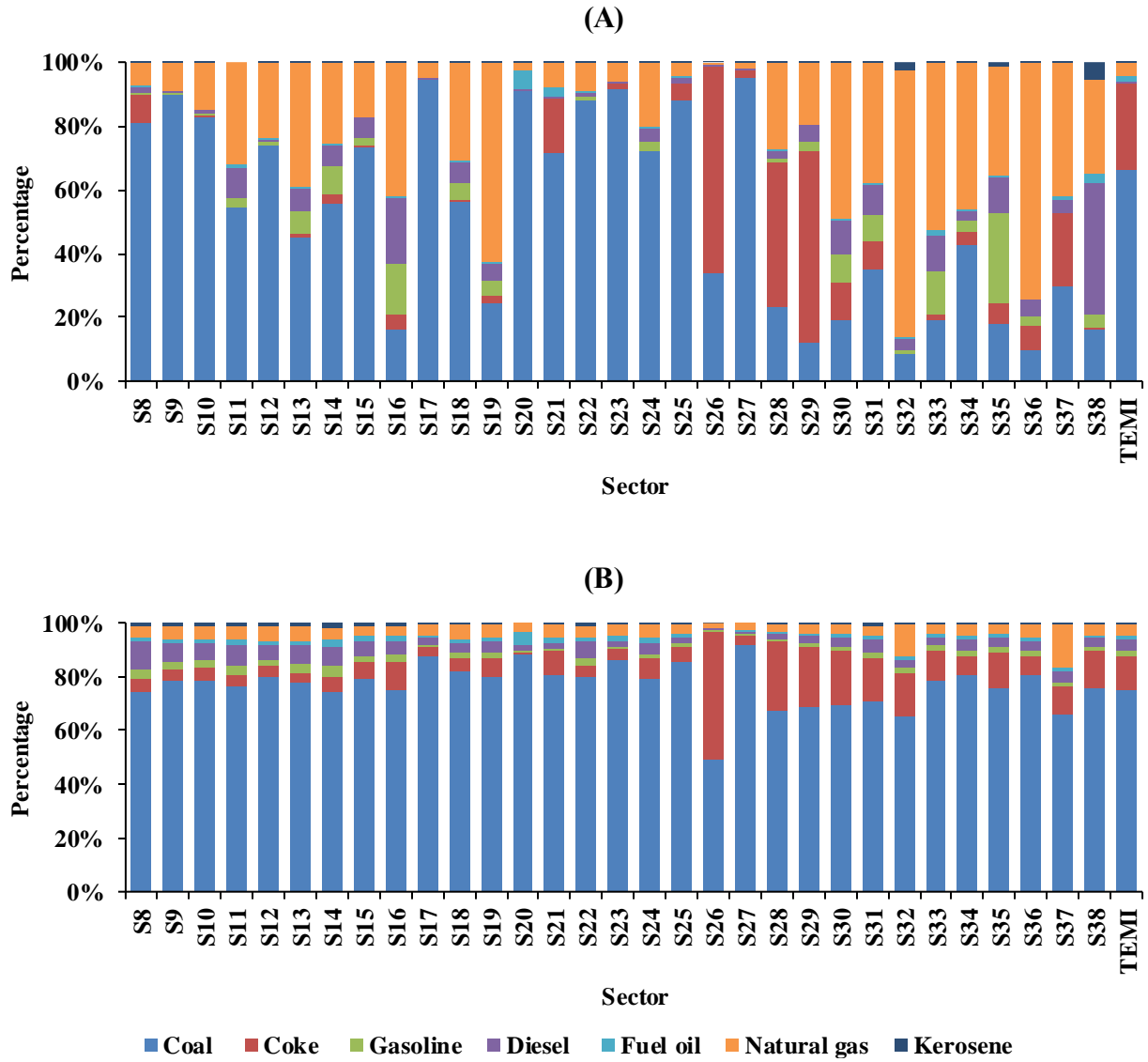


Fig 1: Energy structure of direct carbon emissions (A) and carbon emissions caused by final demand (B) of China's manufacturing sectors in 2018.

3.2 Structural decomposition of carbon emission in manufacturing industry

In the above analysis, we find that the carbon emissions caused by the final demand of manufacturing industry are quite different from the direct carbon emissions in terms of total amount, specific sectors and energy structure, and these changes may be related to the correlation effect between sectors^[38]. Through formula (3), the carbon emissions of various sectors of the manufacturing industry are divided into six parts to further analyze the carbon emissions caused by the final

demand. The decomposition results of each sector and total volume of the manufacturing industry are shown in Figure 2.

On the whole, different components make different contributions to the carbon emission of manufacturing industry. Direct and indirect components account for 37.6% and 62.4% of the carbon emissions caused by the final demand of the manufacturing industry, respectively. This shows that the carbon emission of direct products caused by the final demand of manufacturing industry is not high,

while the carbon emission of indirect products caused by the final demand of manufacturing industry is relatively high. Indirect internal components and direct internal components account for 0.2% and 1.2% of the carbon emissions caused by the final demand of the manufacturing industry respectively, which shows that the carbon emissions of internal products caused by the final demand of the manufacturing industry are not high. Feedback refers to the carbon emissions generated by other departments that need the product input of the manufacturing sector in order to produce products that meet the final needs of the manufacturing sector, reflecting the forward correlation effect between the manufacturing sector and other departments^[39]. Feedback components account for the smallest proportion of emissions, accounting for only 0.1% of the total. Scale component is a component of direct carbon emissions, accounting for 13.3%, which shows that the proportion of direct carbon emissions caused by final demand in manufacturing industry is not high. Indirect spillover and direct spillover account for 62.1% and 23.1% of the carbon emissions caused by final demand in the manufacturing industry, respectively, and they account for the largest proportion of carbon emissions caused by final demand, showing a relatively large backward correlation effect^[40]. In the above, we get that the direct carbon emissions of the manufacturing industry are greater than those caused by the final demand, which shows that other sectors have a significant pulling effect on the manufacturing industry. At the same time, the manufacturing sector needs the support of other sectors to meet the production of the final demand, reflecting the complex industrial correlation effects inside and outside the manufacturing sector.

From the analysis of specific sectors, there are also some differences in the carbon emission contribution of each decomposition component in different sectors.

China's manufacturing industry can be divided into three categories: textile and other light industries, resource processing industry, machinery and electronic manufacturing industry, the specific classification is shown in Table B2^[41]. In the textile and other light industries, except that the scale components and direct internal components of Manufacture of Paper and Paper Products account for 30.5% and 7.8%, the Spillovers of other sectors account for more than 80%, and the indirect Spillovers of all sectors are greater than the direct spillovers. Moreover, in the mechanical and electronic manufacturing industry, except that the scale component of Utilization of Waste Resources accounts for 30%, other departments also have similar characteristics. In the resource processing industry, the scale components of Processing of Petroleum, Coking and Processing of Nuclear Fuel, Manufacture of Raw Chemical Materials and Chemical Products, Smelting and Pressing of Ferrous Metals and Smelting and Pressing of Non-ferrous Metals account for a large proportion, and the scale effect of Processing of Petroleum, Coking and Processing of Nuclear Fuel accounts for 74.4% of the total. Therefore, the direct carbon emissions of textile and other light industries, machinery and electronic manufacturing industry are small, while the carbon emissions caused by final demand are relatively large, which is mainly reflected in the spillover effect of these sectors on the carbon emissions of other sectors. The direct carbon emissions and the carbon emissions caused by final demand of the resource processing industry are relatively large, and the former is much larger than the latter, which shows that such sectors are not only energy-intensive industries themselves, but also have strong spillover effects on other sectors.

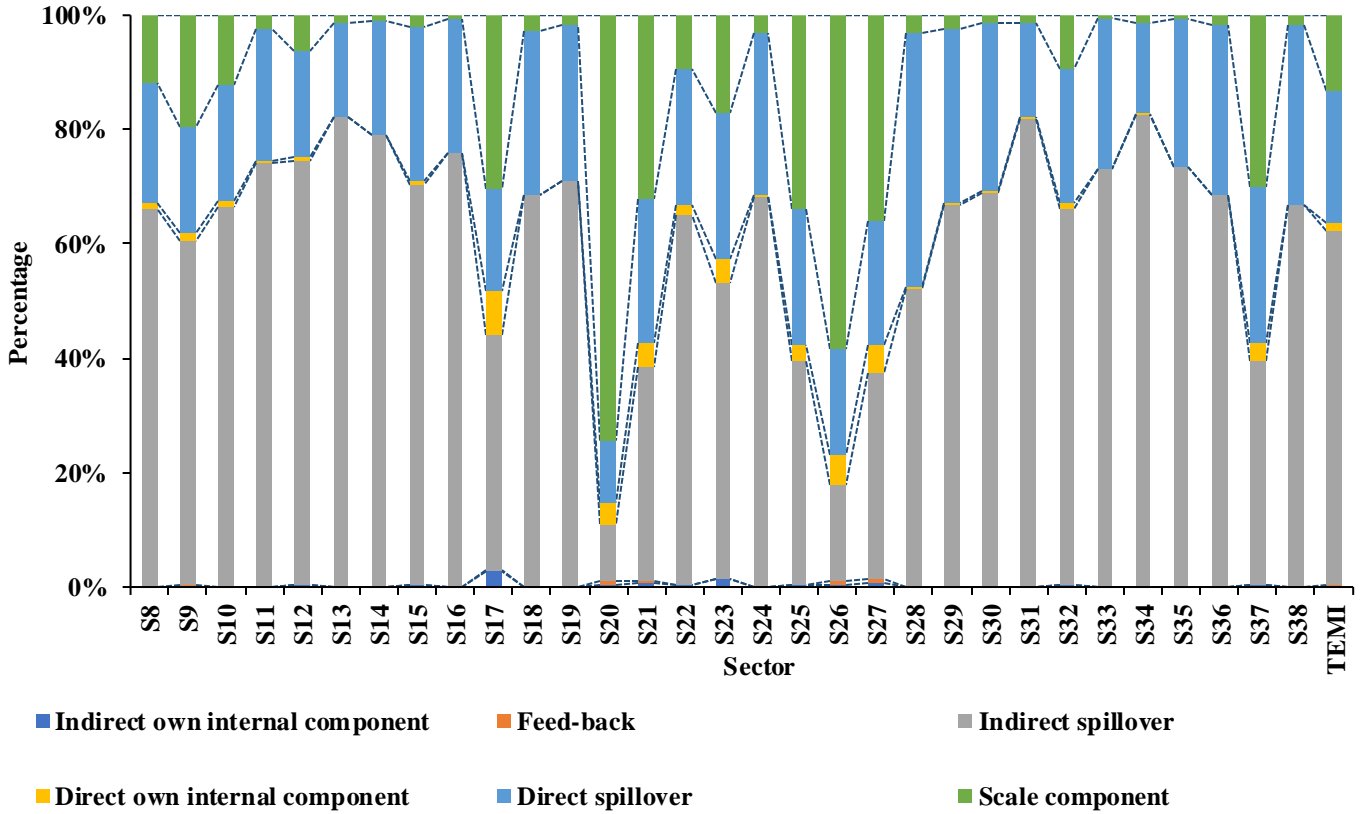


Fig.2: Structural decomposition of manufacturing carbon emissions.

3.3 Transmission path analysis of carbon emission spillover effect in manufacturing industry

In the above, we decompose the carbon emissions caused by final demand, and find that indirect spillover and direct spillover account for 86% of the total, which shows that the manufacturing sector has a great dependence on other sectors for the production of final demand products. Therefore, this part tries to find out the industrial correlation characteristics of internal and external carbon emission in manufacturing industry through the analysis of the transmission path of carbon emission in manufacturing industry, so as to provide ideas for formulating carbon emission reduction policies in manufacturing industry.

Figure 3 shows the spillover components of various sectors of the manufacturing industry to the internal and external carbon emissions of the manufacturing industry. Manufacturing self-spillover

refers to the carbon emissions generated by the production of final demand by the manufacturing sector, which requires product inputs from other sectors of the manufacturing industry^[32]. As can be seen from Figure 3, the self-spillover of the manufacturing industry contributed about 1.39 billion tons of carbon emissions, accounting for 37.6% of the carbon emissions caused by the final demand of the manufacturing industry, indicating that the manufacturing sector has a relatively large product demand for other internal sectors in the production process. The spillover from the manufacturing industry to the production and supply industries of electricity, heat, natural gas and water is also as high as 1.24 billion tons, accounting for 33.6% of the total, which is related to the large amount of carbon emissions caused by China's current use of coal for power generation^[42]. Moreover, the spillover of Transportation, storage and post also plays an

important role in the manufacturing industry., because the supply of raw materials and product sales in the

manufacturing industry need the support of Transportation, storage and post^[43].

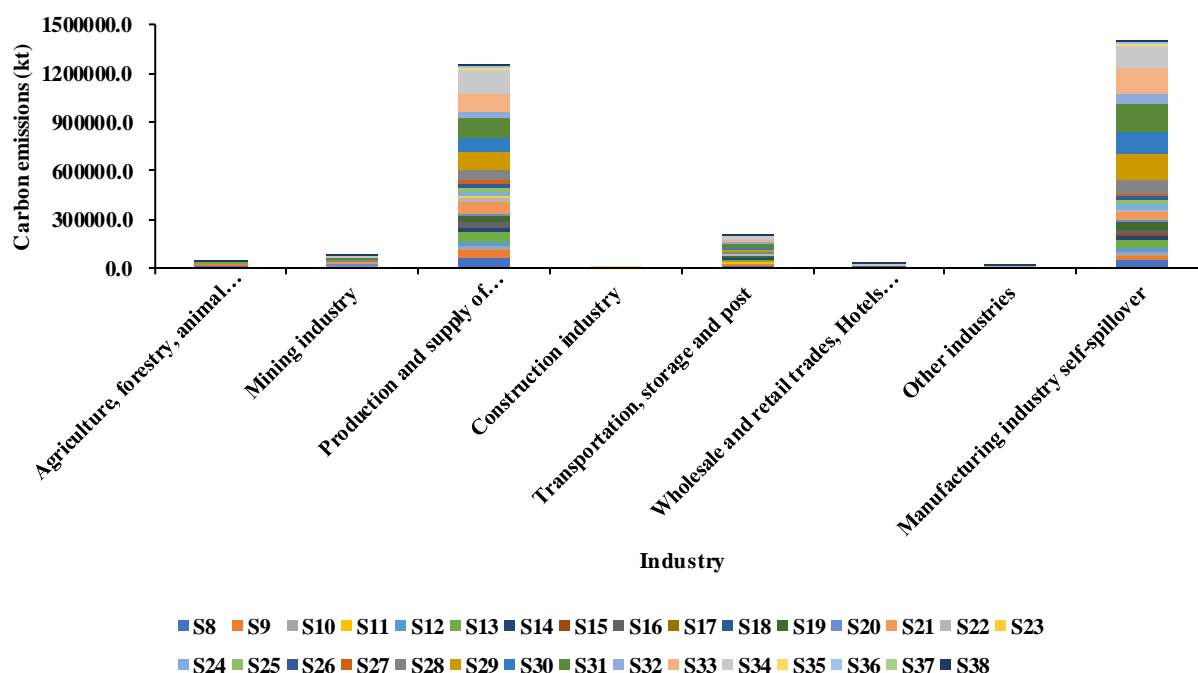


Fig.3: Carbon emission spillover component in manufacturing industry.

From the analysis of specific sectors, in agriculture, forestry, animal husbandry and fishery, Processing of Food from Agricultural Products has the largest spillover, accounting for 44.7% of the carbon emissions provided by agriculture, forestry, animal husbandry and fishery, which is because of the carbon emissions brought by the products of agriculture, forestry, animal husbandry and fishery sector as raw materials. In the same way, the products of mining industry also play the same role in the Processing of Petroleum, Coking and Processing of Nuclear Fuel. Among the Production and supply of electricity, heat, gas and water, the machinery and electronics manufacturing sectors have the largest spillover, followed by the textile and other light industries. The spillover of Manufacture of Raw Chemical Materials and Chemical Products in the resource processing industry is also as high as 69 million tons, accounting for 5.6% of the total contribution of Production and supply of electricity, heat, gas and water. These sectors

have a relatively large carbon emission demand for Production and supply of electricity, heat, gas and water, and may not be low-emission sectors from an intuitive perspective^[44]. When formulating carbon emission reduction policies in such sectors, consideration should be given to improving energy utilization efficiency and optimizing energy structure. All in all, in the internal and external spillovers of the manufacturing industry, the mechanical, electronic manufacturing and light textile industry sectors all account for a relatively large proportion; while the resource processing industry sector has a relatively small proportion except for Manufacture of Raw Chemical Materials and Chemical Products and Manufacture of Rubber and Plastics Products.

Figure 4 shows the transmission path of various energy carbon emissions in the internal and external Spillovers of manufacturing industry. For the spillover from the outside of the manufacturing industry, the coal carbon emissions from the textile and other light

industries, resource processing industry and machinery and electronics manufacturing industries from production and supply industries of electricity, heat, natural gas and water are 310 million tons, 210 million tons and 690 million tons respectively, which are the largest among all carbon emission conduction paths. , which shows that the manufacturing sector, especially the machinery and electronic manufacturing industry, has a relatively large pulling effect on the power industry. Moreover, transportation storage and post contributes a considerable amount of petroleum-derived products to the manufacturing sector, providing support for the supply of manufacturing raw materials, the transfer of semi-finished products, and the sale of products. The self-spillover of manufacturing industry is mainly the transmission of the resource processing industry sector to the other two sectors, with the largest spillover to the machinery and electronic processing

industry, about 900 million tons. The contribution of such sectors to the textile and other light industries, machinery and electronics manufacturing coal carbon emissions is 190 million tons and 580 million tons respectively, and the spillover to their own internal coal carbon emissions is 120 million tons. The contribution of such departments to coke carbon emission of machinery and electronic manufacturing industry is 280 million tons, which is because the raw materials used in machinery and electronic manufacturing industry use products of Smelting and Pressing of Ferrous Metals. Based on the transmission path map of carbon emissions caused by the final demand of manufacturing industry, we can accurately locate the transmission of carbon emissions of a certain energy, so as to provide ideas for formulating policies to optimize the structure of energy carbon emissions, improve technology and adjust product demand.

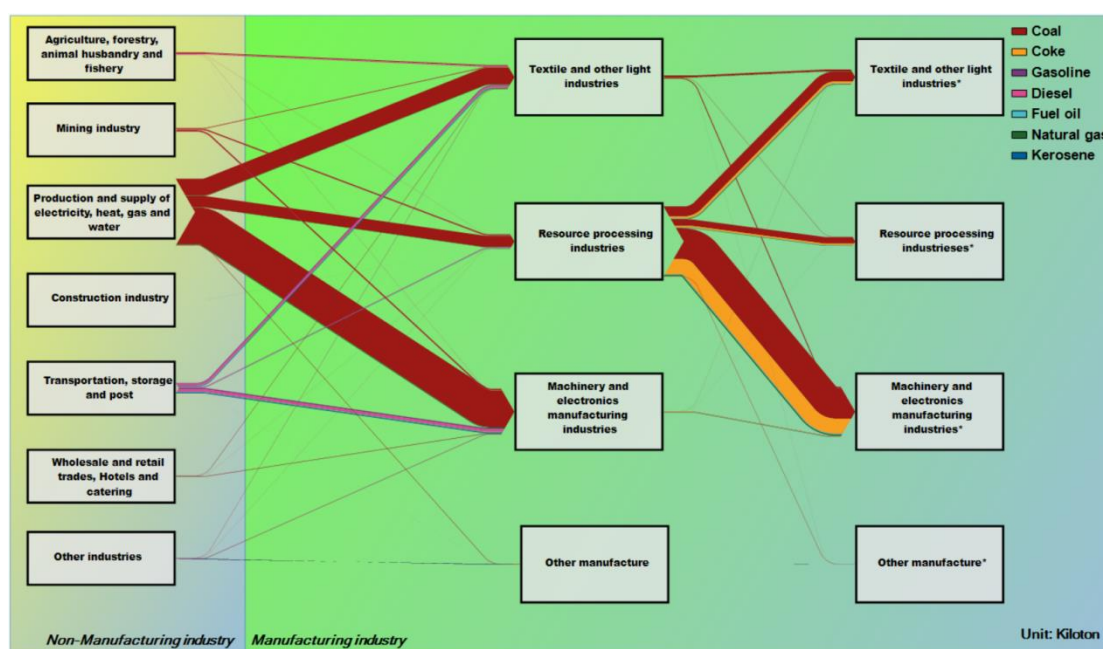
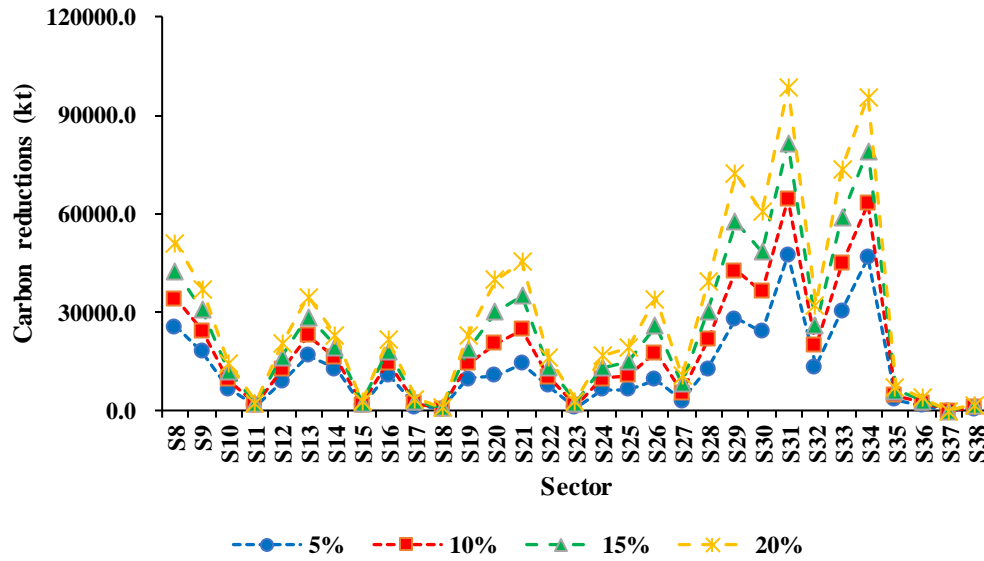


Fig4: Flow map of manufacturing industry carbon emissions.

Note: The left column represents seven industries outside the manufacturing industry, the middle and right columns represent the transmission relationship of internal spillovers in the manufacturing industry, and “*” represents the industries accepted by internal carbon transmission in the manufacturing industry.



.Fig5: Sensitivity analysis of carbon emission reduction in manufacturing industry.

3.4 Sensitivity analysis and scenario prediction

Based on the input-output model, we analyzed the carbon emission behavior and scale of various manufacturing sectors within the framework of production structure, and found three effective implementation ways of carbon emission reduction: Improve energy efficiency by encouraging technological improvements in the manufacturing sector; demand policies that encourage sectors and consumers to reduce or change the demand for carbon inputs; and adjust the energy mix to encourage the use of clean energy. Therefore, we conduct sensitivity analysis on these three factors to quantify the impact of policy implementation on carbon emission reduction in manufacturing industry^[45]. Assuming that energy utilization efficiency, final demand, and total energy consumption are reduced by 5%, the carbon emission reduction potential of each manufacturing sector is analyzed. The sensitivity analysis results are shown in Figure 5. From the impact of the overall change, the three factors have the same carbon reduction effect. From the overall analysis, for every 5% decline in the sensitivity factors, the carbon emissions caused by the final demand of the manufacturing industry will be

reduced by about 190 million tons, accounting for 5.1% of the carbon emissions in 2018, which has a significant reduction effect. From the analysis of specific sectors, policy implementation has different carbon emission reduction potentials for different sectors. The emission reduction effect of Manufacture of General Purpose Machinery, Manufacture of Automobiles and Manufacture of Computers, Communication and Other Electronic Equipment in the machinery and electronic manufacturing industry is obvious, the carbon emission reduction effect of Processing of Petroleum, Coking and Processing of Nuclear Fuel and Manufacture of Raw Chemical Materials and Chemical Products in the resource processing industry is obvious, and the emission reduction effect of Processing of Food from Agricultural Products, Manufacture of Foods and Manufacture of Textile in the textile and other light industries is obvious. Since the 1990s, China's economy has begun to develop rapidly, accompanied by increased dependence on resources and neglect of resource conservation^[46]. Therefore, in order to achieve the strategic objectives of carbon peaking by 2030 and carbon neutralization by 2060, the main problem to be solved in China is how to get rid of the extensive

economic growth model, optimize the investment structure and accelerate technological progress.

Scenario analysis refers to the analysis of scenarios with different tendencies based on the predicted index values, which are generally divided into reference scenarios, positive and negative scenarios of different degrees^[47]. For the forecast of carbon emissions, the positive scenario should be set as a slower growth scenario, and the negative scenario should be set as a faster growth scenario^[48]. In order to find out the policy implementation path to achieve the carbon emission reduction goal of China's manufacturing industry, this study sets up five prediction scenarios of China's manufacturing industry carbon emission before 2060 based on the above decomposition and sensitivity analysis results of manufacturing industry carbon emission, the past evolution trend of various factors, and the effectiveness and potential emission reduction space of existing policy implementation, as shown in Table 2.

The baseline scenario is based on the past development characteristics of manufacturing, assuming that the current economic environment and technological level maintain stable development, no new emission reduction measures are taken, and a possible scenario obtained by predicting the future according to the inertial trend of manufacturing development^[49]. China's "14th Five-Year Plan" proposes that the economy should maintain a medium-to-high speed growth during the "14th Five-Year Plan" period^[50]. Before the formulation of the "14th Five-Year Plan" outline, the National Development and Reform Commission started preliminary research in 2018 and believed that the potential growth rate during the "14th Five-Year Plan" period could be maintained between 5% and 5.5%. Moreover, according to the goal of basically realizing socialist modernization in 2035, China's annual GDP growth rate needs to be

maintained at least 4.7%^[51]. Specific to the manufacturing sector, from 2016 to 2019, the added value of China's manufacturing industry grew by an average annual rate of 8.7%^[52]. According to the data of the *China Industrial Statistical Yearbook* over the years, the proportion of the added value of China's manufacturing industry is basically stable at 27% to 34%^[53]. From the development experience of Germany, South Korea and Japan, three typical industrialized powers in the world, the key process of China's transformation into a manufacturing power should maintain a high proportion of manufacturing added value in GDP, at least more than 25% before 2040^[54]. Therefore, the Baseline Scenario (BL Scenario) believes that the final demand of all sectors of the manufacturing sector will maintain stable growth, and the growth rate can be divided into three stages; the coal-based energy structure is adjusted slowly; the resource utilization efficiency is in a state of moderate natural growth. The setting of the growth rate of the latter two indicators refers to the average annual growth rate of the proportion of non-fossil energy in China's manufacturing industry during the "13th Five-Year Plan" period and the change of the complete consumption coefficient in China's input-output table in 2015, 2017, and 2018^[30, 55].

Made in China 2025 pointed out that the pace of structural adjustment and industrial upgrading of China's manufacturing industry should be accelerated, the proportion of heavy chemical industry and processing trade should be reduced, and the manufacturing industry will gradually upgrade to the high end of the value chain^[56]. From the perspective of investment fields, the development of China's manufacturing industry during the "14th Five-Year Plan" period will focus on equipment and materials manufacturing, aiming at strategic priorities such as new generation information technology, high-end

equipment, new materials, and biomedicine^[57]. During the “13th Five-Year Plan” period, the average growth rate of the added value of high-tech manufacturing industry reached 10.4%, and the proportion of the added value of the above-scale industry has also increased from 11.8% in the early “13th Five-Year Plan” to 15.1%^[58]. Therefore, the DA scenario divides the final demand growth rate of each manufacturing sector into high-tech manufacturing and low-tech manufacturing, and the division is based on the industrial industry classification of the National Bureau of Statistics of China, as shown in Table B3 in Appendix B^[59]. Wang and Wang believes that the medium-speed economic development and the adjustment of the energy structure under the constraints of emission reduction policies are the optimal path to achieve China's “dual carbon” goal^[60]. According to *China energy and power development outlook*, the proportion of non fossil energy in primary energy consumption is expected to reach about 22%, 40%, 69% and 81% in 2025, 2035, 2050 and 2060 respectively, and the total scale of non fossil energy will exceed that of coal before and after 2035^[61]. Therefore, this paper sets up the policy constraint scenario of fossil energy reduction (ED scenario), and appropriately adjusts the energy structure according to the energy planning. The *guiding opinions on promoting the high-quality development of central enterprises and doing a good*

job in carbon peak and carbon neutralization put forward that by 2025, significant progress will be made in the adjustment and optimization of the industrial structure and energy structure of central enterprises, and the energy utilization efficiency of key industries will be greatly improved; By 2030, the energy efficiency of enterprises in key industries will be close to the advanced level of world-class enterprises, and major breakthroughs will be made in green and low-carbon technology; By 2060, the energy efficiency of central enterprises will reach the advanced level of world-class enterprises, making a positive contribution to the country's smooth realization of the goal of carbon neutrality^[62]. Shi and Li set the energy utilization efficiency of high emission industries to increase by 5% and 3% annually from 2021 to 2035 and 2036 to 2060; The policy promotion scenario of an average annual increase of 2% and 1% in other industries^[63]. Based on the above carbon emission accounting, sensitivity analysis results and the production nature of each manufacturing sector, this paper sets the growth rate of energy efficiency for high-emitting sectors and other sectors (EI scenario). Finally, we combine the DA, ED, and EI scenarios to obtain a comprehensive carbon emission reduction policy scenario (CR scenario), and calculated trends in carbon emissions from final demand in manufacturing industry under 5 scenarios.

Table 2: Scenario setting

Scenario	Final demand change (y_j)	Energy structure adjustment (E_k)	Technological innovation (b_{ij})
Base-line scenario (BL scenario)	The final demand in various sectors of the manufacturing sector will maintain steady growth, with an average annual growth rate of 8.7%, 5%, and 3% in before 2025, 2025-2050, and 2051-2060, respectively The growth rate of high-tech manufacturing industry will remain at	The adjustment of energy structure dominated by coal is slow, and the proportion of non fossil energy accounts for an average annual growth of 0.5%	Energy efficiency is in a state of moderate natural growth, with an overall growth rate of about 0.3%
Final demand conducted structural adjustment (DA scenario)	10.4%, 5% and 3% in before 2025, 2025-2050 and 2051-2060 respectively; The growth rate of low-tech manufacturing industry will remain at 5% and 3% in before 2050 and 2051-2060 respectively	Same as the BL scenario	Same as the BL scenario
The use of fossil energy decreased (ED scenario)	Same as the BL scenario	The proportion of non fossil energy in primary energy consumption will reach about 22%, 25%, 40%, 69% and 81% in 2025, 2030, 2035, 2050 and 2060 respectively	Same as the BL scenario
Energy utilization efficiency improved (EI scenario)	Same as the BL scenario	Same as the BL scenario	The energy utilization efficiency of high-emitting sectors (carbon emissions accounting for more than 3%) will increase by 5% and 3% annually before 2035 and 2036-2060 respectively; other sectors will increase by 2% and 1% annually
Comprehensive carbon emission reduction policy (CR scenario)	Same as the DA scenario	Same as the ED scenario	Same as the EI scenario

Figure 6 shows the change trend of carbon emissions caused by the final demand of manufacturing industry in the future until 2060 under five scenarios. BL scenario simulation results show that the carbon emissions caused by final demand of China's manufacturing industry will continue to grow rapidly in the future, and the carbon emissions will reach 18.98 billion tons by 2060, about 5.4 times that of 2018. After considering the development trend of China's manufacturing structure (DA scenario), the growth rate of carbon emissions caused by the final demand of the manufacturing industry will further increase, and the carbon emissions will reach 23.66 billion tons by 2060, about 6.8 times that of 2018. This is because the high-tech manufacturing sector is located in the downstream of the national economic production chain, and the carbon emissions caused by the final demand are far greater than the direct carbon emissions^[64]. With the increase of investment in this sector, its carbon emissions will also increase significantly. The ED scenario shows that the carbon emission of manufacturing industry is developing in an inverted “U” shape, showing a moderate growth trend before 2040, reaching the peak in 2045-2050 and declining slowly after 2045. The EI scenario shows that manufacturing carbon emissions show unstable changes, with a slight decline in emissions before 2025-2030, a moderate growth trend in 2030-2050, and a fluctuating trend in 2050-2060. This shows that only relying on the adjustment of energy structure or the improvement of energy efficiency is not enough to achieve carbon neutrality, and a combination of multiple policy means is needed^[65]. With the continuous improvement of energy efficiency and green technology, and the accelerated transformation of the energy structure, the CR scenario will generally achieve a carbon peak between 2025 and 2030, with a corresponding

peak value between 4.02-4.06 billion tons, followed by a moderate downward trend, and will drop to the level of 2.1 billion tons in 2060, a reduction of 21.56 billion tons compared to the DA scenario, a 40% reduction in carbon emissions compared to 2018. The results show that on the basis of comprehensively considering the development trend of China's manufacturing industry, vigorously improving the energy structure and promoting the transformation and upgrading of energy utilization technology can promote the manufacturing sector to effectively.

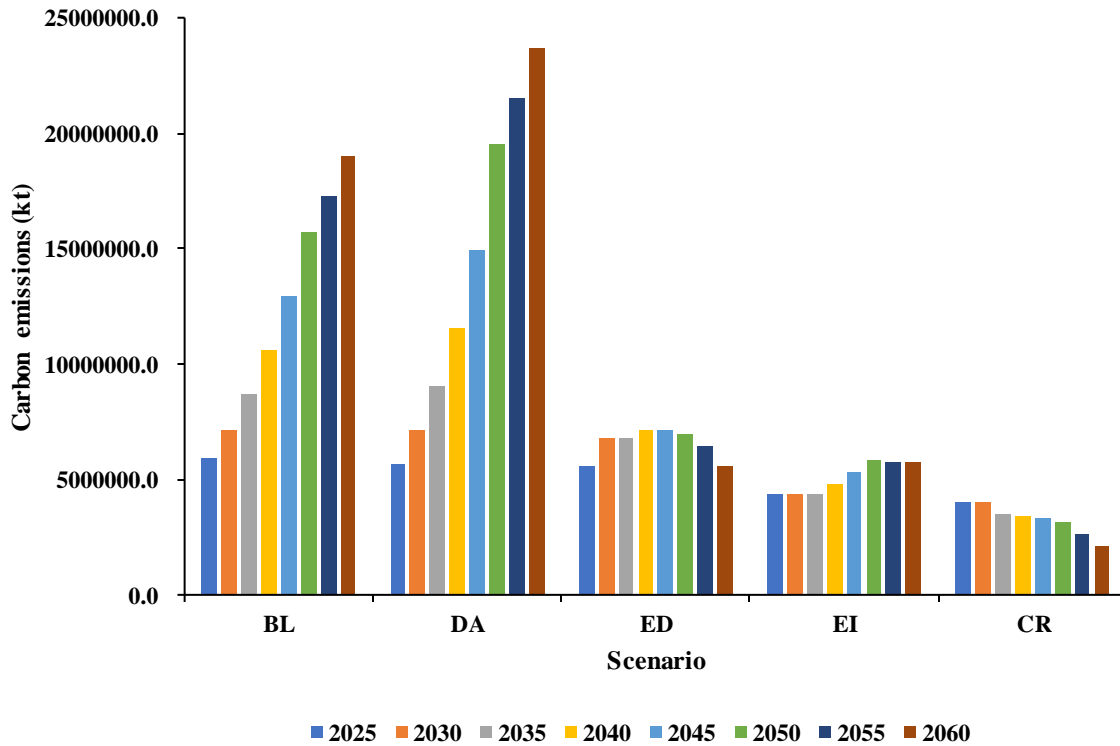


Fig.6: Scenario prediction of carbon emission in manufacturing industry

This paper also forecasts the change trend of carbon emissions caused by the final demand of various sectors of the manufacturing industry from the future to 2060, as shown in Appendix C. Under the BL and Da scenarios, the carbon emissions caused by the final demand of all sectors of the manufacturing industry show a high-speed growth trend. Moreover, the Manufacture of Raw Chemical Materials and Chemical Products in Da scenario has the fastest growth, and its carbon emissions have increased nearly 13 times compared with 2018 by 2060. In the ED scenario, the change of carbon emission of each department is basically consistent with the overall situation. In the EI scenario, the carbon emissions of manufacturing sectors show two trends: the carbon emissions of high emission sectors show a downward trend before 2035,

an upward trend from 2035 to 2050 and a downward trend from 2050 to 2060; The carbon emissions of low emission sectors have always shown a slow upward trend. This is because the policy strength of the EI scenario has a certain effect on high-emission sectors, but has a smaller effect on low-emission sectors, which also shows that it is difficult to achieve emission reduction targets only by relying on a single policy such as energy utilization technology transformation and upgrading. In the CR scenario, the development trend of carbon emissions in various sectors of the manufacturing industry can be divided into three categories: i. carbon emissions are decreasing year by year, with the most obvious downward trend from 2030 to 2035(S8, S9, S13, S20, S26, S28, S29, S30, S31, S32, S33, S34); ii. carbon emissions will maintain rapid

growth before 2050 and reach the peak in 2050-2055(S21, S22, S23); iii. carbon emissions will maintain an increasing trend from 2025 to 2030, show a downward trend from 2030 to 2035, show a slight increase from 2035 to 2040, and reach the peak during 2040-2045(S10, S11, S12, S14, S15, S16, S17, S18, S19, S24, S25, S27, S35, S36, S37, S38). Although on the whole, the CR scenario achieves the carbon peaking target from 2025 to 2030, the carbon peaking time of the manufacturing sector is not consistent, which shows that the realization of carbon emission reduction tasks in various manufacturing sectors requires more targeted policies measure.

4 Discussion

The application of input-output analysis enables us to determine the responsibilities of each department based on the carbon emissions that meet the final needs of the Department^[67]. Indirect pollution can be solved through demand policies, which complement the intervention of direct pollution. Departments that mainly cause carbon emissions through their own production process to meet their own needs can be solved through policies to improve their own technology and production mode. On the contrary, if a sector's responsibility for total emissions mainly comes from emissions from other sectors, it will be effective to encourage the reduction of carbon emissions caused by the final demand of polluting sectors by improving the production technology of input products from other sectors or changing to lower carbon input products. Based on the input-output subsystem method, this paper decomposes the responsibility of each department into six different components, four (Indirect own internal component, Feed-back, Direct own internal component, Scale component) of which represent the emissions generated in the production process of the department, and the other two (Indirect spillover, Direct spillover) show the emissions

generated by the induced activities of the economic department to other departments. These six components enable us to understand in more detail whether the focus of carbon emission reduction should be on the inputs provided by the sector itself, other sectors of the economy or for final consumption. The design of different policies requires in-depth analysis of the departments taking action^[68]. The decomposition of this paper provides a useful tool for studying the relationship between each department and other departments and the production structure. Spillover analysis shows that more than half of carbon emissions are caused by intermediate inputs from different sectors. The further analysis of spillover can accurately locate the carbon emission transmission path of a certain energy, so as to formulate reasonable policies to solve the problem of carbon emission under different circumstances^[32].

The analysis of the manufacturing sector shows that among the direct carbon emissions of various sectors, the Processing of Petroleum, Coking and Processing of Nuclear Fuel and the Smelting and Pressing of Ferrous Metals have the largest carbon emissions, accounting for more than half of the carbon emissions of the whole manufacturing industry, while the carbon emissions of mechanical and electronic manufacturing sectors are very small, accounting for less than 3%. However, among the carbon emissions caused by the final demand of various sectors, the carbon emissions of the Processing of Petroleum, Coking and Processing of Nuclear Fuel and the Smelting and Pressing of Ferrous Metals decreased significantly, accounting for 10%, while the carbon emissions of machinery and electronic manufacturing sectors were large, accounting for more than 50%. Under the current energy consumption situation, blindly advocating the development of high-tech industries with low direct consumption of fossil energy

does not seem to solve the problem of large carbon emissions in manufacturing, or even increase carbon emissions^[69]. Moreover, this study also noted that sectors such as the Manufacture of Raw Chemical Materials and Chemical Products, regardless of direct carbon emissions or carbon emissions caused by final demand, contribute a considerable proportion to the carbon emissions of the national economic production chain. Therefore, a relatively coordinated development mechanism should be adopted according to the carbon emissions of different sectors of the manufacturing industry. For departments with large direct carbon emissions and small carbon emissions of spillover components, the use of fossil energy such as coal should be reduced, and the manufacturing technology within the Department should be improved through tax and other policies to reduce the use of fossil energy per unit output value^[70]. At the same time, carbon capture, carbon sequestration and other technologies to reduce or control carbon emissions should be introduced^[71]. For departments with small direct carbon emissions and large spillover carbon emissions, first of all, through technological innovation, we should reduce the consumption of electricity, heat and raw materials within the Department, improve the utilization efficiency of resources and energy, and improve the energy consumption structure of power generation; Secondly, the government should formulate policies that can form manufacturing industry clusters sharing supporting services, so as to reduce the driving effect of manufacturing sector on carbon emission of transportation industry^[72, 73]. For sectors with large direct carbon emissions and carbon emissions of spillover components, we should improve the energy structure, minimize the use of coal and improve their own resource and energy utilization efficiency^[37].

5 Conclusions

This study uses the input-output model to compare

the direct carbon emissions of the manufacturing sector with the carbon emissions caused by the final demand, and decomposes the carbon emissions caused by the final demand of the manufacturing sector. The results show that the direct carbon emissions of manufacturing industry account for 45.9% of the total emissions, while the proportion of carbon emissions caused by final demand is 34.8%. Based on this result, we should pay attention to the correlation effect between departments, which can be solved through demand policy. The manufacturing industry has a strong dependence on coal, and the proportion of coal carbon emissions in direct emissions has increased from 66.4% to 74.8% of final demand emissions. Therefore, we should adjust the energy structure and promote energy substitution to reduce carbon emissions. The spillover component of carbon emissions caused by final demand in the manufacturing industry is the largest, accounting for 85.2% of the total emissions. Further research shows that the main spillover objects of the manufacturing sector are the energy industry and transportation industry. Among them, the mechanical and electronic manufacturing sector has the largest spillover to the energy industry and transportation industry, mainly showing its demand for electricity and driving effect on the carbon emission of transportation industry. Therefore, the coal-fired power generation industry should actively transform, steadily promote the development of clean energy, and accelerate the construction of a new power system suitable for the development of a high proportion of renewable energy. Moreover, the construction of industrial parks should be actively planned to form industrial clusters sharing supporting transportation industry, so as to reduce the driving effect of manufacturing sector on carbon emission of transportation industry.

In addition, we also conducted sensitivity analysis on the driving factors of manufacturing carbon

emissions, and implemented the scenario prediction of China's manufacturing carbon emissions before 2060. Sensitivity analysis found that encouraging technological progress in the manufacturing industry, encouraging sectors and consumers to reduce or change carbon input demand, and adjusting the energy structure all have significant emission reduction effects, indicating that China urgently needs to get rid of the extensive economic growth model, optimize the investment structure, and accelerate the skill improved. The scenario prediction results show that only relying on the adjustment of energy structure or the improvement of energy efficiency is not enough to achieve the carbon emission reduction target, which requires the combination of a variety of policy means. At the same time, the prediction results of CR scenario also show that more targeted policies and measures are needed for all sectors of the manufacturing industry to achieve the task of carbon emission reduction. From the perspective of manufacturing sector, for the sector with large direct carbon emissions and small spillover component carbon emissions, emission reduction policies can be implemented from the aspects of energy structure, carbon emission intensity and energy utilization efficiency of the production process of the sector. For sectors with small direct carbon emissions and large spillover component carbon emissions, which are mainly reflected in the emission demand for other sectors, Attention should be paid to the carbon emissions of the energy industry, the industry used as raw materials by the sector and the transportation industry. For sectors with large direct carbon emissions and carbon emissions of spillover components, the energy structure, energy efficiency and utilization of raw materials should be improved. Moreover, on the basis of implementing emission reduction policies for various sectors of the manufacturing industry, it is necessary to develop high-tech industries that are in

harmony with the load of the energy industry.

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信息基础设施如何影响城市温室气体排放绩效？

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摘要：由于其网络溢出效应，信息基础设施在促进经济增长和技术创新方面表现突出，受到广泛关注。然而，信息基础设施的生态绩效，特别是其对温室气体排放绩效的影响研究较少。为了研究这一问题，我们利用 2003 年至 2018 年中国 281 个地级市的面板数据，将“宽带中国”政策作为信息基础设施的准自然实验，并进行了时变双重差分分析（DID）。结果表明：（1）信息基础设施显著改善了城市温室气体排放绩效；这一结论在排除了试点选择的内生性、抽样偏差和其他政策干扰之后仍然成立。（2）技术创新、产业结构升级、要素配置优化和第三次集聚是信息基础设施提升温室气体排放绩效的有效渠道。（3）城市规模、数字经济水平、经济地位不同，治理效果也不同。具体而言，在规模较大、数字经济发达、经济地位领先的城市，信息基础设施的减排效果显著，而在其他城市，这一效果有所下降。本研究为中国和其他发展中国家的基础设施向碳中和方式转型提供了洞见。

关键词：信息基础设施；温室气体排放绩效；宽带中国；双重差分法；传导机制

Information infrastructure and greenhouse gas emission performance in urban China: A time-varying difference-in-differences analysis

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Abstract: Owing to its network spillover effect, information infrastructure performs outstandingly in promoting economic growth and technological innovation, and has received widespread attention. However, the ecological performance of information infrastructure, especially its impact on greenhouse gas (GHG) emission performance, has been studied less. To investigate this issue, using panel data for 281 prefecture-level cities in China from 2003 to 2018, we treat the Broadband China policy as a quasi-natural experiment in information infrastructure and conduct a time-varying difference-in-differences (DID) analysis. The results show that: (1) Information infrastructure significantly improves urban GHG emission performance. This conclusion holds even after excluding pilot selection endogeneity, sampling bias, and other policy interferences. (2) Technological innovation, industrial structural upgrading, factor allocation improvement, and tertiary agglomeration are effective channels by which information infrastructure improves GHG emission performance. (3) The treatment effect varies by city size, digital economy level, and economic status. Specifically, information infrastructure exhibits significant emission reduction performance in cities with large size, advanced digital economy, and leading economic status, while this effect drops in other cities. This study provides insights into the infrastructure transition to a carbon-neutral manner in China and other developing countries.

Keywords: Information infrastructure; Greenhouse gas emission performance; Broadband China policy; Difference-in-Differences; Transmission mechanism

Acronyms

GHG	Greenhouse gas
BCP	Broadband China policy
DID	Difference-in-differences
GEP	Greenhouse gas emission performance
GEE	Greenhouse gas emission efficiency
CI	Carbon dioxide emission intensity
MI	Methane emission intensity
NI	Nitrous oxide emission intensity
GCE-DEA	Game-cross efficiency data envelopment analysis
TI	Technological innovation
IU	Industrial structure upgrading
LM	Labor misallocation
CM	Capital misallocation
TA	Tertiary agglomeration
ED	Economic development
FD	Financial development
PD	Population density
OP	Openness
TS	Transportation infrastructure
ES	Employment structure
GDP	Gross domestic product

1. Introduction

Since the Industrial Revolution, the massive emission of greenhouse gases (GHGs) has led to global warming and climate change, which pose a severe challenge to humanity (Spracklen, 2016; Evans et al., 2021). China, as the largest developing country, has experienced rapid industrialization and urbanization, with substantial economic growth and significant improvement in people's living standards (Song et al., 2011; Ebenstein et al., 2015). However, along with it, China contributes the most GHG emissions in the world, surpassing the EU and the United States combined (Chang et al., 2021). To address the climate challenge, the Chinese government proposed to achieve carbon neutrality, that is, net-zero GHG emissions, by 2060. Undoubtedly, reducing GHG emissions is crucial for sustainable development

(Zhang et al., 2021). Also, in developing countries like China, governments have to continuously promote economic growth. In other words, balancing GHG emission reduction targets with economic growth is particularly important. Therefore, how to improve GHG emission performance, that is, the environmentally sensitive productivity considering GHG emissions as an undesirable output, has become essential on the path toward carbon neutrality (Xu et al., 2021).

According to the Emissions Database for Global Atmospheric Research (EDGAR) and *Energy Technology Perspectives 2020*¹³, about 75% of global GHG emissions originate from urban areas, and infrastructure accounts for more than 40%. Although traditional infrastructure such as roads, energy, and buildings perform well in economic benefits (Collier and Venables, 2016), they have locked in high carbon- and resource-intensive for decades, which poses challenges to urban sustainability (Ramaswami et al., 2016; Sun and Cui, 2018). With the increasing pursuit of ecologicalization, many economies have set out to reshape infrastructure. Following this trend, the Chinese government put forward the “new infrastructure” plan, which mainly includes three aspects: information infrastructure, convergence infrastructure, and innovation infrastructure. As the foundational and important component of the new infrastructure, information infrastructure construction has been elevated to the national strategic level. Since 2014, China's Ministry of Industry and Information Technology (MIIT) released the Broadband China policy (BCP) and successively approved three batches of pilot cities to promote information infrastructure construction (Fig. 1). Information infrastructure greatly increases the speed of knowledge dissemination, generating spillover effect that

2020.

¹³ <https://edgar.jrc.ec.europa.eu/>,
[https://www.iea.org/reports/energy-technology-perspectives-](https://www.iea.org/reports/energy-technology-perspectives-2020)

promotes green technology innovations of energy-savings and carbon mitigation (Zeng et al., 2019; Tang et al., 2021). In the exchange process, the distance between suppliers and demanders is shortened, and the barrier of information asymmetry is lowered, which helps the production factors be allocated efficiently and reduces resource waste (Oliver, 2019). In addition, information infrastructure facilitates emerging technologies, such as the Internet, cloud computing, and the Internet of Things, which promote urban informatization and modernization. This gives rise to a highly integrated, intelligent, and collaborative network that optimizes environmental management capabilities (Shi et al., 2018). Predictably, information infrastructure improves connectivity and integration, providing an opportunity for cities' economic transformation, industrial upgrading, and green development. This inspires an urgent question: can information infrastructure construction, as marked by the BCP, improve urban GHG emission performance? Exploring this issue can expand novel ideas for urban infrastructure transition, as well as enrich the perspective for solving the dilemma of GHG emission reduction and economic growth, which is of great significance for achieving carbon neutrality.

Infrastructure belongs to public goods and has certain externalities. In the existing literature, the nexus between traditional infrastructure and GHGs, especially carbon dioxide (CO₂), has received extensive attention. Xie et al. (2017) found that the population agglomeration effect of transportation infrastructure reduces CO₂ emissions, while its growth effect and innovation effect boost CO₂ emissions. In general, transportation infrastructure has a promoting impact on CO₂ emission intensity, and this promotion is more pronounced in large cities. The same view was supported by Churchill et al. (2021), who posited that economic growth is a channel for transportation

infrastructure to enhance CO₂ emissions. In terms of energy infrastructure, Yuan et al. (2018) found that non-fossil power investment fails, and it significantly increases CO₂ emissions. Moreover, owing to the transmittable characteristics of electricity, there is a spatial shift where CO₂ emissions will be outsourced from developed to developing regions. The main reason for this is that non-fossil energy has the structural disadvantage of high material and technology costs, and the expected ecological performance is hard to deliver in the short term (Apergis et al., 2010; Dong et al., 2022a). In contrast, natural gas infrastructure optimizes the energy consumption structure of the residential and industrial sectors, and this substitution effect reduces CO₂ emission intensity (Wu et al., 2019; Dong et al., 2020).

With the increasingly prominent structural contradictions of traditional infrastructure, new infrastructure, such as high-speed rail, 5G, and energy Internet, has attracted researchers' attention (Guo et al., 2020; He et al., 2020; Jia et al., 2021). Preliminary empirical studies have been done on information infrastructure, especially its economic performance. At the macro level, Czernich et al. (2011) validated a positive nexus between broadband penetration and economic growth, with human capital and sound organizational structure enhancing the role of information infrastructure. Liu and Ma (2020) found that traditional infrastructure complement information infrastructure, and they work together to improve urban total factor productivity. At the micro level, Xue et al. (2020) found that information infrastructure

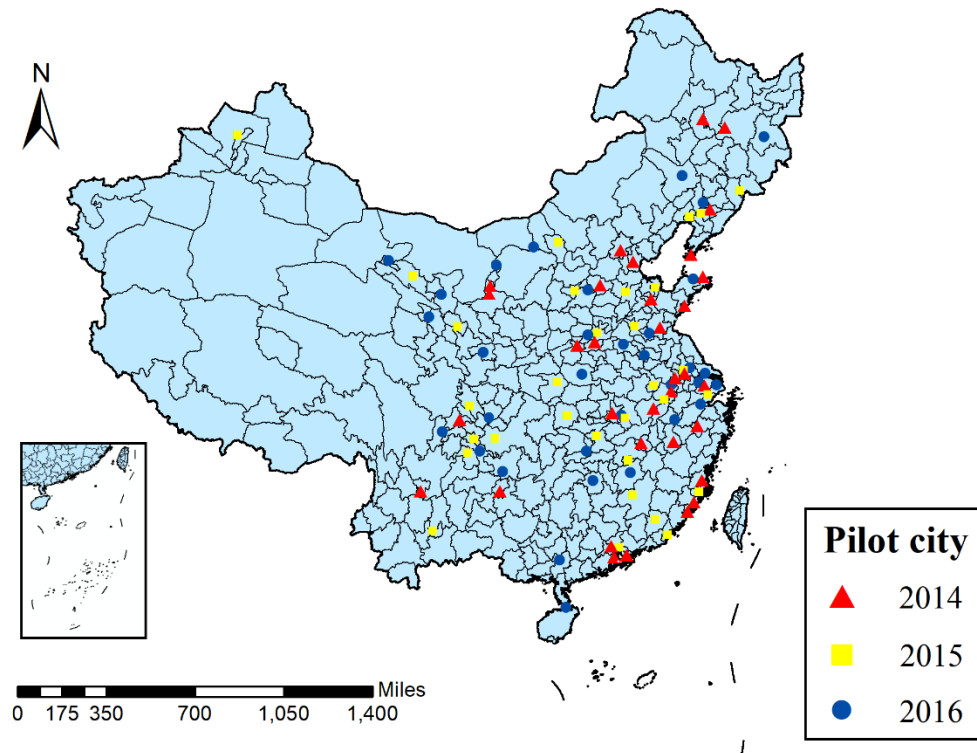


Fig. 1. Broadband China pilot cities

facilitates knowledge exchange and promotes joint innovation among firms. Moreover, there are network effects. In areas with higher broadband penetration, information infrastructure is more conducive to technology diffusion. Still, only a few literatures have explored the ecological performance of information infrastructure. Using provincial panel data, Wu et al. (2021a) implied that information infrastructure not only improves local CO₂ emission efficiency, but also has a positive spillover effect on neighboring areas. Taking China's listed companies as a sample, Tang et al. (2021) revealed that information infrastructure promotes green technology innovation by improving governance structures.

To sum up, sufficient studies have been conducted on the performance of infrastructure, which give us some insights. Three statuses can be found in the existing literature. First, the impact of traditional infrastructure on GHG emissions has been extensively investigated. However, regarding information infrastructure, most studies have focused on its

economic impact, whereas research on its ecological performance has just begun. Second, in terms of the research object, CO₂ has dominated, whereas other non-carbon GHGs have not received enough attention. According to the Paris Agreement, non-carbon GHGs are essential parts of the long-term low-emission development strategy. Therefore, besides CO₂, the emission performance of other GHGs deserves in-depth study. Third, in terms of research methodology, a good empirical strategy is lacking. Although some literature notes the endogeneity of reverse causality and confounders, measuring information infrastructure with proxy variables may lead to biased estimators.

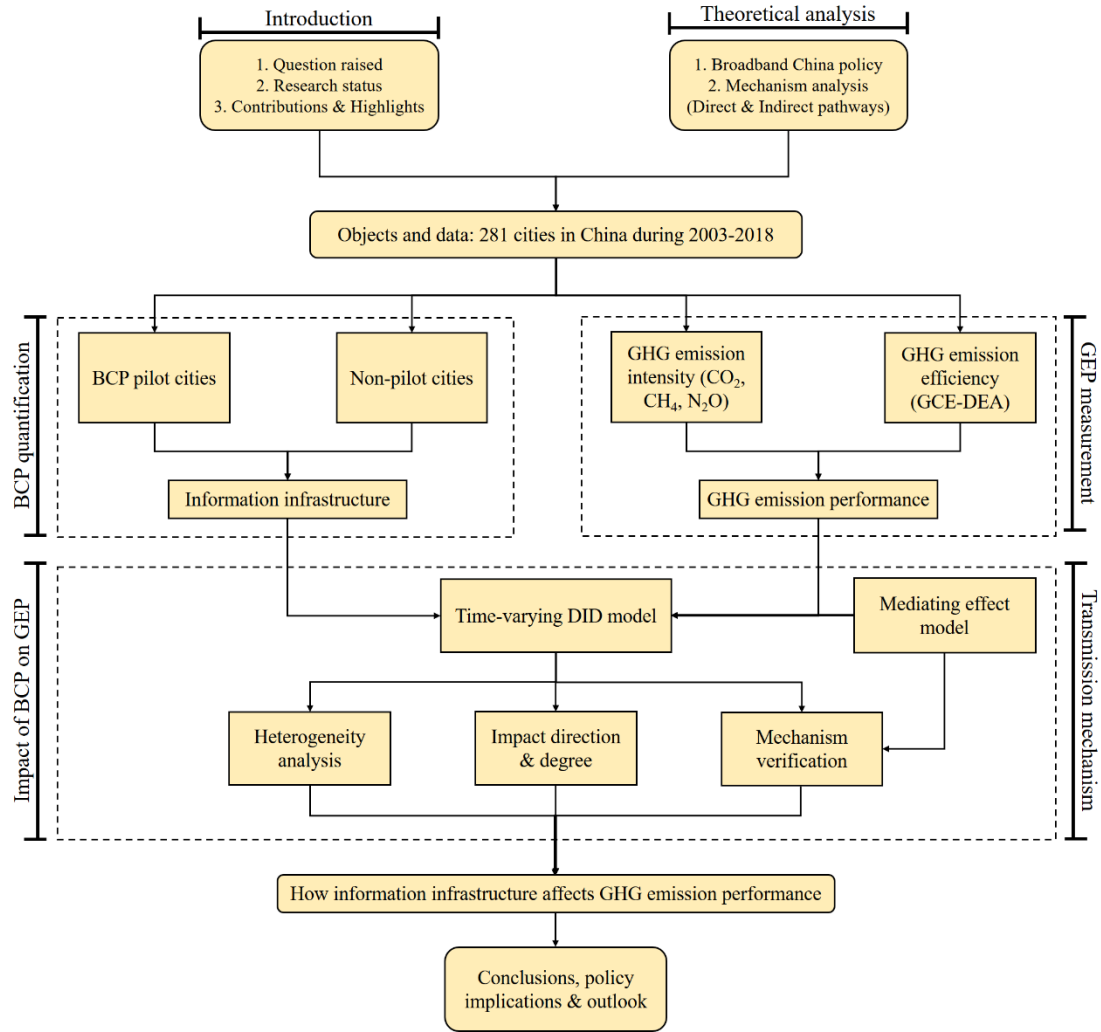


Fig. 2. Research framework.

To fill these gaps, this study proceeds from the following three questions that previous literature fails to answer. First, can information infrastructure improve urban GHG emission performance? Although its core intention is not energy conservation and emission reduction, information infrastructure construction promotes the diffusion of information technology and provides opportunities for economic transformation and the industrial revolution (Wu et al., 2021b). To this end, using a panel data set covering 281 cities in China from 2003 to 2018, we treat the BCP as a quasi-natural experiment for information infrastructure construction and evaluate its impact on urban GHG emission performance. Second, what are the transmission mechanisms by which information infrastructure affects GHG emission performance?

Existing studies have shown that information infrastructure promotes innovation in technology, management, and organization (Paunov and Rollo, 2016; Xue et al., 2020; Ren et al., 2021). Therefore, inspired by Grossman and Krueger (1991, 1995), we investigate the involving mechanisms from a perspective of broad innovation. Third, is there any heterogeneity in the impact of information infrastructure on GHG emission performance across cities? For example, information infrastructure has network effects, so its role may vary by city size (Han and Zhu, 2014). Moreover, construction is just the first step; the marginal contribution of information infrastructure to GHG emission performance depends on its application. Therefore, an in-depth heterogeneity analysis of the treatment effect under different

socioeconomic circumstances is worthwhile.

We see our contribution to the growing literature on information infrastructure fourfold. First, by matching EDGAR grid data to the prefecture-city level, we focus on urban non-carbon GHG emissions. Furthermore, game cross-efficiency data envelopment analysis (GCE-DEA) is used to measure urban GHG emission efficiency in China, and the results are objective and accurate. Second, based on the exogenous event of the BCP, we perform a causal inference on whether information infrastructure improves urban GHG emission performance, which provides rigorous empirical evidence. Third, from four aspects of the technology effect, structure effect, allocation effect, and agglomeration effect, we sort out the transmission mechanism of information infrastructure affecting GHG emission performance, and construct a mediating effect model to identify it, which has certain theoretical contributions. Fourth, a heterogeneity analysis is conducted in terms of city size, digitalization level, and economic status, enriching the research perspective.

The remainder of this paper is organized as follows. Section 2 details the policy background and theoretical analysis. Section 3 describes the research design and data collected. Section 4 provides the empirical results and robustness test. Section 5 is mechanism test. A heterogeneity analysis is conducted in Section 6, and conclusion and policy recommendations are summarized in Section 7. Figure 2 depicts the research framework of this study.

2. Policy background and theoretical analysis

2.1. Broadband China policy

Undoubtedly, the emergence and development of electronic computers have changed the world. If computers are compared to discrete dots, connecting them to achieve informatization requires the superhighway of information infrastructure (Ketinger,

1994). To beat the information technology competition and narrow the digital divide, an information infrastructure planning and construction boom has been launched worldwide since the 1990s. In 1993, the United States implemented the National Information Infrastructure: Action Plan, officially announcing the arrival of the information era. Subsequently, the European Union was touched and proposed an agreement to build a European information superhighway in Economic Growth, Competition, and Employment. In response, many emerging economies, such as South Korea and Singapore, joined them and formulated information infrastructure construction plans.

Following this boom, the Chinese government launched the construction of a national public Internet in 1994. After years of development, although information infrastructure has made progress, prominent shortcomings still remain, such as low coverage, slow rate, and regional imbalances. According to MIIT, as of 2013, China's Internet penetration was only 21%, which is less than one-half of OECD countries, and the average broadband rate was only 857 kbps, which is less than one-tenth of OECD countries. To improve this situation, the State Council of China released the BCP in 2013. Three batches of cities were selected as pilots in 2014, 2015, and 2016, and information infrastructure construction was elevated to a national strategy. In the pilot cities, information infrastructure is vigorously built to boost the broadband rate, improve Internet penetration, and promote digital economy development. In 2020, the China Development and Reform Commission specified seven major areas of new infrastructure: 5G, big data centers, artificial intelligence, industrial Internet, UHV, charging piles for new energy vehicles, and intercity high-speed rail/rail transportation. All of these are closely related to information technology. As

the supporting pillar of the new infrastructure, the strategic significance of information infrastructure is becoming increasingly prominent. It is foreseeable that the BCP will drive structural change and economic transformation, creating great for GHG emissions reduction and carbon neutrality.

2.2. Theoretical hypotheses

2.2.1. Direct impact of information infrastructure on GHG emission performance

Information infrastructure digitizes the economy and improves connectivity (Zhao et al., 2020). On the production side, it narrows the distance between suppliers and demanders, enabling the precise management of firms according to their customers' needs (Khuntia et al., 2018). This promotes the realization of customized production and the satisfaction of personalized appeals, which avoid resource waste caused by ineffective inventory and overproduction and reduce GHG emissions. On the consumption side, as the information infrastructure improves, information acquisition channel is broadened and information processing capacity is enhanced, which effectively alleviates information asymmetry and promotes economic cycle (Wu et al., 2021b). On the distribution side, a well-developed information infrastructure guarantees the efficient operation of the logistics system, which reduces the transshipment of goods and speeds up the circulation of the supply chain, ultimately improving GHG emission performance. In addition, for the governance side, information is also valuable (Barwick et al., 2019). On the one hand, information infrastructure helps regulators to monitor production activities dynamically and instantaneously, thereby regulating high-pollution

and high-emission behaviors in time (Zhang et al., 2019; Yang et al., 2021). On the other hand, the channels for public participation in environmental governance are broadened, and the role of indirect environmental regulation are fully exploited, which in turn stimulates green production behaviors and improves GHG emission performance (Dong et al., 2021a). Based on the above analysis, we propose:

Hypothesis 1: Information infrastructure has a positive impact on urban GHG emission performance.

2.2.2. Indirect impact of information infrastructure on GHG emission performance

In addition to direct impact, innovation is an effective channel through which information infrastructure affects GHG emission performance, as shown in Fig. 3. Inspired by Grossman and Krueger (1991, 1995), we attempt to investigate the indirect mechanism from the following perspectives driven by innovation: technology effect, structure effect, agglomeration effect and allocation effect¹⁴.

Technological innovation is a crucial factor in improving GHG emission performance (Zhu et al., 2021; Cheng et al., 2021). Both the generation of new technologies and the dissemination of existing technologies depend on information transmission efficiency, i.e., the usefulness of knowledge (Hayek, 1945; Romer, 1986). Therefore, connectivity is the source of technological innovation and social development. Information infrastructure breaks the barriers of time and space, greatly accelerates the dissemination of information, and improves innovation efficiency (Liu and Ma, 2020). Relying on information infrastructure, knowledge exchange and technological innovation activities can be accomplished without

¹⁴ Grossman and Krueger (1991, 1995) decomposed the environmental impact into technology effect, structure effect, and scale effect. In a broad sense, they are all "creative destruction" of the original state, i.e., innovation (Schumpeter, 1942). In this study, technological innovation and industrial structure are used to measure technology effect and structure effect. The scale effect is defined as the environmental

externality caused by the expansion of economic activities, and it only induces emissions when changing the type of economic activity. To align this concept with information infrastructure construction, we interpret the part that does not change the type of economic activity as agglomeration effect, and the remaining is interpreted as allocation effect.

geographic displacement of physical elements. This spawns emerging technologies, such as instant messaging, video conferencing, and telecommuting, which profoundly change people's production and lifestyles (Xue et al., 2021). Accordingly, transaction costs are decreased, resource waste is reduced, and production efficiency is improved, which facilitates energy conservation and environmental protection innovations that benefit GHG emission performance (Tang et al., 2021; Dong et al., 2021b). In summary, we propose:

Hypothesis 2: Information infrastructure improves GHG emission performance through technological innovation.

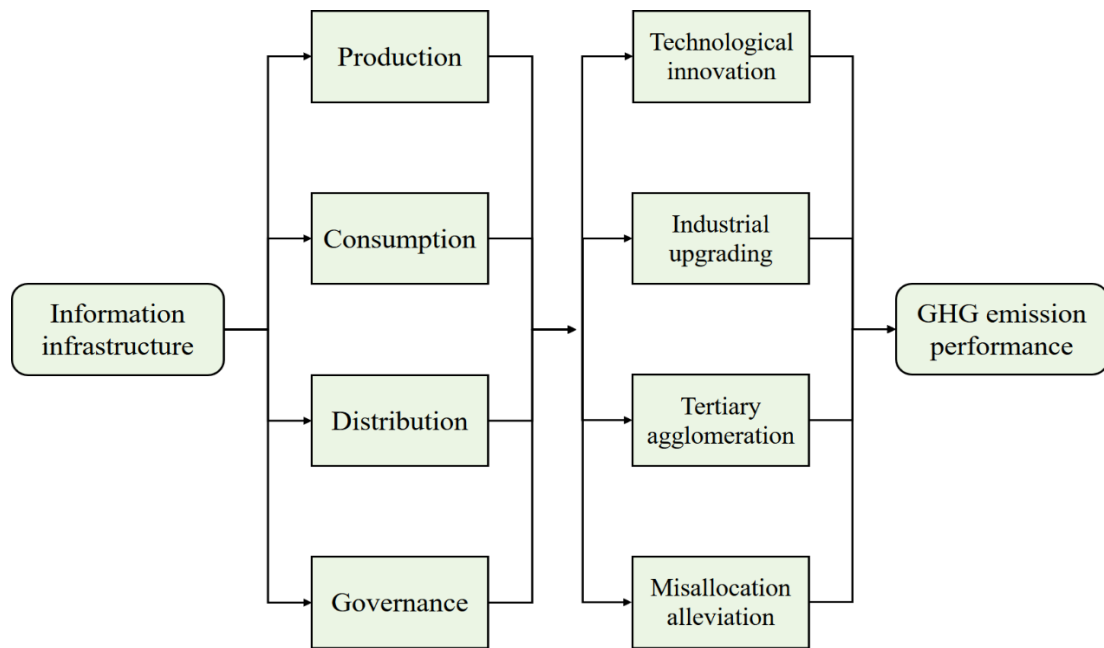


Fig. 3. Transmission mechanisms of information infrastructure affecting GHG emission performance

Information infrastructure construction increases the application of digital technology in the production process, speeds up the product renewal cycle, and drives industrial structure upgrading (Wu et al., 2021b). With the improvement of information infrastructure, the traditional industries are transformed in three paths. First, information infrastructure lowers inter-industry barriers, facilitates the convergence of information industry with traditional manufacturing, forming new

products and formats to optimize the factor structure (Dong et al., 2021c). Second, it drives the embedding of information elements into the manufacturing process. This reduces the dependence on natural resources, improves the specialization and economicization of the division of labor, and promotes industrial structure upgrading (Dong et al., 2021b; Ren et al., 2021). Third, as information asymmetry declines, resources spontaneously flow to emerging industries with high added value, high technology bias, and low energy consumption (Shi et al., 2018; Xu et al., 2021). As a result, the share of emission-intensive industries falls, and GHG emission performance boosts, achieving a win-win situation for economic and

ecological benefits. Based on the above analysis, we propose:

Hypothesis 3: Industrial structure upgrading is a mediating channel for information infrastructure to improve urban GHG emission performance.

Agglomeration is the endogenous feature of a city (Henderson et al., 2019). Industrial agglomeration exhibits positive externalities through the effects of knowledge spillover, talent pools, and economies of

scale, and its contribution in energy-saving and emission-reduction has been verified by many studies (e.g., Yu et al., 2020; Li et al., 2021). For the tertiary industry mainly characterized by servitization, information is an important resource, just like energy and capital. The improvement of information infrastructure benefits producer services such as technology consulting, software R&D, and modern logistics, attracting service enterprises to move in (Shi et al., 2018). Driven by the network effect, human capital and high-tech elements further accumulate, forming a positive feedback loop to improve urban GHG emission performance (Baker et al., 2020). Moreover, information infrastructure improves operational efficiency and management level, which reduces congestion costs under the same agglomeration and enhances urban spatial carrying capacity. This leads to higher optimal economic density and further releases the emission mitigation performance of economic agglomeration (Shao et al., 2019). Based on the above analysis, we propose:

Hypothesis 4: Information infrastructure promotes tertiary agglomeration, thereby improving urban GHG emission performance.

In China, many local governments tend to protect industries with backward productivity, heavy pollution, and high resource dependence to fulfill the tasks of economic growth and employment stability. This distorts factor markets, causes widespread resource misallocation, and reduces GHG emission performance (Hsieh and Klenow, 2009; Lin and Du, 2013; Bai and Bian, 2016; Wu et al., 2021b). Information infrastructure improves resource allocation efficiency through the following three ways. First, information infrastructure construction facilitates information technology development and speeds up factor flow, so that labor, capital, and technology can be reorganized across regions instantaneously (Wu et

al., 2021a; Tang et al., 2021). Second, it lowers information asymmetry, which helps enterprises monitor market demand dynamically (Vithayathil, 2018). Accordingly, enterprises can adjust the production structure and organization mode to schedule production factors flexibly and alleviate resource misallocation (Shi et al., 2018). Third, relying on information infrastructure, new formats, such as big data, cloud computing, and smart city, provide more channels for factor mobility, reshape the allocation form, and alleviate market distortions (Liu and Ma, 2020; Dong et al., 2022b). To sum up, we propose:

Hypothesis 5: Information infrastructure improves urban GHG emission performance by alleviating factor misallocation.

3. Methodology and data

3.1. Research sample

Since 2014, the MIIT of China has set up 120 BCP pilots in three batches. This exogenous shock provides us with an excellent opportunity for causal inference to identify the impact of information infrastructure on GHG emission performance. In this study, 281 prefecture-level cities in China during 2003-2018 are chosen as the research sample, which covers almost the whole nation and effectively reduces sampling bias. Among them, 103 pilot cities are selected as the treatment group (33 in the first batch, 36 second, and 34 third, see Fig. 1), and the remaining 178 cities as the control group. Table 1 shows some characteristics of the treatment and control groups. It can be seen that economic status and population size are important factors affecting the establishment of the BCP pilot.

Table 1

Characteristics of cities in the control group and control group by the BCP roll-out.

	Batch 1	Treatment Batch 2	Batch 3	Control
Number of cities	33	36	34	178
Population (10 ⁴ people)	575.68 (329.94)	454.99 (525.66)	470.35 (316.32)	402.95 (223.98)
GDP per capita (10 ⁴ yuan)	3.90 (2.32)	2.84 (2.34)	2.49 (1.90)	1.83 (1.20)
Urban area (km ²)	2908.23 (3128.30)	2760.64 (5071.94)	2201.93 (2480.91)	2450.25 (7113.26)
CO ₂ emissions (10 ⁴ ton)	4575.66 (6949.23)	3009.13 (3580.35)	3007.86 (2257.68)	2667.92 (3184.58)
CH ₄ emissions (10 ⁴ ton)	23.90 (24.33)	15.46 (15.20)	21.19 (18.99)	19.83 (22.55)
N ₂ O emissions (ton)	2953.03 (2803.83)	2821.62 (4312.83)	2685.37 (1862.34)	2491.06 (1634.86)
Relief amplitude (m)	0.49 (0.62)	0.75 (0.81)	0.77 (0.97)	0.85 (0.89)
Digital inclusive financial index	175.39 (63.85)	159.39 (61.35)	157.21 (62.83)	150.99 (60.88)

Notes: All characteristics are measured by the 2003-2018 average, except for digital inclusive financial index (2011-2018 average). Standard deviations are in parentheses.

3.2. Econometric strategy

3.2.1. Time-varying DID

Given that the BCP is implemented in batches, a time-varying difference-in-differences (DID) model is established to investigate the impact of information infrastructure on GHG emission performance:

$$GEP_{it} = \alpha_0 + \alpha_1 D_{it} + \alpha X_{it} + \varepsilon_{it} \quad (1)$$

where i denotes city and t denotes year. GEP_{it} is GHG emission performance. The dummy variable D_{it} represents the BCP, a proxy variable for information infrastructure. X_{it} is a vector of control variables, and ε_{it} is the random disturbance term. In empirical analysis, city fixed effect (FE), year FE, and province-by-year FE are controlled to capture unobserved confounders as much as possible. Besides, the natural logarithm form is taken for all continuous variables to mitigate heteroskedasticity interference.

3.2.2. Parallel trend test

Satisfying the parallel trend assumption, i.e., the average outcomes of treated and control units would have followed parallel paths in the absence of the treatment, is a prerequisite for the accurate evaluation of the DID model. Referring to Beck et al. (2010), the event study is used to test parallel trend, set as follows:

$$GEP_{it} = \beta_0 + \sum_{\tau=-8}^4 \beta_{\tau} dummy_{it\tau} +$$

$$\beta X_{it} + \varepsilon_{it} \quad (2)$$

where τ represents the term relative to BCP implementation. Let T denotes the year of BCP implementation in pilot city c ; then, $\tau_c = t - T$ in year t . $dummy_{it\tau}$ is a set of counterfactual dummy variables. For the control group, $dummy_{it\tau}$ equals 0. For pilot city c , assume that the BCP is implemented in τ years before/after, $dummy_{c\tau} = 1$; otherwise $dummy_{c\tau} = 0$. To avoid complete multicollinearity, we truncate the data, and this does not affect the estimated results (Bu and Shi, 2021). For $\tau < 0$, if the estimated coefficients β_{τ} are all not significant, it would indicate that the parallel trend test passes.

3.2.3. Mediating effect model

In the theoretical analysis, we propose four possible transmission mechanisms by which information infrastructure affects GHG emission performance. To verify Hypotheses 2–5, a mediating effect model is constructed as follows:

$$M_{it} = \eta_0 + \eta_1 D_{it} + \eta X_{it} + \varepsilon_{it} \quad (3)$$

$$GEP_{it} = \varphi_0 + \varphi_1 D_{it} + \varphi_2 M_{it} + \varphi X_{it} + \varepsilon_{it} \quad (4)$$

where M_{it} stands for the mediating variable, and other variables are set as Eq. (1). In this study, sequential regression is used to test the validity of the mediating effect (Baron and Kenny, 1986), and the specific process is shown in Fig. 4.

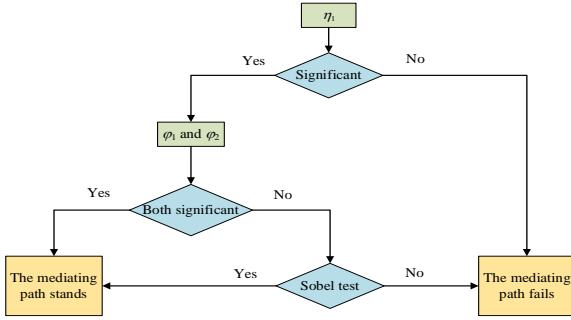


Fig. 4. Mediating effect test process

3.3. Variable description

3.3.1. Dependent variable

Numerous studies have explored the measurement of GHG emission performance, which can be divided into two categories: single-factor indicators and total-factor indicators. The former is defined as GHG emission intensity, i.e., GHG emissions per gross domestic product (GDP), which is relatively one-sided (Dong et al., 2021c). The latter is defined as GHG emission efficiency, i.e., the distance deviates from the production frontier, which takes into account the substitution relationship among factors (Xu et al., 2021). Both a reduction in GHG emission intensity and an increase in GHG emission efficiency imply a higher GHG emission performance. In this study, we place these two indicators in a unified context to explore the emission-reduction performance of information infrastructure.

(1) GHG emission intensity. Limited by data availability, three major GHGs, CO₂, methane (CH₄), and nitrous oxide (NO₂), are considered. The

greenhouse effect of different GHGs varies, so their emissions cannot be simply added up¹⁵. Therefore, this study takes their respective emission intensity as the dependent variable. CO₂ emission intensity (CI), as measured by CO₂ emissions per GDP; CH₄ emission intensity (MI), as measured by CH₄ emissions per GDP; N₂O emission intensity (NI), as measured by NO₂ emissions per GDP. The raw GHG emissions are obtained from the grid data of EDGARv6.0, with a spatial resolution of 0.1×0.1 degrees. Using ArcGIS 10.8, we match it to prefecture-level cities in China.

(2) GHG emission efficiency (GEE). Because of the advantages in dealing with undesirable outputs, DEA has been a popular method in efficiency measurement. However, traditional DEA has some deficiencies. First, for multiple decision-making units with an efficiency of 1, it cannot re-rank them hierarchically. Second, it does not consider the game between decision-making units, and the efficiency is obtained by self-evaluation. Under the context of decentralized incentives, local governments play an important role in urban GHG emission reduction. Ignoring the non-cooperative game between local governments may lead to biased measurement results (Liu and Dong, 2021). To avoid these problems, we use GCE-DEA to measure GHG emission efficiency (Liang et al., 2008). It applies the game theory to DEA model, which not only combines self-evaluation and mutual evaluation, but also avoids conflicts between decision-making units, making the efficiency measurement results objective and accurate. Inspired by previous studies (e.g., Xu et al., 2021; Wu et al., 2021; Dong et al., 2021b), labor, capital stock, and energy consumption are selected as inputs, real GDP as desirable output, and CO₂, CH₄, and N₂O emissions as

¹⁵ Due to the inconsistency of standards, global warming potential (GWP) values are not used in the main text to convert all GHGs into CO₂, but this does not affect our core findings. After converting all GHGs into CO₂ by 100-year GWP with

reference to IPCC (*Climate Change 2021: The Physical Science Basis*, <https://www.ipcc.ch/report/ar6/wg1/>), the sign and statistical significance of estimated coefficients do not change. Limited by space, results are available on request.

undesirable outputs. Among them, the capital stock is calculated using the perpetual inventory method with a depreciation rate of 9.6%. Referring to Shi and Li (2020), energy consumption is obtained by matching provincial energy consumption to prefecture-city level using the stable night-time satellite lighting data derived from the National Oceanic and Atmospheric Administration of the U.S.

3.3.2. Core independent variable

The DID term D is used to represent the BCP. For the control group, $D = 0$. For the treatment group, $D = 1$ after the BCP implementation, and $D = 0$ otherwise. In this study, we focus on its estimated coefficient α_1 , which reflects the treatment effect of the BCP.

3.3.3. Mediating variable

(1) Technological innovation (TI). In existing studies, patent counts were a widely used technological innovation indicator (Wang and Wang, 2020; Cheng et al., 2021). Considering the size gap between cities and lagging patent approvals, we adopt patent applications per capita to represent technological innovation.

(2) Industrial structure upgrading (IU). Industrial upgrading is a dynamic process in which industrial level keeps rising. We used industrial structure grade coefficient to measure industrial structure upgrading: $IU_{it} = \sum_{n=1}^3 (Y_{int}/Y_{it} \times n)$, where Y_{it} denotes GDP, and $n = 1, 2$, and 3 denote primary, secondary, or tertiary industries, respectively. Its increase reflects the evolution of the industrial structure from primary to secondary to tertiary industries (Yuan and Zhu, 2018).

(3) Tertiary agglomeration (TA). Agglomeration refers to the density of economic activities per unit of effective space, which is commonly measured by the spatial Gini coefficient, location entropy index, and output density. The spatial Gini coefficient and location entropy index ignore the spatial bias caused by geographic unit differences (Shao et al., 2019).

Therefore, following Zhou et al. (2019), we use the value added by tertiary industry per built-up area to measure tertiary agglomeration.

(4) Factor misallocation, including labor misallocation (LM) and capital misallocation (CM). In this study, the production function method is used to calculate factor misallocation (Hsieh and Klenow, 2009). Drawing on Bai and Bian (2016), we measure the labor price using the average urban wage, and measure the capital price using the average 1-year loan rate.

3.3.4. Control variable

To mitigate the estimation bias caused by missing variables, a series of control variables are introduced, constructed as follows:

(1) Economic development (ED), as measured by GDP per capita. There is a coupling nexus between economic growth and GHG emissions (Sheng et al., 2020). As economy develops, its contribution to GHG emission reduction gradually grows (Dong et al., 2019).

(2) Financial development (FD), as measured by the ratio of the total balance of deposits and loans to GDP. There is widespread information asymmetry in late-developing countries, and the resulting financial misallocation exacerbates environmental degradation (Dar and Asif, 2017). In contrast, financial development promotes clean technology development in developed countries, which mitigates GHG emissions (Khan et al., 2019).

(3) Population density (PD), as measured by the population per unit area. Population agglomeration not only improves the sharing and utilization efficiency of infrastructure, but also enhances the penetration of green technologies, which have a suppressive effect on GHG emissions (Liu et al., 2017; Meng and Han, 2018; Wang and Li, 2021).

(4) Openness (OP), as measured by the ratio of total exports and imports to GDP (Li and Wei, 2021).

According to the classic pollution haven hypothesis, openness boosts GHG emissions in developing countries.

(5) Transportation infrastructure (*TS*), measured by urban road area per capita (Lin and Chen, 2020). As a representative traditional infrastructure, it is a typical policy tool for investment-led growth (Zheng et al., 2018). Due to the carbon lock-in effect, transportation

infrastructure lowers urban GHG emission performance (Xie et al., 2017).

(6) Employment structure (*ES*), as measured by the share of tertiary employment (Liu and Ma, 2020). The optimization of employment structure is an important part of economic transformation, which helps to improve productivity and reduce GHG emission intensity (Gao et al., 2021).

Table 2
Summary statistics.

Variable	Obs.	Unit	Mean	S. D.	Min	Max
Dependent variable						
<i>CI</i>	4496	ton/10 ⁴ yuan	5.317	6.674	0.017	87.139
<i>MI</i>	4496	ton/10 ⁴ yuan	0.416	0.558	0.644	5.947
<i>NI</i>	4496	kg/10 ⁴ yuan	6.132	9.822	0.010	159.909
<i>GEE</i>	4496	-	0.351	0.112	0.048	0.881
Independent variable						
<i>D</i>	4496	dummy	0.091	0.288	0	1
Mediating variable						
<i>TI</i>	4496	Piece/10 ⁴ people	4.137	11.215	0.005	228.987
<i>IU</i>	4496	-	2.239	0.144	1.822	2.806
<i>TA</i>	4496	10 ⁴ yuan/km ²	3.519	1.988	0.138	13.997
<i>LM</i>	4496	-	0.953	1.172	-1.358	7.772
<i>CM</i>	4496	-	5.399	0.722	4.137	7.045
Control variable						
<i>ED</i>	4496	10 ⁴ yuan	2.282	1.780	0.180	2.747
<i>FD</i>	4496	-	2.121	1.052	0.508	12.508
<i>PD</i>	4496	people/km ²	428.386	329.068	4.700	2661.542
<i>OP</i>	4496	-	0.198	0.367	0.002	4.622
<i>TS</i>	4496	km ² /people	14.392	6.755	0.390	60.070
<i>ES</i>	4496	%	52.722	13.154	9.910	94.821

3.4. Data sources

The initial data used in this study are from the China Statistical Yearbook, China Energy Statistical Yearbook, China City Statistical Yearbook, China Urban Construction Statistical Yearbook, provincial

statistical yearbooks, municipal statistical bulletins, CNRDS platform, and EDGRA database, and have been converted into 2000 constant price. Table 2 shows the descriptive statistics of variables.

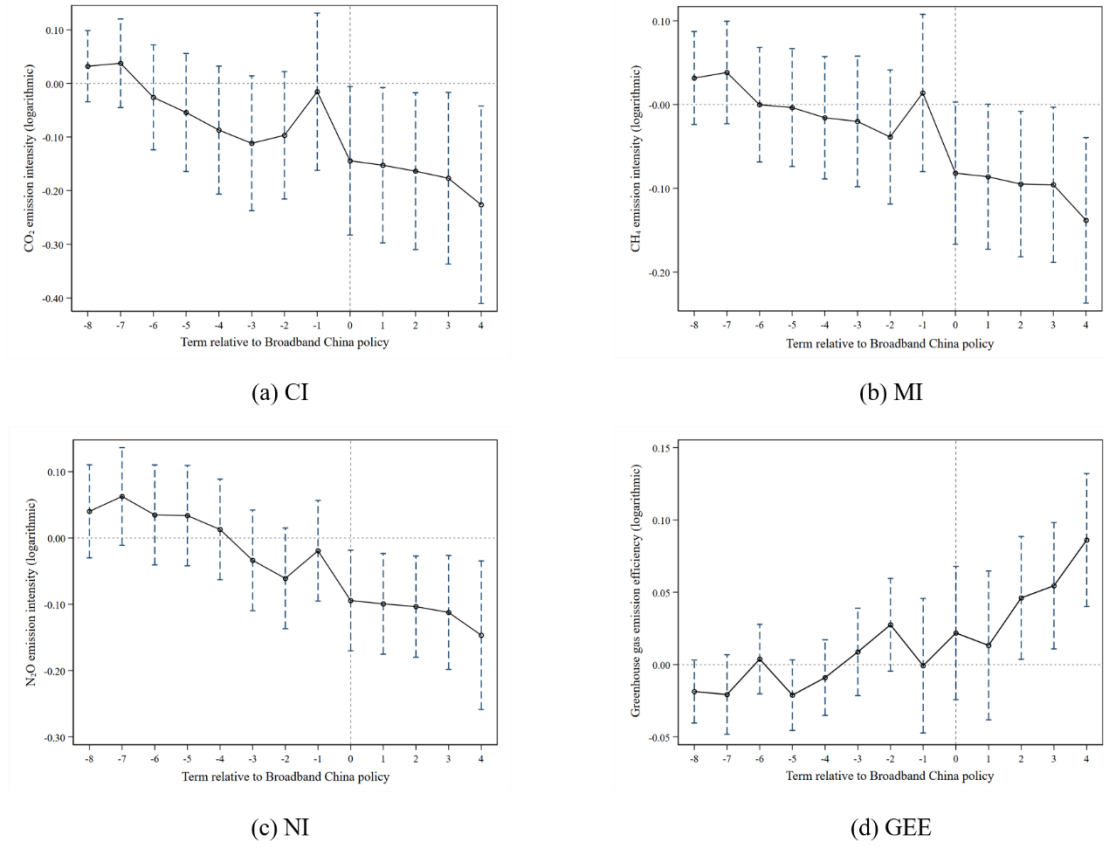


Fig. 5. Parallel trend test results.

Note: The results are derived by constructing counterfactual using event study method. The underlying regression contains all control variables to mitigate potential confounders. The blue dashed line shows the 95% confidence interval of β_τ , which are constructed by standard errors clustered at the prefecture-city level.

4. Results and discussion

4.1. Parallel trend test

Using the event study method, the parallel trend test is conducted, with the results shown in Fig. 5. For all four dependent variables, the 95% confidence interval of the estimated coefficient β_τ contains 0 when $\tau < 0$. This indicates that there is no significant difference in the change of GHG emission intensity and GHG emission efficiency between the treatment group and the control group before the BCP implementation. Therefore, the parallel trend test passes, and the DID model is suitable for evaluating the treatment effect of the BCP.

4.2. Baseline results

By Eq. (1), the impact of the BCP on urban GHG emission performance is estimated, and the results are shown in Table 3. In Models 1–3, the estimated coefficients of D are all negative at the 1% significance

level, which indicates that the BCP reduces the emission intensity of CO_2 , CH_4 , and N_2O . In Model 4, the estimated coefficient of D is significantly positive, indicating that the BCP induces urban GHG emission efficiency. After introducing the control variables, the sign and significance of the estimated coefficients do not change, as shown in Models 5–8. In summary, information infrastructure improves urban GHG emission performance, and Hypothesis 1 has been therefore verified. On the one hand, information infrastructure construction increases Internet penetration and facilitates the dissemination and sharing of knowledge and technology (Yunis et al., 2018; Tang et al., 2021), and the resulting green technology innovation improves GHG emission performance (Xu et al., 2021). On the other hand, information infrastructure reduces transaction costs, accelerates factor flow, and optimizes allocative

efficiency (Wu et al., 2021). This reduces resource waste, improves productivity, and has a positive impact

4.3. Robustness tests

4.3.1. Endogeneity

The DID model cleverly overcomes the endogeneity by comparing the treatment group and the control group before and after the shock. However, its validity depends on randomized experiments, which may not be the case in reality. The selection of BCP pilots is influenced by economic development, city size, and telecommunication base, and the policy endogeneity will lead to biased DID estimators. To address this issue, we use urban topographic relief as an instrumental variable (IV) for the following two reasons. First, topographic relief is an important factor affecting information infrastructure construction. The greater the topographic relief, the higher the construction cost, and the lower the operation

on GHG emission performance.

efficiency. This is also verified by the fact that the average topographic relief of the three batches of pilot cities increases successively (Table 1). Therefore, the topographic relief satisfies the correlation condition. Second, as a physical geographic factor, the topographic relief satisfies the exogeneity condition. Table 4 shows the estimation results with topographic relief as an IV. In the first stage, the estimated coefficient of IV is significant, and the F-value is much greater than 10, indicating that the weak IV problem is ruled out. In the second stage, the estimated coefficients of D remain significant at the 1% level, and their signs are consistent with the baseline regression, which indicates that information infrastructure still improves urban GHG emission performance after overcoming the endogeneity of pilot selection.

Table 3
Baseline results.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
	$\ln CI$	$\ln MI$	$\ln NI$	$\ln GEE$	$\ln CI$	$\ln MI$	$\ln NI$	$\ln GEE$
D	-0.351*** (0.025)	-0.544*** (0.023)	-0.594*** (0.024)	0.239*** (0.019)	-0.094*** (0.017)	-0.083*** (0.016)	-0.088*** (0.021)	0.092*** (0.016)
$\ln ED$					-0.546*** (0.015)	-0.844*** (0.013)	-0.914*** (0.021)	0.332*** (0.014)
$\ln FD$					0.123*** (0.033)	0.058** (0.024)	0.079** (0.031)	-0.139*** (0.028)
$\ln PD$					-0.151* (0.088)	-0.377*** (0.096)	-0.440*** (0.117)	0.062 (0.063)
$\ln OP$					0.023*** (0.008)	0.015** (0.006)	0.019 (0.011)	-0.019*** (0.007)
$\ln TS$					0.076*** (0.015)	0.024* (0.012)	-0.006 (0.017)	0.062 (0.063)
$\ln ES$					0.071** (0.035)	0.039 (0.026)	-0.096** (0.045)	0.325*** (0.041)
Cons.	1.193*** (0.002)	-1.430*** (0.002)	1.241*** (0.002)	-1.121*** (0.002)	1.854*** (0.015)	0.960* (0.546)	4.629*** (0.712)	-2.825*** (0.393)
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province-by-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjust- R^2	0.123	0.138	0.129	0.105	0.735	0.933	0.873	0.529

<i>Obs.</i>	4496	4496	4496	4496	4496	4496	4496	4496
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Note: “ln” before variables denotes taking the logarithm form. Standard errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

Table 4
Estimation results with topographic relief as an instrumental variable.

	First stage		Second stage			
	Model 9	Model 10	Model 11	Model 12	Model 13	Model 14
	<i>D</i>	<i>D</i>	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>
<i>IV</i>	-0.107*** (0.005)	-0.072*** (0.017)				
<i>D</i>			-0.273*** (0.088)	-0.264*** (0.069)	-0.226*** (0.060)	0.665*** (0.131)
<i>Cons.</i>	0.050*** (0.005)	-2.691** (1.099)	1.467** (0.590)	0.569 (0.568)	4.333*** (0.800)	-1.585* (0.837)
<i>Control</i>	No	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Province-by-year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Adjust-R²</i>	0.145	0.223	0.709	0.920	0.867	0.031
<i>F-value</i>	380.00	136.23				
<i>Obs.</i>	4496	4496	4496	4496	4496	4496

Note: “ln” before variables denotes taking the logarithm form. For brevity, the estimated results of control variables are not reported. Standard errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$. The F-value is used to test weak IV.

4.3.2. Time-varying confounders

In traditional DID, random disturbance terms are assumed to be homogeneous. However, there are obviously heterogeneous among cities, which leads to selection bias and depressed estimation accuracy. Matching is a good way to solve this problem (Heckman et al., 1998). In this study, the propensity score matching (PSM) and generalized synthetic control (GSC) methods are used to capture time-varying confounders. Among them, PSM is the most commonly used matching method. Using 1:1 radius matching, we match the treatment group and the control group with control variables in 2013 (the year before the BCP implementation) as the identification features of sample points (Xue et al., 2020). The GSC method was proposed by Xu (2017), which unifies the synthetic control method and interactive fixed effects (Bai, 2009; Abadie et al., 2010). It effectively captures unobserved confounders, which not only solves the

selection bias, but also avoids the systematic errors of traditional matching (Heckman, 2008). Table 5 reports the estimation results of the PSM-DID and GSC methods. For all specifications, the estimated coefficients remain significant above the 5% level, and the signs are consistent with the baseline regression. This implies that information infrastructure improves urban GHG emission performance, and the core findings of this study are robust.

Table 5
Estimation results of PSM-DID and GSC models.

	PSM-DID				GSC			
	Model 15	Model 16	Model 17	Model 18	Model 19	Model 20	Model 21	Model 22
	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>
<i>D</i>	-0.065*** (0.021)	-0.041** (0.016)	-0.035*** (0.013)	0.037** (0.015)	-0.044*** (0.014)	-0.082*** (0.035)	-0.082*** (0.027)	0.043** (0.021)
<i>Control</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Province-by-year FE</i>	Yes	Yes	Yes	Yes				
<i>No. of factors</i>					2	2	3	2
<i>Adjust-R²</i>	0.738	0.948	0.899	0.506				
<i>Obs.</i>	3664	3664	3664	3664	4496	4496	4496	4496

Note: “*ln*” before variables denotes taking the logarithm form. For brevity, the estimated results of control variables are not reported. The number of common factors is obtained by a cross-validation procedure (Xu, 2017). Standard errors are in parentheses. The standard errors of PSM-DID estimator are clustered at the prefecture-city level, and the standard errors of GSC estimator are obtained through 2000 times bootstrap. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

4.3.3. Eliminate other policy interference

Since the Chinese government proposed the New Urbanization plan in 2011, several urban construction policies have been implemented simultaneously. These policies may affect urban GHG emission performance and interfere with the reliability of the BCP evaluation results. As relatively large-scale new urbanization strategies, the ecological performance of smart city policy and low-carbon city policy has been widely verified (e.g., Shi et al., 2018; Song et al., 2020; Yu and Zhang, 2021; Dong et al., 2022b), and they should be excluded in preference. To this end, we introduce these two policies into the benchmark model to eliminate as much interference as possible. As shown in Table 6, although the magnitude of the estimated coefficient decreases, the significance remains consistent with the baseline results. Therefore, the BCP still suppresses

GHG emission intensity and boosts GHG emission efficiency at the 1% significance level, and our estimation results are robust.

4.3.4. Placebo test

To further exclude the influence of other unknown contingent factors, a placebo test is performed by 1000 times random sampling. Each time, 33, 36, and 34 cities are selected as three batches of pilots respectively, and the remaining 178 cities as the control group to estimate Eq. (1). As shown in Fig. 6, most of the estimated coefficients are distributed near 0, with a p-value greater than 0.1, indicating that the BCP has no significant effect in these 1000 samples. Therefore, the placebo test passes, and the positive impact of information infrastructure on urban GHG emission performance is not caused by chance.

Table 6

Estimation results eliminating the interference of smart city policy and low-carbon city policy.

	Model 23	Model 24	Model 25	Model 26	Model 27	Model 28	Model 29	Model 30
	$\ln CI$	$\ln MI$	$\ln NI$	$\ln GEE$	$\ln CI$	$\ln MI$	$\ln NI$	$\ln GEE$
<i>D</i>	-0.146*** (0.026)	-0.216*** (0.030)	-0.238*** (0.030)	0.109*** (0.019)	-0.076*** (0.016)	-0.073*** (0.015)	-0.080*** (0.020)	0.066*** (0.016)
<i>Smart</i>	-0.284*** (0.021)	-0.410*** (0.023)	-0.430*** (0.027)	0.196*** (0.016)	-0.070*** (0.016)	-0.031*** (0.011)	-0.022 (0.019)	0.098*** (0.013)
<i>Low-carbon</i>	-0.191*** (0.027)	-0.392*** (0.030)	-0.456*** (0.038)	0.093*** (0.017)	-0.026* (0.014)	-0.026* (0.014)	-0.062* (0.032)	0.026** (0.013)
<i>Cons.</i>	1.267*** (0.006)	-1.304*** (0.006)	1.381*** (0.007)	-1.166*** (0.004)	1.824*** (0.543)	0.873 (0.541)	4.496*** (0.719)	-2.716*** (0.392)
<i>Control</i>	No	No	No	No	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Province-by-year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Adjust-R²</i>	0.337	0.413	0.389	0.260	0.741	0.934	0.874	0.549
<i>Obs.</i>	4496	4496	4496	4496	4496	4496	4496	4496

Note: “*Smart*” denotes smart city policy and “*Low-carbon*” denotes low-carbon city policy. “*ln*” before variables denotes taking the logarithm form. For brevity, the estimated results of control variables are not reported. Standard errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

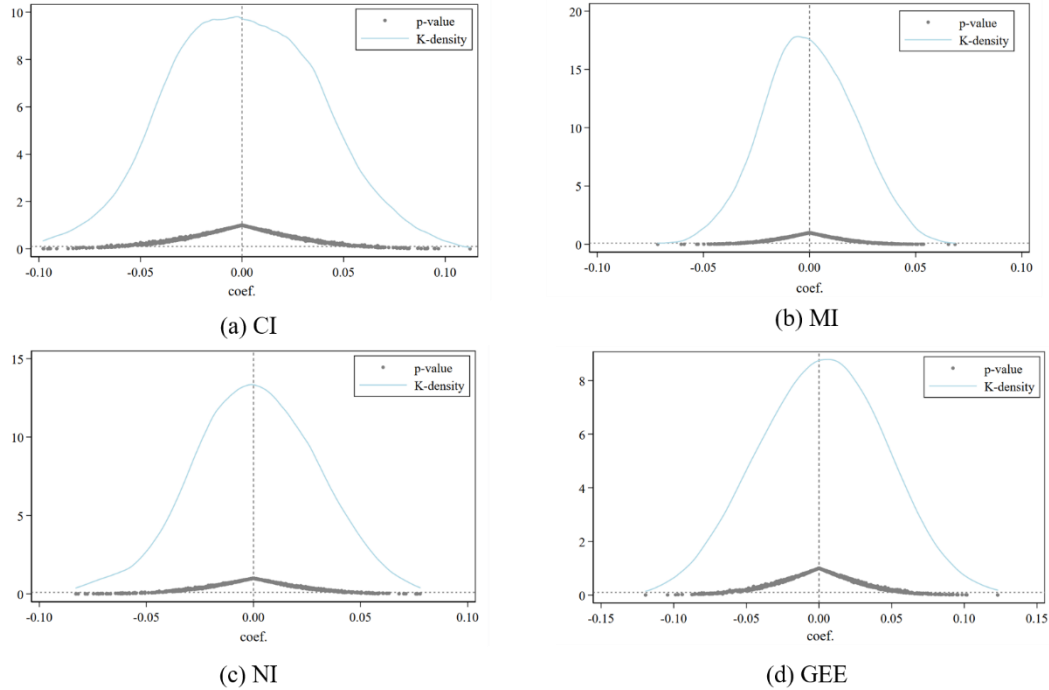


Fig. 6. Placebo test results.

Note: The results are derived by constructing counterfactual using 1000 times random sampling. The underlying regression contains all control variables to mitigate potential confounders. The blue line represents the kernel density curve of the estimated coefficients, and the standard errors are clustered at the prefectural-city level.

Table 7
Mediation effect results for technological innovation.

	Model 31	Model 32	Model 33	Model 34	Model 35
	<i>lnTI</i>	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>
<i>D</i>	0.261*** (0.055)	-0.091*** (0.017)	-0.067*** (0.014)	-0.075*** (0.020)	0.084*** (0.016)
<i>lnTI</i>		-0.013*** (0.005)	-0.061*** (0.013)	-0.052*** (0.020)	0.027*** (0.009)
<i>Cons.</i>	-4.965** (2.251)	1.791*** (0.544)	0.652 (0.512)	4.367*** (0.666)	-2.706*** (0.388)
<i>Control</i>	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes
<i>Province-by-year FE</i>	Yes	Yes	Yes	Yes	Yes
<i>Adjust-R²</i>	0.845	0.736	0.938	0.875	0.532
<i>Obs.</i>	4496	4496	4496	4496	4496

Note: “ln” before variables denotes taking the logarithm form. For brevity, the estimated results of control variables are not reported. Standard errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

5. Mechanism tests

Baseline estimates imply that information infrastructure improves urban GHG emission performance. So, what transmission mechanism does this achieve? In the theoretical analysis, we summarize the innovation effect, structure effect, agglomeration effect, and allocation effect of information infrastructure. In this section, these pathways are tested in turn.

First, the mediating role of technological innovation is estimated, and the results are shown in Table 7. In Model 31, the estimated coefficient of *D* is 0.261, with a significance level of 1%, indicating that information infrastructure promotes technological innovation. In Models 32–34, the estimated coefficients of *lnTI* are all negative at the 1% significance level, which indicates that technological innovation mitigates GHG emission intensity. In Model 35, the estimated coefficient of *lnTI* is significantly positive, indicating that technological innovation improves GHG emission efficiency. To sum up, the mediating pathway whereby information infrastructure improves urban GHG emission performance through technological innovation exists, and Hypothesis 2 is therefore verified. The

improvement of information infrastructure lowers the communication cost, improves knowledge diffusion efficiency, and forms a spillover effect (Li and Du, 2021). This effectively enhances urban connectivity and promotes technological innovation in smart management, green manufacturing, and energy-saving (Wu et al., 2021b), which alleviates resource dependence and improves urban GHG emission performance (Zhao et al., 2021; Liu and Dong, 2021).

Second, we explore the mediating effect of industrial structure upgrading, with the results shown in Table 8. In Model 36, the estimated coefficient of *D* is positive at the 1% significance level, indicating that information infrastructure promotes industrial structure upgrading. In Models 37–40, the estimation results imply that industrial structure upgrading significantly contributes to GHG emission performance. Information infrastructure reduces information asymmetry, allows high-tech elements to flow spontaneously to efficient sectors, and helps industrial structure upgrading (Ren et al., 2021). It promotes the convergence of traditional industries with information technology, transforming the industrial structure from factor-intensive to technology-intensive (Dong et al., 2021c). Moreover, information

infrastructure gives rise to emerging industries, such as the Internet of Things, big data, and cloud computing, which stimulates new economic growth points (Lin and Zhou, 2021a). As a result, the industrial structure upgrading represented by informatization and

servitization reduces energy consumption, increases productivity, and improves GHG emission performance (Lin and Zhou, 2021b). In summary, the mediating pathway of industrial structure upgrading exists, and Hypothesis 3 is verified.

Table 8
Mediation effect results for industrial structure upgrading.

	Model 36	Model 37	Model 38	Model 39	Model 40
	<i>lnIU</i>	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>
<i>D</i>	0.015*** (0.002)	-0.086*** (0.018)	-0.075*** (0.016)	-0.081*** (0.021)	0.082*** (0.016)
<i>lnIU</i>		-0.564** (0.271)	-0.568** (0.269)	-0.465* (0.264)	0.702*** (0.246)
<i>Cons.</i>	0.476*** (0.085)	2.123*** (0.584)	1.230*** (0.575)	4.850*** (0.741)	-3.159*** (0.421)
<i>Control</i>	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes
<i>Province-by-year FE</i>	Yes	Yes	Yes	Yes	Yes
<i>Adjust-R²</i>	0.565	0.737	0.934	0.873	0.535
<i>Obs.</i>	4496	4496	4496	4496	4496

Note: “ln” before variables denotes taking the logarithm form. For brevity, the estimated results of control variables are not reported. Standard errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

Third, the mediating role of tertiary agglomeration is examined, and the results are presented in Table 9. In Model 41, the estimated coefficient of *D* is positive at the 1% significance level, indicating that information infrastructure promotes tertiary agglomeration. As shown in Models 42–45, the estimation results imply that tertiary agglomeration improves GHG emission performance. In short, tertiary agglomeration is an effective channel for information infrastructure to improve urban GHG emission performance, and Hypothesis 4 has been therefore verified. The market- and technology-

oriented characteristics make the tertiary industry more dependent on information accessibility (Dong and Liu, 2015). Cities with well-developed information infrastructure attract more producer services to move in, forming agglomeration effects and economies of scale (Shi et al., 2018). This facilitates the agglomeration of high-tech elements and the sharing of infrastructure, thereby reducing transportation costs, management costs, and transaction costs, and improving GHG emission performance (Lin and Tan, 2019; Zhao et al., 2021).

Table 9
Mediation effect results for tertiary agglomeration.

	Model 41	Model 42	Model 43	Model 44	Model 45
	<i>lnTA</i>	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>
<i>D</i>	0.091*** (0.025)	-0.089*** (0.017)	-0.077*** (0.015)	-0.078*** (0.019)	0.083*** (0.015)
<i>lnTA</i>		-0.053** (0.026)	-0.073*** (0.022)	-0.108*** (0.032)	0.094*** (0.022)
<i>Cons.</i>	-0.859 (0.956)	1.809*** (0.538)	0.897* (0.534)	4.537*** (0.678)	-2.744*** (0.401)
<i>Control</i>	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes
<i>Province-by-year</i>	Yes	Yes	Yes	Yes	Yes
<i>FE</i>					
<i>Adjust-R²</i>	0.622	0.737	0.934	0.875	0.538
<i>Obs.</i>	4496	4496	4496	4496	4496

Note: “ln” before variables denotes taking the logarithm form. For brevity, the estimated results of control variables are not reported. Standard errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

Fourth, Table 10 shows the estimation results with factor misallocation as a mediator. In Models 46–47, the estimated coefficients of *D* are both negative at the 5% significance level, indicating that information infrastructure alleviates labor misallocation and capital misallocation. As shown in Models 48–51, factor misallocation significantly exacerbates GHG emission intensity and deteriorates GHG emission efficiency. On the one hand, information infrastructure greatly weakens space-time barriers, accelerates factor flow, and improves regional resource integration efficiency

(Wu et al., 2021a). On the other hand, benefiting from information infrastructure construction, the digital economy and digital industries are boosted, which transform traditional organization and management modes (Liao et al., 2020). As a result, the improved allocation efficiency not only amplifies the marginal output of factors, but also reduces the frictional cost of factor flow (Li and Du, 2021). In conclusion, information infrastructure improves urban GHG emission performance by alleviating factor misallocation, and Hypothesis 5 is therefore verified.

Table 10
Mediation effect results for factor misallocation.

	Model 46	Model 47	Model 48	Model 49	Model 50	Model 51
	<i>lnLM</i>	<i>lnCM</i>	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>
<i>D</i>	-0.078** (0.031)	-0.140*** (0.007)	-0.025* (0.014)	-0.064*** (0.016)	-0.076*** (0.022)	0.060*** (0.016)
<i>lnLM</i>			0.052*** (0.011)	0.031*** (0.009)	0.022* (0.013)	-0.068*** (0.020)
<i>lnCM</i>			0.467*** (0.038)	0.119*** (0.026)	0.084** (0.037)	-0.185*** (0.032)
<i>Cons.</i>	-0.259 (1.197)	1.695*** (0.326)	1.076** (0.521)	0.766 (0.546)	4.489*** (0.725)	-2.529*** (0.365)
<i>Control</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Province-by-year</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>FE</i>						
<i>Adjust-R²</i>	0.444	0.516	0.773	0.935	0.873	0.553
<i>Obs.</i>	4496	4496	4496	4496	4496	4496

Note: “ln” before variables denotes taking the logarithm form. For labor misallocation, non-negative standardization is performed before estimation. For brevity, the estimated results of control variables are not reported. Standard

errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

6. Heterogeneity analysis

6.1. City size

Information infrastructure has network effects, so its emission reduction performance may vary by city size. According to *The Adjustment of Standards for The Division of City Size* (2014), the entire sample is divided into two groups: one for small and medium-sized (SME) cities with less than 1 million inhabitants in urban areas, and the other for large cities. By constructing interaction terms, the heterogeneity effect of city size is estimated, with the results presented in Table 11. The BCP improves GHG emission performance in large cities at the 1% significance level, but its impact on SME cities is relatively small, with a decreased significance. There are many reasons for this result. First, in large cities, more residents use information tools, which amplifies the knowledge spillover effects of information infrastructure (Xue et al., 2020). Second, high-end industries and fiscal resources in SME cities are relatively insufficient to provide support for industrial structure upgrading and resource allocation optimization (Shi et al., 2018). Third, large cities have abundant human capital. As carriers of knowledge and innovation, talents contribute to the emission reduction performance of

information infrastructure (Ahmed et al., 2021).

6.2. Digital economy level

For any infrastructure, construction is just the beginning, and application determines its performance. According to *The Peking University Digital Financial Inclusion Index of China* (Guo et al., 2020), we divide the entire sample into two groups by digital economy level. This is a relatively comprehensive index that measures urban digital economy from multiple dimensions of breadth, depth, and convergence. As can be seen in Table 12, information infrastructure significantly improves GHG emission performance in cities with a high digital economy level, while its impact on cities with a low digital economy level is not significant. Owing to the lack of supporting industries, much of China's infrastructure is underutilized and lying idle, which leads to wasted resources and increased financial burden (Zheng et al., 2014). In cities with underdeveloped digital economy, information infrastructure lacks application carriers, and its emission reduction performance is difficult to exert. Therefore, deepening the convergence of information technology and industry to increase the utilization of information infrastructure is essential to improving urban GHG emission performance.

Table 12
Heterogeneity analysis results for digital economy level.

	Model 56	Model 57	Model 58	Model 59
	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>
<i>D × High</i>	-0.106*** (0.022)	-0.107*** (0.020)	-0.119*** (0.025)	0.121*** (0.018)
<i>D × Low</i>	-0.065* (0.038)	-0.023 (0.015)	-0.010 (0.030)	0.016 (0.028)
<i>Cons.</i>	1.828*** (0.539)	0.905* (0.531)	4.559*** (0.697)	-2.757*** (0.402)
<i>Control</i>	Yes	Yes	Yes	Yes
<i>City FE</i>	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes
<i>Province-by-year FE</i>	Yes	Yes	Yes	Yes
<i>Adjust-R²</i>	0.736	0.934	0.874	0.533
<i>Obs.</i>	4496	4496	4496	4496

Note: “ln” before variables denotes taking the logarithm form. 142 cities in the High group and 139 in the Low group. For brevity, the estimated results of control variables are not reported. Standard errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

6.3. Economic status

Fiscal and material support is important in information infrastructure construction, and the treatment effect of the BCP may vary in cities with different economic statuses. Inspired by Shi and Li (2020), the entire sample is divided into two groups, one for economically leading cities whose GDP per capita is among the top four in their located province, and the other for cities that are relatively lagging economically. As shown in Table 13, the BCP improves the GHG emission performance in economically leading cities, whereas it has no significant impact on

cities with a relatively lagging economic status. With a favorable position in provincial-level planning, economically leading cities can obtain more external resources to guarantee information infrastructure construction (Lin and Zhou, 2021). Moreover, these cities have well-developed industries and technology, which can better release the emission reduction performance of information infrastructure. Correspondingly, the resources in economically backward cities are insufficient, and the BCP does not function well.

Table 13

Heterogeneity analysis results for economic status.

	Model 60	Model 61	Model 62	Model 63
	<i>lnCI</i>	<i>lnMI</i>	<i>lnNI</i>	<i>lnGEE</i>
<i>D × Lead</i>	-0.114*** (0.026)	-0.130*** (0.022)	-0.129*** (0.030)	0.140*** (0.019)
<i>D × Lag</i>	-0.069*** (0.020)	-0.024 (0.017)	-0.036 (0.024)	0.029 (0.023)
<i>Cons.</i>	1.763*** (0.543)	0.746 (0.538)	4.443*** (0.706)	-2.602*** (0.397)
<i>Control</i>	Yes	Yes	Yes	Yes
<i>Fixed FE</i>	Yes	Yes	Yes	Yes
<i>Year FE</i>	Yes	Yes	Yes	Yes
<i>Province-by-year FE</i>	Yes	Yes	Yes	Yes
<i>Adjust-R²</i>	0.736	0.934	0.873	0.534
<i>Obs.</i>	4496	4496	4496	4496

Note: “ln” before variables denotes taking the logarithm form. 101 cities in the Lead group and 180 in the Lag group. For brevity, the estimated results of control variables are not reported. Standard errors are in parentheses, which are clustered at the prefecture-city level. *: $p < 0.10$, **: $p < 0.05$, ***: $p < 0.01$.

7. Conclusion and policy implications

7.1. Conclusion

As a new infrastructure, information infrastructure performs outstandingly in enhancing economic efficiency, yet its ecological performance has not received sufficient attention. Using 281 prefecture-level cities in China from 2003 to 2018 as the research sample, we investigate the impact of information infrastructure on urban GHG emission performance by taking the Broadband China policy as a quasi-natural experiment. The main findings are as follows. First, our study provides strong evidence that information infrastructure improves urban GHG emission performance based on rich robustness tests. Second, technological innovation, industrial structure

upgrading, tertiary agglomeration and factor allocation are the mediating channels for information infrastructure to improve urban GHG emission performance. Third, for heterogeneity analysis, information infrastructure exerts significant emission reduction performance in cities with large size, advanced digital economy, and leading economic status, while its impact on GHG emission performance drops in other cities.

7.2. Policy implications

This study provides insights for infrastructure transformation and GHG emission performance improvement, and the following policy implications can be derived.

First, this study implies that infrastructure

transformation represented by information infrastructure construction is conducive to urban GHG emission performance. Therefore, the pilot scope of the BCP should be further expanded to increase the penetration of information infrastructure to release its emission reduction performance. In terms of industrial layout, policymakers ought to guide the convergence of information industry with traditional industries, provide support for the digital economy and related derivative industries, and improve the utilization efficiency of information infrastructure. In urban management, digital technologies should also be widely adopted to leverage its role in smart management, green manufacturing, and resource conservation, thereby improving urban GHG emission performance.

Second, the mechanism analysis shows that information infrastructure improves urban GHG emission performance by promoting technological innovation, upgrading industrial structure, optimizing factor allocation, and deepening tertiary agglomeration. Therefore, the strategic position of technological innovation should be carried out in information infrastructure construction. In this process, it is necessary to provide a good research environment, strengthen the cultivation of talents, and provide sufficient human capital for information technology innovation. At the same time, the link role of information technology should be fully exploited to deepen the convergence of talent, capital, and technology to promote industrial structure upgrading. As public service providers, policymakers ought to establish information-sharing platforms to leverage the role of information technology in correcting market distortions. In addition, funds and policy facilitation can be provided for producer services to optimize the industrial layout, exert their agglomeration effect, and improve urban GHG emission performance.

Third, the heterogeneity analysis results imply that city size, digital economy level, and economic base contribute to the role of information infrastructure in improving GHG emission performance. Therefore, tariffs should be reduced to expand the scale of telecommunications users, increase the penetration of information infrastructure, and exert the network effect. For cities with a low digital economy, it is necessary to develop digital projects with local characteristics. Local governments should also introduce high-tech digital enterprises, cultivate digital industrial parks, and integrate information technology into all aspects of urban management. For economically lagging cities, fiscal support should be provided to increase investment in information infrastructure. Special funds can also be established to attract more social capital to participate in the construction and utilization of information infrastructure, better implement the BCP, and improve urban GHG emission performance.

7.3. Outlook and deficiencies

Although this is the first study to evaluate the impact of information infrastructure on GHG emission performance, there are still some limitations, which are the directions for future work. First, due to the late implementation of the BCP, the emission reduction performance of information infrastructure found in this study is short-term, and the long-term treatment effect needs to be further verified. Second, a complete cost-benefit analysis should be done to better clarify the performance of information infrastructure, which can inspire other countries, especially developing countries, to break the carbon lock-in of infrastructure. Third, information technology has spillover effects, and information infrastructure construction may affect the GHG emission performance of neighboring cities. Therefore, a spatial DID model can be used to capture the spillover effects in further study.

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风电产业政策、信贷融资与企业创新：高管海外经历的调节作用

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摘要：以高管海外经历为调节变量、信贷融资为中介变量，基于创新质量和创新效率双视角、探索了不同类型风电产业政策对企业技术创新的驱动机制。结果表明：各类产业政策整体上对风电企业创新质量具有显著的提升作用，综合型、激励型政策对风电企业创新效率具有显著的提升作用，而抑制型政策对创新效率的提升作用不显著；信贷融资在风电产业政策对企业创新质量和创新效率驱动过程中起部分中介作用；高管海外经历在各类产业政策对企业创新质量、创新效率以及信贷融资作用路径上均呈现显著正向调节作用，能够有效削弱抑制型政策对企业信贷融资的不利影响，起到显著放大产业政策对企业创新质量、创新效率和信贷融资的杠杆作用。

关键词：产业政策；创新质量；创新效率；信贷融资；高管海外经历

Wind power industry policy, credit financing and corporate innovation: reconciling the overseas experience of executives

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Abstract: Using overseas experience of executives as a moderating variable and credit financing as a mediating variable, the driving mechanisms of different types of wind power industrial policies on firms' technological innovation are explored from the perspectives of both innovation quality and innovation efficiency. The results of the empirical study show that: the overall effect of various types of industrial policies on the innovation quality of wind power enterprises is significantly enhanced; comprehensive and incentive policies have a significant effect on the innovation efficiency of wind power enterprises, while inhibitory policies do not have a significant effect on the enhancement of innovation efficiency; credit financing plays a partially mediating role in the driving process of wind power industrial policies on the innovation quality and innovation efficiency of enterprises; the overseas experience of executives plays a significant role in the driving effect of various types of industrial policies on the innovation quality, innovation efficiency and credit financing of enterprises. The overseas experience of senior executives has a significant positive moderating effect on the effect of various industrial policies on innovation quality, innovation efficiency and credit financing, effectively weakening the negative impact of inhibitory policies on credit financing and significantly amplifying the leverage effect of industrial policies on innovation quality, innovation efficiency and credit financing of enterprises.

Keywords: industrial policy; quality of innovation; innovation efficiency; credit financing; executive overseas experience

一、引言

2020年9月,国家主席习近平在第75届联合国大会上首次提出中国碳达峰和碳中和的“3060”战略目标(习近平,2020),自此我国进入了低碳发展的新阶段,而技术创新则是实现“3060双碳目标”的决定性因素。在此背景下,能源结构低碳转型压力与日俱增,清洁能源作为传统化石能源的重要替代能源,对我国能源结构改善、环境保护和经济社会系统性变革具有深远影响(Wang et al, 2022; Carlson D et al, 2021)。相比其他清洁能源,风能在商业化发展、规模化开发和技术方面更具优势(Chy A et al, 2021)[□],成为我国总体应对新旧动能转换、环境污染和能源紧缺的新平衡点。然而,随着风电产业的不断发展,严重的短板问题也日益显露,如严重的“弃风”现象、电网落后和风电场建设质量较低等;更重要的是企业创新质量和创新效率相对较低,核心技术仍受制于人(Zhang et al, 2018)[□]。

为促进企业技术创新,国内外普遍采取制定产业政策来刺激企业进行有效的技术创新。遗憾的是,随着产业扶持政策的持续投入,虽然刺激了我国风电企业规模的迅速发展,但技术创新质量和效率却没有显著提升,实现国际产业链升级和产业跨越式发展的目标尚未达成,国内风电企业仍面临核心技术被“卡脖子”的困境(Carlson D et al, 2021)。如何制定与实施有效的产业创新政策提升风电企业创新质量和效率提升成为各界普遍关注的问题。

梳理现有研究文献可以发现,融资难一直以来都是新能源产业发展的一大困难(Zhao & Chen, 2016)[□],虽然近年来国家陆续出台相关政策破解风电企业信贷融资难题,但融资约束依然是风电企业高质量发展面临的重要难题。同时,具有海外经历的高管能给企业带来更为先进的管理知识、创新理念、社会资源和技术资源,这使得高管在参与企业的战略制定和决策时更偏向于技术创新(贺亚楠等, 2021[□]; 鲁小凡等, 2021[□])。那么,高管海外经历能否缓解企业的融资压力以及提升企业的融资能力?能否促进企业创新?这些问题学术界尚未给出清

晰的解答。本文以高管海外经历为调节变量、信贷融资为中介变量,基于创新质量和创新效率双视角,探索了我国不同类型风电产业政策对企业技术创新的驱动机制。

二、理论分析与研究假设

1、产业创新政策与风电企业创新

现有学者关注了抑制型、激励型政策对企业创新的影响:一方面,诸如财税支持、并网支持和政府采购等激励型政策有利于降低市场的不确定性,降低产品市场进入成本,从而激发企业创新行为(Schleich et al, 2017)[□];另一方面,无论是案例研究还是实证研究都强调了抑制型政策对企业技术创新具有极其重要的影响,以环境规制为代表的抑制型产业创新政策有利于企业获得长期创新质量和竞争优势,增强了企业技术进步和培育核心技术创新的动力(Tian Y et al, 2021)[□]。本文将风电产业创新政策分为激励型、抑制型两类,不分类别的一揽子产业政策总体称为综合型,并假设:

H1: 各类产业政策(综合型 H1a、激励型 H1b、抑制型 H1c)对企业创新质量产生正向影响;

H1: 各类产业政策(综合型 H1d、激励型 H1e、抑制型 H1f)对企业创新效率产生正向影响;

2、产业政策与企业信贷融资

企业创新所需的资金等关键创新要素市场供给资源配置权仍由政府掌控,银行信贷资源通常跟随政府规划流向特定支持行业企业(Sapienza, 2004)[□],因此,政府在金融资源配置中发挥着重要作用。何熙琼等的研究(2016)[□]认为受产业政策扶持的行业和企业会产生较高的信用担保预期,从而降低了企业外部融资成本,这有利于提升企业信贷融资能力。当政府出台支持性的产业政策,意味着企业能够获得政府提供的稳定现金流进行研发投资,从而提升企业创新的成功率,这在很大程度上向银行传递了有利的政策信号,增强了银行对风电等新能源企业的放贷信心,从而有利于提升风电企业信贷融资能力(Bose U et al, 2019)[□]。由此,本文提出如下研究假设:

H2 各类产业政策(综合型 H2a、激励型 H2b、

抑制型 H2c) 对企业信贷融资产生正向影响。

3、产业政策、企业信贷融资与企业创新

Amore et al. (2013)^[1] 研究发现银行信贷在企业技术创新中发挥重要作用，银行业放松管制对创新活动的效率和质量产生显著积极影响。Corsatea et al. (2014)^[2] 的研究更是认为企业债务融资是风电产业创新发展的关键资源。因此，推动新能源产业发展需要发达金融市场的支持以促进创新效率提升。同时，金融市场还可以分散企业清洁能源技术研发投资的失败风险，鼓励企业充分挖掘清洁能源技术的巨大商业潜力，从而促进企业创新 (Yu C H et al., 2021)^[3]。童馨乐等 (2022)^[4] 最新研究成果表明贯穿于战略性新兴产业和高新技术企业创新全过程的支持性产业政策如政府补贴等对银行等外部投资者具有积极的信号传递作用，从而对企业创新产生积极影响。综上所述，本文提出以下假设：

H3 企业信贷融资在各类产业政策（综合型 H3a、激励型 H3b、抑制型 H3c）与企业创新质量之间起中介作用；

H3 企业信贷融资在各类产业政策（综合型 H3d、激励型 H3e、抑制型 H3f）与企业创新效率之间起中介作用；

4、高管海外经历的调节作用

已有相关研究发现，具有海外经历的高管能够显著刺激企业创新。首先，“高管梯队理论”认为企业管理者的认知结构、价值观念、个人特质和个人经历等因素会不同程度地影响其决策偏好和公司的治理水平 (Hambrick D C et al, 1984)^[5]。其次，具有海外经历的高管通常都会受到海外教育和职业的影响，这类人群往往具有创新思维和全球化视野，并且掌握了国外先进的科技知识和现代化的企业治理能力，这对企业高质量创新至关重要。最后，高管的海外经历能够有效激发高管的创新动力 (Armstrong & Vashishtha, 2013)^[6]。基于以上分析，本文提出如下假设：

H4 高管海外经历在各类产业政策（综合型 H4a、激励型 H4b、抑制型 H4c）与企业创新（创新质量和创新效率）之间具有调节作用；

H4 高管海外经历在各类产业政策（综合型 H4d、激励型 H4e、抑制型 H4f）与企业信贷融资之间具有调节作用；

基于分析，本文理论研究模型构建如图 1 所示：

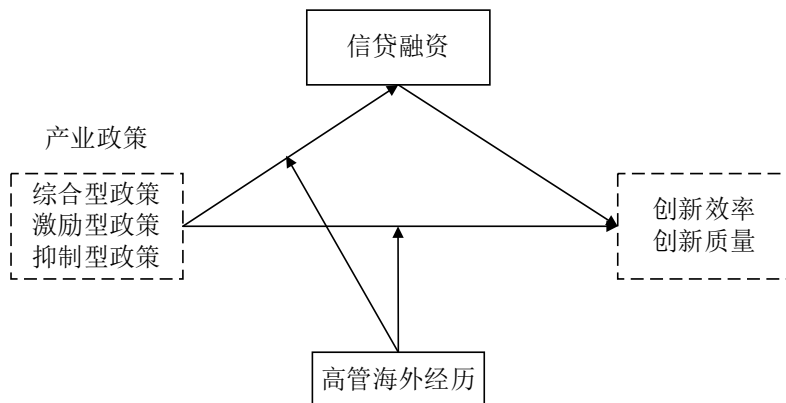


图 1 研究理论模型

三、研究设计

1、数据来源与样本选择

本文通过北大法宝数据库和中国政府各部委门户网站共梳理获得 2004-2020 年间中国中央政府各部门发布的 262 项相关产业政策。

本文以风电产业上市公司作为研究样本，剔除了样本期间内 ST、*ST 企业以及上市时间不足三年

的企业样本数据 (Song et al., 2015)^[7]，最终获得沪深两市 A 股 56 家风电企业的有效样本。样本中有关企业的相关特征变量数据来自于 CCER 和 CSMAR 数据库，专利数据来自于 CSMAR 和壹专利数据库。由于 CSMAR 和 CCER 数据库中 2008 年以前风电企业具有海外经历高管数据缺失较多，为了保障数据准确性和研究时效性，本文研究时间范围最终锁定在

2008-2020 年期间。

2、变量定义及测度

(1) 被解释变量

本文被解释变量包含以下两个：一是以风电企业当年的发明专利申请量占专利申请总量的比重衡量企业创新质量。二是参考现有研究（冯根福，2017；Hirshleifer et al., 2013），以专利申请量与研发

投入自然对数的比值测度企业创新效率。

(2) 解释变量

产业政策是由产业政策综合力度衡量。产业政策力度借鉴（Wang and Zou, 2018）研究成果对其赋值，具体标准如表 1 所示，分值越高、政策力度越大。

表 1 产业政策形式赋值标准

分值。	政策形式。
5。	全国人民代表大会及其常务委员会颁布的法律（简称法律）
4。	国务院颁布的条例、各部门的部令（简称条例部令）
3。	国务院颁布的暂行条例/意见/规划；各部门的条例/规定（简称意见规定）。
2。	各部门的意见、纲要、规划、办法、暂行规定（简称办法）
1。	通知、公告。

并借鉴现有研究成果（王娟茹和张渝，2018），将产业政策分为激励型政策和抑制型政策，具体如图 2 所示。进一步，分别计算各项具体政策措施并

累加最终获得激励型政策和抑制型政策力度之和，相应的产业综合政策力度为激励型政策力度和抑制型政策力度之和。

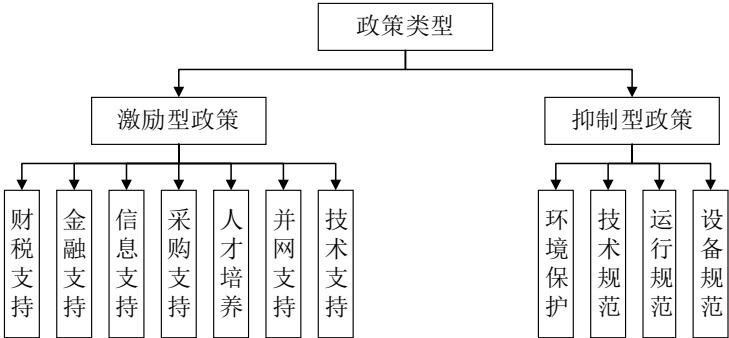


图 2 产业政策工具分类

(3) 中介变量

企业信贷融资。借鉴王旭（2015）的研究，本文选取银行信贷强度来测度风电企业的融资能力，即短期借款与长期借款之和与企业总资产的比值。

(4) 调节变量

高管海外经历。参考鲁小凡等（2021）的研究成果，本文以风电企业当年高级管理人员团队中具有海外经历的高管人数与高管总人数的比值来衡量，其中海外经历包含海外工作经历与海外教育经

历。

(5) 控制变量。

参考已有研究成果，本文引入企业规模、所有权性质、投资机会（Wang et al., 2018）、股权集中度、两职合一、产权比率、独立董事比例（朱德胜和周晓珮，2016）、高管股权激励（田轩和孟清扬，2018）和市场发育程度（Tian et al., 2019）作为控制变量。

以上各变量的具体名称、测度及代码如表 2

所示。

表 2 变量定义与测度

变量类型	变量名称	变量符号	变量测度
因变量	创新质量	Patentir	发明专利量/专利申请总量
	创新效率	Pefffi	专利申请量/研发投入自然对数
	产业综合政策	CPE	政策综合力度
自变量	激励型政策	Incentive	财税支持、金融支持、信息支持、采购支持、人才培养、并网支持、技术支持 7 项政策力度之和
	抑制型政策	Regulatp	环境保护、技术规范、运行规范与设备规范 4 项政策力度之和
中介变量	信贷融资	Loan	(长期借款+短期借款)/总资产
调节变量	高管海外经历	Oversea	海外经历高管人数/高管总人数
	企业规模	Insize	企业员工总数的自然对数
	所有权性质	Ownership	国有企业记为 1，民营企业记为 0
	产权比率	EQR	负债总额/所有者权益总额
控制变量	投资机会	Tobin'Q	(流通股市值+非流通股数*每股净资产+负债账面价值)/总资产
	股权集中度	Herfi10	公司前 10 位大股东持股比例平方和
	两职合一	Dual	董事长和总经理兼任记为 1，否则记为 0
	独立董事比例	Indepentr	独立董事人数/董事总人数
	高管股权激励	MEI	高管持股总数/企业总股本
	市场发育程度	SOEV/GRDP	国有控股工业企业利润总额/地区生产总值

3、回归模型与检验方法

由于政策措施的实行带有滞后性，本文对政策进行滞后一期处理以减少内生性问题（韩超等，2017）[□]。相应的，在研究产业政策对风电企业创新的影响和作用机制时也进行滞后一期处理，在此基础上借鉴 Yu et al.（2016）[□]、杨柳青（2016）[□]等的研究成果构建模型如下：

$$Patentir = \alpha_0 + \alpha_1 Pi + \sum CV + \varepsilon \quad (1)$$

$$Pefffi = \alpha_0 + \alpha_1 Pi + \sum CV + \varepsilon \quad (2)$$

$$Loan = \beta_0 + \beta_1 Pi + \sum CV + \varepsilon \quad (3)$$

$$Patentir = \gamma_0 + \gamma_1 Pi + \gamma_2 Loan + \sum CV + \varepsilon \quad (4)$$

$$Pefffi = \gamma_0 + \gamma_1 Pi + \gamma_2 Loan + \sum CV + \varepsilon \quad (5)$$

高管海外经历在不同类型政策与企业创新质

量、创新效率和信贷融资中的调节作用，本文构建如下模型：

$$Patentir = \theta_0 + \theta_1 Pi + \theta_2 Oversea + \theta_3 Pi \times Oversea + \sum CV + \varepsilon \quad (6)$$

$$Pefffi = \theta_0 + \theta_1 Pi + \theta_2 Oversea + \theta_3 Pi \times Oversea + \sum CV + \varepsilon \quad (7)$$

$$Loan = \theta_0 + \theta_1 Pi + \theta_2 Oversea + \theta_3 Pi \times Oversea + \sum CV + \varepsilon \quad (8)$$

其中产业政策 Pi 包含产业综合政策 P1、激励型政策 P2 以及抑制型政策 P3。CV 和 ε 分别表示控制变量和随机误差项。本文主要借鉴温忠麟和叶宝娟（2004）[□]的中介效应检验程序，采用层次回归法判断中介效应是否存在。

四、实证结果与分析

驱动效果做回归分析，具体回归结果如表 3 所示：

1、产业政策对创新质量、创新效率和企业信贷融资的回归分析

本文借助 StataMP 16 软件，对风电产业政策的

表 3 产业政策对企业创新质量与创新效率的回归分析

变量	模型 1 (Patentir)			模型 2 (Peffi)		
	CPE	Incentp	Regulatp	CPE	Incentp	Regulatp
CPE	0.047** (2.142)			0.056* (1.932)		
Incentivep		0.049** (2.237)			0.059* (2.002)	
Regulatp			0.043* (1.753)			0.062 (2.141)
Insize	-0.054 (-1.134)	-0.061 (-1.198)	-0.046 (-0.954)	0.182** (2.044)	0.182** (2.044)	0.182** (2.044)
Ownership	-0.024 (-0.212)	-0.026 (-0.232)	-0.021 (-0.187)	0.182 (2.884)	0.182 (2.884)	0.181 (2.884)
EQR	0.010 (0.648)	0.010 (0.640)	0.011 (0.664)	0.026 (5.031)	0.026 (5.033)	0.026 (5.030)
Tobin'Q	0.015 (0.956)	0.015 (0.902)	0.017 (1.034)	0.063 (0.338)	0.063 (0.338)	0.063 (0.338)
Herfi10	0.050 (1.456)	0.051 (1.505)	0.047 (1.371)	0.031 (2.679)	0.031 (2.689)	0.031 (2.665)
Dual	-0.016 (-0.260)	-0.015 (-0.255)	-0.017 (-0.275)	0.012 (0.599)	0.012 (0.611)	0.013 (0.622)
Indepentr	-0.050** (-2.572)	-0.050** (-2.567)	-0.051** (-2.584)	-0.138*** (-0.935)	-0.137** (-0.935)	-0.137** (-0.923)
MEI	0.010** (0.166)	-0.019* (-0.992)	0.008** (0.136)	-0.020 (-1.031)	0.012 (0.202)	-0.018 (-0.937)
SOEV/GRD	0.054** (2.041)	0.056** (2.104)	0.051* (1.939)	-0.008 (-0.849)	-0.008 (-0.831)	-0.009 (-0.889)
P	0.505*** (8.382)	0.505*** (8.425)	0.503*** (8.304)	0.430*** (8.377)	0.430*** (8.398)	0.429*** (8.288)
Cons						
N	273	273	273	272	272	272
R2	0.151	0.154	0.146	0.176	0.180	0.183
F	3.08***	3.15***	2.99***	3.29***	3.24***	3.39***
Mean VIF	1.27	1.26	1.28	1.28	1.28	1.29

注：*，**，***分别表示在 10%、5%和 1%的水平下显著；双尾检验，括号内为各系数 t 值。

由表 3 可知，模型 1 和模型 2 中 VIF 值均小于 10，说明模型 1 和模型 2 中不存在多重共线性。模型 1 结果显示综合型产业政策对企业创新质量具有显著的正向影响 ($\beta=0.047$, $p<0.05$)，表明政府颁布一揽子风电产业政策，整体上有助于激发企业创新行为更多地开展创新活动，从而有效地提升企业创新质量；激励型产业政策对风电企业的创新质量具有显著的正向影响 ($\beta=0.049$, $p<0.05$)，表明激励型政策能够培养形成风电技术利基市场和扩大市场需求，进一步降低风电企业研发成本，这与 Hsiao Y L, Sheng N, Fu S, et al. (2021)^[1]的研究结论一致；抑制型政策对企业创新质量同样具有显著的正向作用 ($\beta=0.043$, $p<0.1$)，表明抑制型政策可以改

善企业技术创新环境，提升企业核心竞争力。

模型 2 结果显示综合型产业政策、激励型产业政策对风电企业创新效率具有显著的正向影响 ($\beta=0.056$, $p<0.1$; $\beta=0.059$, $p<0.1$)，表明中央政府出台一系列产业政策通过刺激企业创新行为，改善企业创新环境，增加企业创新产出，从而提升风电企业创新效率；抑制型产业政策对风电企业创新效率提升没有通过检验 ($\beta=0.062$, $p>0.1$)，说明抑制型产业政策对风电企业创新效率的提升作用不显著，这可能是由于当前抑制型风电产业政策聚焦风电产业整体创新产出数量较多，忽视了创新效率的提升在改善风电产业自主创新能力中的贡献，从而导致针对创新效率的政策数量和政策力度较小；另

一个可能的原因在于效率的提升除了政策等外部刺激外更多依赖于企业内部研发和治理水平的提升。

关于控制变量，独立董事占比无论对创新质量还是创新效率都呈现明显的负相关，但企业规模越大越有利于创新效率的提升。高管股权激励和市场发育程度对企业创新质量具有显著正向作用，但对风电企业创新效率的提升作用并不显著；前者可能与公司的考核方式有关，我国多数公司对高管和员

工的考核激励指标指向产出数量和质量而非效率；后者说明市场发育程度只能为企业研发创新提供良好的外部环境，但是作为研发效率而言，则更多来自企业研发基础和对研发要素配置优化及内部公司治理水平，即企业创新研发效率更多依赖企业内部研发创新环境。

产业政策对风电企业的信贷融资检验结果如表 4 所示，模型中 VIF 均小于 10，说明该模型中不存在多重共线性。

表 4 产业政策对企业信贷融资的回归分析

变量	模型 3 (Loan)		
	CPE	Incentp	Regulatp
CPE	0.012* (1.678)		
Incentivep		0.012* (1.719)	
Regulatp			0.012 (1.602)
lnsize	-0.055*** (-3.399)	-0.055*** (-3.421)	-0.054*** (-3.358)
Ownership	0.012 (0.358)	0.012 (0.355)	0.012 (0.366)
EQR	0.027*** (5.030)	0.027*** (5.030)	0.027*** (5.032)
Tobin'Q	-0.010* (-1.866)	-0.010* (-1.893)	-0.010* (-1.824)
Herfi10	0.030*** (2.680)	0.030*** (2.690)	0.030*** (2.657)
Dual	0.012 (0.621)	0.012 (0.617)	0.013 (0.624)
Indepentr	-0.003 (-0.460)	-0.003 (-0.461)	-0.003 (-0.462)
MEI	0.003 (0.260)	0.003 (0.253)	0.003 (0.268)
SOEV/GRDP	-0.007 (-0.851)	-0.007 (-0.829)	-0.008 (-0.892)
Cons	0.170*** (8.588)	0.170*** (8.598)	0.170*** (8.566)
N	272	272	272
R2	0.180	0.181	0.180
F	3.81***	3.82***	3.78***
Mean VIF	1.26	1.26	1.27

注：*，**，***分别表示在 10%、5%和 1%的水平下显著；双尾检验，括号内为各系数 t 值

由模型 3 可以看到，产业政策整体对风电企业信贷融资具有显著正向影响 ($\beta=0.012$, $p<0.1$)，表明银行通过产业政策的传导收到了关于风电产业

技术优势、发展前景等方面良好的信号，通过政策干预等方式创造有利于产业发展的优良条件，从而提升风电企业从银行获取信贷融资的可能性 (Bose

U et al , 2019); 激励型产业政策对风电企业信贷融资具有显著的正向影响 ($\beta=0.012$, $p<0.1$), 说明激励型政策促使政府向风电企业提供大量的直接补助, 有效提升风电企业盈利能力, 同时银行信贷资源也是跟随政府导向进行配置, 遵从“政治优序融资” (李广子和刘力, 2020), 使得银行更倾向于将信贷资源配置给效率较高且被政府激励型政策支持的企业; 抑制型产业政策对风电企业的信贷融资影响不显著 ($\beta=0.012$, $p>0.1$), 即抑制型政策对提升风电企业信贷融资能力拉动作用不明显, 可能的原因在于政府对风电企业有关风电设备规范以及相关技术标准的建立, 增加了企业研发成本和风险从而降低了企业短期内预期盈利, 同时使一部分不具备研发实力的企业面临经营生产困难, 因此无

法满足银行的短期回报率要求。投资机会和企业规模对企业信贷融资均具有显著的负向影响, 表明大规模和发展前景良好的企业自有现金流和抗风险能力表现良好, 会对银行信贷产生一定的挤出效应 (朱德胜和周晓珮, 2016)。产权比率在一定程度上可以反映企业的对外融资能力, 检验结果显示产权比率对企业信贷融资具有显著的正向影响, 说明产权比率越高企业对外融资能力越强, 越能有效利用产业政策带来的有利信息获得更多信贷融资。模型 3 的检验结果显示, 股权集中度显著正向影响企业信贷融资, 表明股权集中度越高、公司稳定性越强越容易获得银行的认可和信贷支持。

2、信贷融资的中介效应回归分析

表 5 企业信贷融资的中介效应检验结果

变量	模型 4 Patentir	模型 5 Patentir	模型 6 Patentir	模型 7 Peffi	模型 8 Peffi	模型 9 Peffi
CPE	0.043* (1.949)			0.053* (1.665)		
Incentivep		0.045** (2.120)			0.056** (1.932)	
Regulatoryp			0.039* (1.671)			0.060 (1.544)
Loan	0.353* (1.683)	0.348* (1.660)	0.362* (1.720)	0.378* (1.532)	0.379* (1.455)	0.363* (1.545)
lnsize	-0.035 (-0.701)	-0.040 (-0.795)	-0.027 (-0.543)	-0.042 (-0.822)	-0.038 (-0.785)	-0.031 (-0.699)
Ownership	-0.028 (-0.271)	-0.029 (-0.286)	-0.025 (-0.245)	-0.043 (-0.311)	-0.031 (-0.345)	-0.045 (-0.368)
EQR	0.001 (0.065)	0.001 (0.064)	0.001 (0.067)	0.001 (0.078)	0.001 (0.077)	0.002 (0.081)
Tobin'Q	0.019 (1.150)	0.018 (1.096)	0.020 (1.227)	0.021 (1.253)	0.020 (1.119)	0.022 (1.202)
Herfi10	0.039 (1.128)	0.041 (1.179)	0.036 (1.042)	0.040 (1.235)	0.044 (1.312)	0.041 (1.119)
Dual	-0.018 (-0.300)	-0.018 (-0.294)	-0.019 (-0.316)	-0.021 (-0.312)	-0.021 (-0.301)	-0.022 (-0.336)
Indepentr	-0.049** (-2.532)	-0.049** (-2.527)	-0.050** (-2.544)	-0.057* (-2.756)	-0.058* (-2.745)	-0.059* (-2.765)
RIE	-0.008 (-0.219)	-0.008 (-0.220)	-0.008 (-0.223)	-0.004 (-0.199)	-0.004 (-0.211)	-0.004 (-0.221)
SOEV/GRDP	0.057** (2.152)	0.058** (2.210)	0.054** (2.058)	0.061* (2.224)	0.067* (2.199)	0.065* (2.078)
Cons	0.444*** (6.373)	0.446*** (6.418)	0.441*** (6.297)	0.355*** (5.989)	0.354*** (5.921)	0.351*** (5.887)
N	272	272	272	272	272	272
R2	0.162	0.164	0.160	0.154	0.152	0.150
F	3.07***	3.13***	2.98***	3.31***	3.37***	3.12***
Mean VIF	1.46	1.46	1.47	1.67	1.68	1.67

注: *, **, ***分别表示在 10%、5%和 1%的水平下显著; 双尾检验, 括号内为各系数 t 值。

信贷融资的中介效应检验结果如表 5 所示：由模型 1、4、5 可知，产业综合政策（激励型政策）对企业创新质量的回归系数由 0.047（0.049）下降至 0.043（0.045）P 值<0.1 仍然显著，且中介变量企业信贷融资的回归系数显著 $\beta=0.353$ （ $\beta=0.348$ ），说明信贷融资在激励型政策、产业综合政策对风电企业创新质量的驱动路径上起部分中介作用；由模型 2、7、8 可知，产业综合政策（激励型政策）对企业创新效率的回归系数由 0.056（0.059）下降至 0.053（0.056）P 值<0.1，但仍然显著，且中介变量企业信贷融资的回归系数显著 $\beta=0.378$ （ $\beta=0.379$ ），说明企业信贷融资在激励型政策以及产业综合政策与企业创新效率之间起着部分中介作用；由模型

3 和模型 6 可知，抑制型政策对企业信贷融资的回归系数不显著（ $\beta=0.012$, $p>0.1$ ），而抑制型政策对企业创新质量的回归系数显著（ $\beta=0.039$, $p<0.1$ ）；进一步做 Sobel 检验（ $p>0.1$ ）发现，信贷融资在抑制型产业政策对风电企业创新质量驱动路径上中介效应不显著；由模型 3 和模型 9 可知抑制型产业政策对信贷融资和创新效率的回归系数均不显著（ $\beta=0.012$, $p>0.1$; $\beta=0.060$, $p>0.1$ ），说明信贷融资在抑制型产业政策对风电企业创新效率作用路径上中介效应不显著。

3、高管海外经历的调节效应回归分析

调节变量高管海外经历在产业政策对创新质量和创新效率路径上的检验结果如表 6 所示：

表 6 高管海外经历的调节效应检验结果

变量	模型 10	模型 11	模型 12	模型 13	模型 14	模型 15
	Patentir	Peffi	Patentir	Peffi	Patentir	Peffi
CPE	0.059*** (2.626)	0.061** (2.737)				
Incentivep			0.060*** (2.786)	0.062** (2.753)		
Regulatoryp					0.056** (2.362)	0.059 (2.664)
Oversea	0.010 (0.166)	0.011 (0.203)	0.008 (0.136)	0.010 (0.199)	0.012 (0.202)	0.013 (0.196)
CPE×Oversea	0.049** (2.444)	0.057** (2.532)				
Incentivep×Oversea			0.047** (2.417)	0.055** (2.464)		
Regulatoryp×Oversea					0.052** (2.470)	0.058** (2.573)
Insize	-0.056 (-1.161)	-0.047 (-1.023)	-0.060 (-1.243)	-0.049 (-1.113)	-0.050 (-1.019)	-0.042 (-1.002)
Ownership	-0.013 (-0.131)	-0.021 (-0.127)	-0.015 (-0.152)	-0.023 (-0.119)	-0.010 (-0.096)	-0.019 (-0.084)
EQR	0.011 (0.668)	0.009 (0.558)	0.011 (0.656)	0.009 (0.556)	0.011 (0.691)	0.009 (0.581)
Tobin'Q	0.010 (0.637)	0.005 (0.526)	0.009 (0.580)	0.008 (0.438)	0.012 (0.722)	0.011 (0.654)
Herfi10	0.059* (1.726)	0.043* (1.636)	0.060* (1.760)	0.040* (1.678)	0.057* (1.664)	0.047* (1.701)
Dual	-0.006 (-0.107)	-0.004 (-0.098)	-0.006 (-0.100)	-0.004 (-0.095)	-0.008 (-0.127)	-0.006 (-0.102)
Indepentr	-0.049** (-2.554)	-0.042** (-2.336)	-0.049** (-2.554)	-0.041** (-2.254)	-0.050** (-2.560)	-0.040** (-2.278)
MEI	0.054** (2.080)	0.061** (2.134)	0.053** (2.023)	0.062** (2.156)	0.057** (2.178)	0.062** (2.272)
SOEV/GRDP	0.054** (2.050)	0.065** (2.151)	0.055** (2.107)	0.066** (2.171)	0.051* (1.958)	0.067* (2.035)
Cons	0.492*** (8.233)	0.493*** (8.271)	0.491*** (8.165)	0.431*** (8.012)	0.433*** (8.145)	0.430*** (8.002)
N	273	272	273	272	273	272

R ²	0.175	0.164	0.178	0.167	0.171	0.162
F	3.13***	3.24***	3.18***	3.27***	3.05***	3.19***
Mean VIF	1.34	1.43	1.33	1.44	1.35	1.44

注：*，**，***分别表示在 10%、5%和 1%的水平下显著；双尾检验，括号内为各系数 t 值。

调节变量高管海外经历在产业政策对信贷融资路径上的检验结果如表 7 所示：

表 7 高管海外经历的调节效应检验结果

变量	模型 16	模型 17	模型 18
	Loan	Loan	Loan
CPE	0.015** (1.996)		
Incentivep		0.014** (2.028)	
Regulatoryp			0.015* (1.934)
Oversea	-0.019 (-0.992)	-0.020 (-1.031)	-0.018 (-0.937)
CPE×Oversea	0.014** (2.196)		
Incentivep×Oversea		0.014** (2.175)	
Regulatoryp×Oversea			0.015** (2.216)
Insize	-0.057*** (-3.548)	-0.057*** (-3.561)	-0.056*** (-3.523)
Ownership	0.016 (0.464)	0.015 (0.456)	0.016 (0.479)
EQR	0.027*** (5.114)	0.027*** (5.109)	0.027*** (5.122)
Tobin'Q	-0.012** (-2.273)	-0.012** (-2.300)	-0.012** (-2.226)
Herf10	0.035*** (3.112)	0.035*** (3.113)	0.035*** (3.103)
Dual	0.014 (0.714)	0.014 (0.712)	0.014 (0.712)
Indepentr	-0.003 (-0.426)	-0.003 (-0.431)	-0.003 (-0.421)
MEI	0.009 (1.063)	0.009 (1.040)	0.010 (1.109)
SOEV/GRDP	-0.008 (-0.892)	-0.008 (-0.875)	-0.008 (-0.924)
Cons	0.166*** (8.469)	0.166*** (8.469)	0.166*** (8.446)
N	272	272	272
R ²	0.207	0.207	0.206
F	3.83***	3.84***	3.82***
Mean VIF	1.34	1.33	1.35

注：*，**，***分别表示在 10%、5%和 1%的水平下显著；双尾检验，括号内为各系数 t 值。

由表 6 和表 7 可知,模型 10 中的 CPE×Oversea、模型 12 中的 Incentivep×Oversea、模型 14 中的 Regulatoryp×Oversea、模型 11 中的 CPE×Oversea、模型 13 中的 Incentivep×Oversea、模型 15 中的 Regulatoryp×Oversea、模型 16 中的 CPE×Oversea、

模型 17 中的 Incentivep×Oversea 以及模型 18 中的 Regulatoryp×Oversea 回归系数均为正,且通过显著性检验,表明样本企业的高管海外经历在产业政策对企业创新质量、创新效率以及产业政策对企业信贷融资三条驱动路径上均具有显著的调节作用。

上述结果表明，高管的海外经历能够显著放大产业政策对风电企业创新质量、创新效率和信贷融资能力的提升作用。说明在我国风电产业创新过程中，具有海外工作或学习经历的高管的确能够利用自己接触或者掌握的最前沿创新技术、范式、创新资源以及技术预见能力提升企业创新质量和创新效率，这与周泽将等(2014)^[1]学者的研究结论一致，具有海外经历的高管数量越多越有利于企业高质量创新。

4、稳健性检验

为了检验上述研究结果的稳健性和可靠性，本文采用替换中介变量指标重新检验企业信贷融资的中介效应，重新估计产业政策对企业创新质量和创新效率的影响。本文采用长期借款与短期借款之和与企业有形资产的比率重新测度企业信贷融资，

其中有形资产=资产总计—无形资产净额—商誉净额，结果如表 8 所示。在中介效应检验中，产业综合政策和激励型政策对企业信贷融资的回归系数略有下降，但都仍然在 10%水平下显著 ($\beta=0.013$ $p<0.1$; $\beta=0.012$, $p<0.1$)，而抑制型政策对企业信贷融资的回归系数呈正相关但仍不显著 ($\beta=0.013$, $p>0.1$)；在调节效应检验中， $CPE \times Oversea$ 、 $Incentivep \times Oversea$ 以及 $Regulatoryp \times Oversea$ 对替换后的企业信贷融资指标的回归系数均同样为正且都显著，说明高管海外经历在风电产业政策与样本企业信贷融资之间的调节作用依旧显著。综上，替换中介变量指标后的回归结果均表明原有研究结论不存在因测量误差导致的内生性问题，基本结论仍然一致，因此模型估计结果是稳健的。

表 8 稳健性检验

变量	中介效应检验						调节效应检验					
	Loanreplace	Patentir	Peffi	Loanreplace	Patentir	Peffi	Loanreplace	Patentir	Peffi	Loanreplace	Loanreplace	Loanreplace
CPE	0.013*	0.045**	0.043**							0.016**		
	(1.682)	(2.032)	(2.013)							(2.011)		
Incentivep				0.013*	0.047**	0.045**					0.016**	
				(1.721)	(2.207)	(2.078)					(2.042)	
Regulatoryp							0.013	0.041*	0.039**			0.016*
							(1.608)	(1.748)	(2.004)			(1.949)
Loanreplace		0.347*	0.369*		0.342*	0.364		0.356*	0.378			
		(1.752)	(1.801)		(1.728)	(1.797)		(1.790)	(1.814)			
Oversea										-0.022	-0.023	-0.021
										(-1.105)	(-1.145)	(-1.049)
CPE×Oversea										0.016**		
										(2.309)		
Incentivep×Oversea											0.015**	
											(2.295)	
Regulatoryp×Oversea												0.017**
												(2.319)
Insize	-0.056***	-0.039	-0.053	0.056***	-0.044	-0.058	-0.055***	-0.031	-0.045	-0.058***	-0.058***	-0.057***
	(-3.246)	(-0.783)	(-0.901)	(-3.267)	(-0.880)	(-0.892)	(-3.205)	(-0.620)	(-0.881)	(-3.409)	(-3.421)	(-3.385)
Ownership	0.016	-0.026	-0.017	0.016	-0.028	-0.019	0.017	-0.024	-0.015	0.020	0.020	0.021
	(0.454)	(-0.258)	(-0.197)	(0.451)	(-0.272)	(-0.206)	(0.461)	(-0.233)	(-0.183)	(0.567)	(0.560)	(0.581)
EQR	0.029***	0.000	0.000	0.029***	0.000	0.000	0.029***	0.000	0.000	0.029***	0.029***	0.029***
	(5.093)	(0.019)	(0.019)	(5.092)	(0.019)	(0.019)	(5.094)	(0.022)	(0.020)	(5.191)	(5.186)	(5.199)
Tobin'Q	-0.010*	0.018	0.038	-0.010*	0.017	0.037	-0.009*	0.020	0.040	-0.012**	-0.012**	-0.012**
	(-1.708)	(1.129)	(1.654)	(-1.735)	(1.635)	(1.129)	(-1.665)	(1.209)	(1.698)	(-2.146)	(-2.175)	(-2.097)
Herf10	0.032***	0.038	0.017	0.032***	0.040	0.019	0.032***	0.035	0.014	0.038***	0.038***	0.038***

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	(2.696)	(1.098)	(0.972)	(2.706)	(1.149)	(0.996)	(2.674)	(1.011)	(0.836)	(3.168)	(3.169)	(3.160)
Dual	0.014	-0.020	-0.027	0.014	-0.019	-0.026	0.014	-0.021	-0.028	0.016	0.016	0.016
	(0.661)	(-0.325)	(-0.436)	(0.657)	(-0.319)	(-0.421)	(0.665)	(-0.340)	(-0.445)	(0.758)	(0.757)	(0.755)
Indepentr	-0.004	-0.042**	-0.037**	-0.004	-0.042**	-0.037**	-0.004	-0.043**	-0.035**	-0.004	-0.004	-0.004
	(-0.604)	(-2.077)	(-1.883)	(-0.602)	(-2.065)	(-1.882)	(-0.610)	(-2.100)	(-1.865)	(-0.584)	(-0.587)	(-0.582)
MEI	0.012	0.057**	0.044**	0.012	0.055**	0.044**	0.013	0.059**	0.044**	0.011	0.011	0.011
	(1.349)	(2.166)	(2.006)	(1.330)	(2.119)	(2.074)	(1.383)	(2.243)	(2.104)	(1.175)	(1.150)	(1.223)
SOEV/GRDP	-0.008	0.057**	0.448**	-0.008	0.059**	0.550**	-0.009	0.055**	0.446**	-0.009	-0.008	-0.009
	(-0.890)	(2.171)	(2.083)	(-0.869)	(2.091)	(2.171)	(-0.931)	(2.075)	(2.044)	(-0.937)	(-0.921)	(-0.969)
Cons	0.177***	0.440***	0.471***	0.176***	0.442***	0.473***	0.177***	0.437***	0.468***	0.172***	0.172***	0.173***
	(8.443)	(6.356)	(6.664)	(8.452)	(6.400)	(6.658)	(8.423)	(6.280)	(6.652)	(8.329)	(8.335)	(8.315)
N	272	272	272	272	272	272	272	272	272	272	272	272
R ²	0.183	0.153	0.144	0.184	0.156	0.147	0.182	0.148	0.139	0.213	0.213	0.212
F	3.86***	2.85***	2.84***	3.88***	2.92***	2.91***	3.84***	2.76***	2.75***	3.96***	3.97***	3.95***
Mean VIF	1.26	1.46	1.37	1.26	1.45	1.36	1.27	1.46	1.37	1.34	1.33	1.35

注：“*”、“**”、“***” 分别表示在 10%、5%、1%水平下显著，括号内为标准误差。

五、结论与政策建议

1、研究结论

如何有效激励风电企业进行创新活动，促使企业创新质量和创新效率的双增长，实现经济增长动力由要素驱动转向创新驱动是当前政府面临的重要问题。本文基于质量和效率双视角、以信贷融资为中介变量、高管海外经历为调节变量、以 2008-2020 年间风电企业上市公司为样本，探讨了我国风电产业政策对样本企业技术创新的作用机制问题。实证分析发现：

(1) 总体而言，无论从创新质量还是创新效率提升方面看，我国政府发布的系列产业政策对样本企业的技术创新具有显著促进作用，但不同政策类型的驱动效果存在显著差异；综合型和激励型产业政策对于风电企业改善融资约束、提升信贷融资能力具有显著的正向影响，而抑制型产业政策则不显著，究其原因在于抑制型产业政策多为相关技术标准和运营准则的规范政策，易在短期内增加企业创新成本和风险致使银行难以评估企业研发项目质量、潜在风险，因此抑制了信贷机构对企业投资的积极性。

(2) 受“形式主义”和“短期利益”影响，独立董事无论对创新质量还是效率都呈现典型的负相关，但企业规模越大越有利于创新效率的提升。高管股权激励和市场发育程度对于企业创新质量具有显著正向影响，但对风电企业创新效率影响并不显著。前者可能与我国多数公司对高管和员工的考核指标指向产出数量和质量而非效率；后者说明市场发育程度只能为企业研发创新提供良好的外部环境，但是作为研发效率而言，则更多来自企业研发基础和对研发要素配置优化及内部公司治理水平，即企业创新研发效率更多依赖企业内部研发创新环境。

(3) 信贷融资在不同作用路径上的中介作用效果不同。在政策对创新质量和创新效率的作用路径上，激励型和综合型政策能够显著改善风电企业信贷融资能力，缓解融资压力，进而提升企业的创新质量和效率；而抑制型政策对改善企业信贷融资

效果不显著。因此，信贷融资在激励型、综合型产业政策对企业创新质量和效率作用路径上起中介作用，而在抑制型政策对企业创新质量和效率作用路径上不起中介作用。

(4) 实证结果显示高管海外经历能够显著正向调节不同类型产业政策对企业创新质量、创新效率和信贷融资的刺激作用，表明高管海外经历能够显著放大产业政策对企业创新质量、创新效率和信贷融资的杠杆作用。相对而言，拥有海外经历的高管有更多机会接触最优质的创新资源和更前沿的创新技术及理念，因此也更有动力积极整合内部技术优势和产业政策等稀缺资源，更加关注创新质量和创新效率的提升。

2、政策建议

基于以上分析和讨论，本文建议如下：

(1) 政府应继续提升对风电产业的政策扶持力度，提高产业政策的可操作性和精准性；在政策顶层规划设计时，根据风电产业不同研发阶段和政策需求，优化政策内部结构、合理调整激励性产业政策和抑制型产业政策比例，注重不同类型如激励型和抑制型政策的协同和匹配，发挥政策协同效果为风电企业创新发展创造空间。

(2) 进一步健全我国信贷市场和完善银行融资服务体系，发挥银行信贷在缓解风电企业创新融资约束中的主导地位，探索融资机构针对不同生命周期阶段的风电产业创新发展的信贷支持政策，拓展风电企业融资渠道，增强信贷市场投资活力，使金融中介更好地服务于实体经济发展和核心技术创新。

(3) 优化高管结构和管理。企业要控制独立董事的数量，将企业创新质量和创新效率纳入与高管绩效考核挂钩。尤其要重视对海外人才的吸纳，企业高管团队建立和管理过程中应吸纳适当比例的具有海外经历的人才进入高管团队，并给予更大的支持力度和权限，以帮助企业精准识别技术创新方向，补齐企业技术创新短板，从而提升企业创新质量和创新效率，提高我国风电产业国际创新链的地位和价值。

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中国食品浪费政策干预效果评估及情景预测 ——基于 1955-2021 年政策分析

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摘要：食品浪费干预政策作为减少食物损失和浪费的主要工具，不仅有利于保障国家粮食安全，同时对减少食物浪费相关温室气体排放起到至关重要的作用，然而未有研究对中国食品浪费政策干预效果进行分析。本研究基于对 1955-2021 年 67 年间中国出台的 874 份食品浪费政策文本分析，运用 Latent Dirichlet Allocation (LDA) 模型和柯布—道格拉斯生产函数二元回归模型，评估食品浪费政策的力度和干预效果。进一步通过支持向量回归机建模，在七种情景模式下对 2022-2030 年七种主要食物浪费量进行预测，选择最优政策组合。研究发现：（1）中国食品浪费政策数量、年政策力度及累计年政策力度逐年上升，而年平均政策力度呈现下降趋势。（2）四种政策工具中，自愿型政策的发布数量、累计力度和平均力度最高，其次是强制型、指令型和激励型政策，政策力度与大豆、蔬菜、水果、牛奶等七种主要食品浪费量均具有显著的负相关关系，但无论哪种类型政策对谷类浪费的干预效果均不佳。（3）自愿型政策对食品浪费的总体干预效果最好，其次是强制型、激励型、指令型政策。同时，自愿型政策对食物浪费导致的二氧化碳排放抑制作用最好，其次是强制型、指令型、激励型政策。（4）情景预测证实，以自愿型政策为主导的组合模式干预效果最佳。最后基于结果提出政策未来发展方向，本研究对优化食品浪费政策体系提供有益补充，为国家食品浪费干预给予现实指导。

关键词：食品浪费政策；政策力度；政策干预效果；LDA 模型；支持向量机；政策组合模型

Assessment of policy effectiveness for the food waste reduction in China based on policy quantification from 1955 to 2021

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Abstract: As a major tool to reduce food loss and waste, food waste intervention policies not only contribute to national food security but also play a crucial role in reducing greenhouse gas emissions associated with food waste, however, no study has analysed the effectiveness of food waste intervention policies in China. This study used Latent Dirichlet Allocation models and Cobb-Douglas regression models to assess the effectiveness of food waste intervention policies in China, based on the analysis of 874 food waste policy texts issued in China from 1955 to 2021. Further modeling by support vector regression machine was used to predict the amount of food waste in seven groups for 2022-2030 to select the optimal policy mix. It was found that: (1) The number, policy power yearly and cumulative annual policy power of food waste policies in China increased each year, while the average annual policy power showed a decreasing trend. (2) Among the four policy instruments, voluntary policies had the highest number of releases, cumulative power and average power, followed by coercive, directive and incentive policies. (3) Voluntary policies had the best overall intervention effect on food waste, followed by coercive, incentive and directive policies. At the same time, voluntary policies were the most effective in curbing CO₂ emissions due to food waste, followed by coercive, directive and incentive policies. (4) Scenario predictions confirmed that a combined policy model intervention led by voluntary policies works best. Finally, based on the results, future directions for policy development are proposed.

Keywords: food waste policy; policy power; policy effectiveness; LDA model; support vector machine;

碳达峰目标下火电行业最优减排量及碳配额均衡价格研究— 基于分数布朗运动模型和最优控制理论的实证分析

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摘要 碳配额交易市场和清洁能源的低碳发电技术，是电力行业降低 CO_2 排放，实现碳达峰和碳中和目标的关键手段。在以火电企业为参与主体的全国碳交易上线交易正式启动的背景下，考虑到气电代替煤电需要的单位减排能源转换成本的随机性，本文将金融分形市场中的分数布朗运动模型引入到火电企业减排策略决策过程中以降低碳减排成本，建立了合规期内的随机最优化模型；在碳市场出清条件下，得到碳配额价格服从混合分数布朗运动过程；结合动态优化原理和分数 Itô 公式，以碳减排量和交易量为控制变量，推导出最优总合规成本满足的哈密顿-雅可比-贝尔曼 (H-J-B) 方程，并求得解析解，进一步得到最佳减排量和碳配额均衡价格公式。以 2021-2030 年为一合规期，在保障电力供应、保证经济增长的前提下，利用现实数据进行数值模拟，结果表明：不同达峰年份情景下的最优减排量和合意的碳配额均衡价格均呈现逐年递增的趋势，合规期前期，达峰时间越晚，最优减排量和碳配额均衡价格越高，在合规期后期，则呈现相反的态势；碳减排设备系数对碳交易均衡价格有正的影响，且影响程度较小；Hurst 指数对碳配额均衡价格影响显著，间接说明了碳配额交易价格明显会受到能源价格波动的影响；初始碳配额对最优减排量和碳配额均衡价格均有负的影响，且对最优减排量影响较为突出。研究结果可以为火电企业制定减排策略和碳市场的碳定价提供参考基准。

关键词 碳达峰；混合分数布朗运动模型；最优控制；碳排放权价格

Optimal reduction and carbon allowance equilibrium price of thermal power industry under the target of carbon peak—Empirical analysis based on fractional Brownian motion model and optimal control principle

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Abstract The carbon allowance trading market and low-carbon power generation technologies from clean energy sources are important tools for the power industry to reduce CO_2 emissions and achieve the targets of carbon peak and carbon neutrality. However, the current research on the optimal emission reduction and the equilibrium price of carbon allowance for thermal power enterprises are relatively deficient, based on the comprehensive consideration of the stochasticities for the fuel-switching cost per unit emission reduction for clean energy instead of coal power generation and the price of carbon allowance trading. Therefore, this paper chooses the fractional Brownian motion model to characterize the "leptokurtosis and fat-tail" of historical data on unit abatement cost, and concludes that the carbon allowance price conforms to the mixed fractional Brownian motion process under the condition that the carbon market reaches equilibrium. A stochastic optimization model is established from the perspective of minimizing the total cost of thermal power enterprises during the compliance period. Combining the dynamic optimization principle and the fractional Itô's formula, the Hamilton-Jacobi-Bellman (H-J-B) equation for the optimal total compliance cost is derived with the amount of the carbon reduction and the trading volume as the control variables, and its analytical solution is found to further obtain the formulas for the optimal emission reduction and carbon allowance equilibrium price. Taking 2021-2030 as a compliance period, numerical simulations are carried out using real data under the premise of ensuring power supply and economic growth. The results indicate

that the optimal emission reduction and the desired equilibrium price of carbon allowance under different scenarios of carbon peak year show an increasing trend yearly. In the early stage of the compliance period, the later the peak time, the higher the optimal emission reduction and the equilibrium price of carbon allowance. The opposite situation appears in the late part of the compliance period. The coefficient of carbon emission reduction equipment has a small positive effect on the equilibrium price of carbon trading. The Hurst index has a significant impact on the equilibrium price of carbon allowances, which indirectly indicates that the trading price of carbon allowances will obviously be affected by fluctuations in energy prices. The initial carbon allowance has a negative impact on both the optimal emission reduction and the equilibrium price of carbon allowances, with the optimal emission reduction influenced prominently. The research results can provide a reference benchmark for thermal power enterprises to develop emission reduction and carbon pricing strategies in the carbon market.

Key words carbon peak; fractional Brownian motion; optimal control; carbon emission allowance price

工业集聚、环境规制对大气污染物排放的影响：来自中国的证据

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摘要：生产集约化和环境规制是降低大气污染排放规模的关键。基于 2005-2019 年中国 30 个省份的面板数据，本研究探究了工业集聚和环境规制对大气污染物排放的影响以及它们的协同减污效应。结果表明：第一，工业集聚与大气污染物排放的关系是倒 U 型的，只有当工业集聚超过一定阈值后，它才能发挥显著的减污绩效。环境规制的波特效应被实证研究所支持，它有利于抑制大气污染物排放。在解决内生性后，该发现依然稳健。（2）大气污染物排放存在空间依赖性，工业集聚和环境规制存在空间溢出效应。工业集聚对临近地区的影响也为倒 U 型，环境规制增加了周边地区的污染排放，验证了污染避难所效应。（3）随着环境规制力度的增强，其自身对大气污染物排放的边际影响更加显著。此外，在环境规制强的地区，工业集聚的拐点值下降，使得集聚的溢出效应和减污绩效更早发挥。本研究为中国和其他发展中国家发挥工业集聚和环境规制的协同减污效应提供了经验证据和政策启示。

关键词：大气污染物排放；工业集聚；环境规制；工具变量；空间杜宾模型

Industrial Agglomeration, Environmental Regulation and Atmospheric Pollutant Emissions: Evidence from China

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Abstract: Production intensification and environmental regulation are key to reducing atmospheric pollution emissions (APEs). Based on panel data covering 30 provinces in China during 2005-2019, we explore the impact of industrial agglomeration and environmental regulation on APEs and their synergistic pollution reduction effects. The results show that: First, the nexus between industrial agglomeration and APEs is U-shaped, and it can exert significant pollution reduction performance only when industrial agglomeration exceeds the turning point. Our study supports the Porter effect that environmental regulation mitigates APEs, and this conclusion remains robust after alleviating endogenous. (2) There is a spatial dependence in APEs and spatial spillover in industrial agglomeration and environmental regulation. Similarly, industrial agglomeration has an inverted U-shaped effect on APEs of adjacent areas. Besides, the pollution refuge effect that environmental regulation increases APEs of adjacent areas is validated. (3) As environmental regulation increases, its marginal impact on APEs becomes more significant. In addition, the turning point of industrial agglomeration decreases, which allows the spillover effect to play out earlier. This study provides empirical evidence and policy implications for China and other developing countries to exploit the synergistic pollution reduction effects of industrial agglomeration and environmental regulation.

Key Words: Atmospheric pollutant emissions; Industrial agglomeration; Environmental regulation; Instrumental variables; Spatial Durbin model

数字经济抑制了大气污染物排放吗？-基于省际数据的研究

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摘要：本文基于 2012-2019 年的中国省级面板数据，运用中介效应模型和空间杜宾模型，探究数字经济对大气污染排放的作用机制和区域影响差异。结果表明：数字经济通过促进技术创新影响大气污染物排放，该结论经稳健性检验依然成立；数字经济发展与 $PM_{2.5}$ 、 SO_2 和 NO_x 之间存在先促进后抑制的“倒 U 型”溢出效应，且拐点值低于直接效应拐点值，产业结构升级对 $PM_{2.5}$ 、 SO_2 和 NO_x 存在负的空间外溢效应；进一步研究发现，数字经济对大气污染呈现显著的空间异质性，东部地区数字经济整体处于拐点值右侧，对大气污染基本呈现抑制作用，而西部地区多数尚未跨过拐点值，且溢出效应拐点值要高于直接效应；中部地区数字经济对 $PM_{2.5}$ 存在负的线性溢出效应，对 NO_x 不存在空间溢出效应。针对实证结果，本文提出相关政策建议。

关键词：数字经济 大气污染 中介效应 空间杜宾模型 异质性

Does the digital economy curb air pollution? -An empirical analysis from provincial data of China

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Abstract: This study uses China's provincial panel data during 2012-2019 to explore the mechanism and regional differences in impacts of digital economy on $PM_{2.5}$, SO_2 and NO_x in China. Results show that the digital economy affects air pollutants by promoting technological innovation; "inverted U-shaped" spillover effects exist between digital economy and air pollutants, the inflection points are lower than the inflection point of direct effect, and the industrial structure upgrading has a negative spatial spillover effect on $PM_{2.5}$, SO_2 and NO_x ; Further study finds that the digital economy in China's eastern and western regions have "inverted U-shaped" relationships with air pollution, and the digital economy in the eastern region is on the right side of the inflection point, which basically has a suppressive effect on air pollution, while the inflection point of the spillover effect in the western region is higher than that of the direct effect. The digital economy in the central region has a negative linear spillover effect on $PM_{2.5}$ and no spatial spillover effect on NO_x . Policy implications are put forth related to these empirical results.

Keywords: digital economy, air pollution, intermediate effect, spatial heterogeneity

Quality evaluation of industrial statistics based on BL-TOPSIS: A case study of China's coal and its downstream industries

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Abstract: The authenticity and quality of industrial statistical data directly affect all types of systematic research based on it. Considering the limitations of extant data quality evaluation literature on research objects and evaluation methods, we constructed a new data quality comprehensive inspection and evaluation model based on Benford Law-Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), selected coal-related industries as the research object, and conducted an empirical test along the research path of “Industry→Province→Indicator”. The results showed that at an industry level, the quality of statistical data for China’s coal-related industries from 2001 to 2016 was generally poor. Among the eight sample industries selected, the data quality for five industries, including coal, electricity, and steel, was assessed as poor or a slightly poor. Furthermore, at the provincial-level, there is significant spatial heterogeneity in the quality of statistical data of various industries affected by factors such as economic structure, marketization level and industrial diversity. Compared with other types of statistical indicators, industry financial indicators are more prone to data quality problems at the indicator level and the suspiciousness indicators of different industries show certain common characteristics and some industry differences. To improve the quality of industrial statistical data and reduce the possible adverse impact of data quality problems, based on the research findings, we propose targeted countermeasures and suggestions on how to prevent data fraud, and effectively identify and rationally use suspicious data.

Keywords: Industrial statistics, Data quality, Comprehensive evaluation, Coal-related industry

区域生态文明建设多元主体参与意愿的生发机制研究 ——基于“认知-态度-意愿”的生成逻辑

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摘要：文基于“认知-态度-意愿”的生成逻辑，分析区域生态文明建设多元主体的认知认识、心理因素、规范因素等前因变量，并引入情境因素作为调节变量，构建区域生态文明建设多元主体参与意愿的生发机制。研究表明：女性群体比男性有更高的参与意愿，受教育水平越高的主体其参与意愿则更加强烈，教育科研人员、在校大学生及政府机关单位人员在这过程中起到主要调控作用；生态文明建设的支持度、个人主观规范、社会规范、参与责任意识和满意度对参与意愿均有直接正向作用，而个体认知因素通过参与责任意识间接影响参与意愿；引导政策与建设背景等情境因素，显著调节了个人支持度、主观规范、社会规范对多元主体生态文明建设参与意愿的影响效应。最后，本文提出推动多元主体参与生态文明建设中的相关政策建议。

关键词：生态文明，参与意愿，多元主体，生发机制，结构方程模型

Study on the Generation Mechanism of the Willingness of Multiple Subjects to Participate in the Construction of Regional Ecological Civilization--Based on the Generative Logic of "Cognition Attitude Willingness"

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Abstract: This paper analyzes the antecedent variables such as cognitive cognition, psychological factors and normative factors of multiple subjects in the construction of regional ecological civilization, and introduces situational factors as regulatory variables to construct the generation mechanism of multiple subjects' willingness to participate in the construction of regional ecological civilization based on the generative logic of "cognition attitude will". The research shows that female groups have higher willingness to participate than men, and the subjects with higher education level have stronger willingness to participate. Educational researchers, college students and government personnel play a major regulatory role in this process; The support of ecological civilization construction, personal subjective norms, social norms, sense of responsibility and satisfaction have a direct positive effect on the willingness to participate, while individual cognitive factors indirectly affect the willingness to participate through the sense of responsibility; Situational factors such as guiding policies and construction background significantly adjust the impact of personal support, subjective norms and social norms on the willingness of multiple subjects to participate in the construction of ecological civilization. Finally, this paper puts forward relevant policy suggestions to promote multiple subjects to participate in the construction of ecological civilization.

Key words: ecological civilization, Willingness to participate, Multiple subjects, Germinal mechanism, structural equation model

Carbon Emissions trading, regional heterogeneity, and green innovation: Evidence from a quasi-natural experiment in China

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Abstract: China has implemented carbon trading pilot policy to force incumbent firms to conduct green innovation. However, there are significant differences in economic development, system design and policy enforcement among the eight pilot regions. To this end, we try to use the synthetic control approach to identify the heterogeneous effect of regional ETSs on green innovation. Furthermore, we also test the regional-specific effect through the moderated regression analysis, take the roles of carbon market liquidity, ETS coverage and regional economic development into account. Finally, we adopt the dynamic regression model to verify the annual treatment effect of the ETS as well as the varying effect on green innovation from different pilot ETSs. The empirical results show that only Hubei and Guangdong ETSs have effectively promoted the green innovation, while the Tianjin ETS has a short-term promotion effect before the economic sluggish period. However, the pilot ETSs in other regions have not a positive effect on green innovation with the different evolution path. Meanwhile, only in Hubei and Guangdong can the pilot ETSs have a continuous positive effect on green innovation on year-by-year basis. The appropriate industrial coverage and emissions control target as well as the active trading platform have been identified as important factors to positively moderate the effect of regional ETS on promoting green innovation. Then the Chinese central government should take full account of the regional heterogeneity and then make full use of the national ETS to promote green innovation. The local regulators can have some flexibility to determine and adjust the appropriate emissions reduction target promptly. Furthermore, the policymakers should take the emissions from primary energy consumption in the major energy-intensive industrial sectors as the main coverage of the national ETS. In addition, the regulators can further strengthen the supervision on allowance trading and compliance behavior of the incumbent firms.

Key Words: Emissions trading; Regional heterogeneity; Green innovation; Synthetic control model; Moderating effect model; Dynamic effect

基于变分模态分解和孤立森林的合意工业产能利用率区间估计方法及应用

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摘要：在国家供给侧结构性改革和高质量发展双重战略背景下，为实现工业产能过剩的精准判别与调控，提出了一种基于变分模态分解和孤立森林的合意工业产能利用率区间估计方法。首先用变分模态分解将复杂时序分解成多个较为简单且特征清晰的模态固有函数；然后采用孤立森林对分量集合进行异常值的多尺度识别，确定异常值域，并估计合意产能利用率区间；最后以煤炭行业为例验证了模型的有效性，并揭示了煤炭产能过剩致因机理。结果表明：该方法引入自适应的分解步骤能够有效降低非线性、非平稳的复杂序列分析难度，并采用无监督算法自适应地确定阈值，有效克服了传统统计与经验方法的主观性和缺乏理论依据的局限性；我国煤炭行业的合意产能利用率区间为 73.13%~86.31%，且相较于现行经验标准（79~82%），更加符合我国煤炭行业发展实际；经过 2016-2020 年阶段性去产能工作，煤炭产能利用率显著提高，但仍略低于合意区间下限；煤炭需求变化对产能过剩的影响存在提前期，并易掩盖体制扭曲导致的产能过剩。该研究为工业产能过剩风险监测与判别提供了量化分析工具，为深化煤炭产能过剩治理提供了决策依据。

关键词：产能利用率；合意区间；变分模态分解；孤立森林

An Estimation Method and Application of Consensual Industrial Capacity Utilization Interval Based on Variational Mode Decomposition and Isolation Forest Method

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Abstract: Under the background of the dual national strategy of supply-side structural reform and high-quality development, to achieve precise identification and control of industrial overcapacity, an estimation method of consensual industrial capacity utilization interval based on Variational Mode Decomposition and Isolation Forest Method is proposed. Firstly, the complex time series is decomposed into several simple and clear modal intrinsic functions by variational modal decomposition; Then, the outliers of the component set are identified by using isolated forest, the outliers range is determined, and the desirable capacity utilization range is estimated; Finally, taking the coal industry as an example, the effectiveness of the model is verified, and the causal mechanism of coal overcapacity is revealed. The results show that the adaptive decomposition step introduced in this method can effectively reduce the difficulty of nonlinear and non-stationary complex sequence analysis, and the unsupervised algorithm is used to adaptively determine the threshold, and effectively overcome the subjectivity and the limitation of lack of theoretical basis of the traditional statistical and empirical methods; the consensual capacity utilization interval of China's coal industry is 73.13% ~ 86.31%, and is more in line with the actual development of China's coal industry compared with the current empirical standard (79 ~ 82%); after the phased de-capacity work in 2016-2020, the utilization rate of coal capacity increased significantly, but still slightly lower than the lower limit of the consensual industrial; there is a lead time for the impact of changes in coal demand on overcapacity, and it is easy to cover up the overcapacity caused by system distortion. This study provides a quantitative analysis tool for the monitoring and identification of industrial overcapacity risks and provides a decision-making basis for deepening

the governance of coal overcapacity.

Keywords: capacity utilization; consensual interval; variational mode decomposition; isolation forest

一、引言

多年来我国工业产能过剩“久调未决”，严重制约了工业行业的结构升级和可持续发展，并成为国家供给侧结构性改革和经济高质量发展的桎梏。我国工业产能过剩呈现出普遍性、持久性、复杂性等显著特征^[1]。从国家统计局统计数据来看，工业行业产能过剩已处于较为严重的状态。2019年我国16个重点工业行业产能利用率不足70%，其中钢铁、电解铝、化纤行业的产能利用率仅为66.2%、67.3%、53.5%。然而需要强调的是，在新冠疫情全球肆虐、地缘政治冲突加剧、环境约束加强等多重因素叠加背景下，这些已产能过剩严重的行业仍有一批在建、待建的大型项目，产能过剩呈加剧之势。为此，各级政府制定了一系列产能过剩化解措施，但产能过剩问题并未得到有效抑制，反而陷入“产能过剩—产能化解—产能不足—产能激励—产能再过剩”的治理困境^[2]。究其原因，主要在于传统产能过剩治理模式缺乏必要的前瞻性和精准性。

实现产能过剩精准治理的前提条件是对产能过剩的准确判别以及过剩程度的精确度量，其核心问题可以归结为合意产能利用率区间的确定。产能利用率标准的误判极易加大决策偏差风险，并给行业、社会、经济带来一系列连锁性的灾难性影响。具体而言，若合意产能利用率区间设定过高，那么政府决策者为缩小现实与标准间的差距，可能会实施相应的去产能政策，而去产能过程必将涉及资产处置、人员安置等问题，甚至由于过度去产能而导致产能短缺^[3]；若合意产能利用率区间设置过低，那么可能给政府决策者造成产能不足的错觉，从而鼓励投资，激发全社会的投资热情，引发新一轮的产能过剩^[4]。因此，合意产能利用率区间的精准确立是跳出产能过剩与产能不足间恶性循环的关键。

目前，现有研究主要聚焦于产能过剩的形成机理^[5,6]、治理机制^[7,8]、测度方法^[9,10]等方面，而鲜有涉及合意产能利用率区间的估计方法。在实践中，合意产能利用率区间没有统一标准。日本和欧美国

家普遍认为产能利用率的正常值应该在83~86%之间，但其是根据本国经济运行总结出来的本国经验，而不是普适规律，并不能以之为标准来分析我国工业行业的产能利用情况。我国通常将产能利用率的现行经验标准（79~82%）作为调控依据，学者们也常将其作为参照^[11]。实际上，基于经验确定的合意产能利用率区间尽管有其合理性，但也存在一定问题。具体而言：首先，基于经验总结的“合意区间”是否精确，是否“合意”值得商榷；其次，这一标准忽略了行业间的异质性，我国工业行业众多，各行业的行业特征、技术特点、发展阶段等方面存在显著差异^[12]，拿“一把尺子”去度量不同行业产能利用情况显然是不适宜的。

当前常用的阈值确定方法包括经验分析和统计分析法，这些方法能够为阈值的确定提供一定的方法参照，但存在主观性强，理论依据不严谨等缺陷^[13]。经验分析法中常用多数原则、半数原则、少数原则来划分区间，这些原则的设置缺乏严格的理论依据，且原则的应用标准模糊。统计分析法根据统计误差理论，用中心值加上标准差的倍数来确定阈值，其公式为 $Threshold = \bar{x} - k\sigma$ 。该方法能够从数据分布规律中定量地确定阈值，但也存在一定的局限性，主要体现为常数 k 值的选取往往依据研究人员个人经验、风险偏好等主观确定。因此，亟须探索更客观、更合理的阈值确定方法。变分模式分解（Variational Mode Decomposition, VMD）是一种能够自适应地从复杂数据中提取特征的方法^[14]；孤立森林（Isolation Forest, IF）是一种无需量化密度、距离等指标，通过分割平面即能识别样本的稀疏性的无监督方法^[15]。两种方法的结合能够降低复杂序列异常值识别难度，这为合意工业产能利用率区间估计提供了新思路。鉴于此，本文拟融合VMD和IF方法对合意工业产能利用率区间估计进行探索性研究，并选取煤炭行业进行方法有效性的实证检验，以期工业产能过剩风险监测与判别提供科学有效的量化分析工具，并为深化煤炭产能过剩治

理提供政策靶向和决策依据。

二、合意工业产能利用率区间估计模型构建

1、模型框架

鉴于传统合意产能利用率区间确定方法主观性、经验性以及缺乏动态性，提出一种基于 VMD-IF 的合意产能工业产能利用率区间估计方法，其流

程如图 1 所示。首先，用 VMD 将非平稳、非线性、复杂的数据分解成多个较简单的固有模态函数（Intrinsic Mode Function, IMF），即提取数据多维特征；其次，采用孤立森林对分解的 IMF 集合（多维特征）及每一 IMF 进行多尺度识别，找出离群点集，并进行异常成因分析；最后，根据离群点集估计合意产能利用率区间。

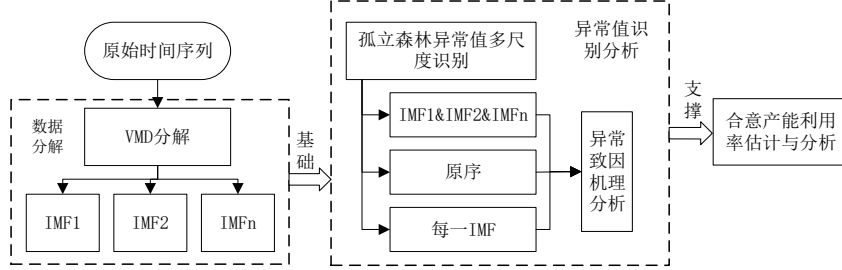


图 1：合意工业产能利用率估计流程

2、VMD 方法

鉴于序列显著的非平稳性、非线性、高复杂性，选择基于完全非递归筛选模式的 VMD 方法将序列分解成多个较简单分量，以期更好地分析序列性质与特征。VMD 简要步骤如下：

Step1: 对 IMF 进行希尔伯特变换以得到的 IMF 的带宽，计算 $u_k(t)$ 的单侧频谱，得到：

$$(\delta(t) + \frac{j}{\pi t}) * u_k(t) \quad (1)$$

Step2: 将一个预先估计的中心频率 $e^{-j\omega_k t}$ 混合到 IMF 上，即：

$$[(\delta(t) + \frac{j}{\pi t}) * u_k(t)] e^{-j\omega_k t} \quad (2)$$

Step3: 引入约束条件，形成变分优化问题：

$$\begin{aligned} \min_{\{u_k\}, \{\omega_k\}} & \left\{ \sum_{k=1}^K \left\| \partial_t [(\delta(t) + \frac{j}{\pi t}) * u_k(t)] e^{-j\omega_k t} \right\|_2^2 \right\} \\ \text{s.t.} & \sum_{k=1}^K u_k(t) = x(t) \end{aligned} \quad (3)$$

上式中： K 为 IMF 个数；

$\{u_k\} = \{u_1, u_2, \dots, u_K\}$, $\{\omega_k\} = \{\omega_1, \omega_2, \dots, \omega_K\}$ 为 u_k 的频率中心。

Step4: 在二次惩罚因子 α 和拉格朗日乘子 $\lambda(t)$ 基础上，构建扩展拉格朗日函数 $L(\{u_k\}, \{\omega_k\}, \lambda)$ ，将约束转化为非约束问题：

$$\begin{aligned} L(\{u_k\}, \{\omega_k\}, \lambda) = & \alpha \sum_{k=1}^K \left\| \partial_t [(\delta(t) + \frac{j}{\pi t}) * u_k] e^{-j\omega_k t} \right\|_2^2 + \\ & \left\| x(t) - \sum_{k=1}^K u_k(t) \right\|_2^2 + \left\langle \lambda(t), x(t) - \sum_{k=1}^K u_k(t) \right\rangle \end{aligned} \quad (4)$$

3、IF 方法

IF 方法是基于无监督异常检测方法，其特点在于关注异常值的特征，因此能够快速找到分布稀疏、离群远的点。IF 通分割平面来寻找异常值，步骤如下：

Step1: 随机从待测数据中选择 k 个点作为根节点；

Step2: 随机确定一个样本特征，并随机产生分割点 $p(\min < p < \max)$ ；

Step3: 根据特征和分割点构建一个超平面，将小于 p 的数据放入左孩子节点，将大于 p 的数据放入右孩子节点；

Step4: 循环 Step2~Step3，直到孩子节点中只有一个数据时跳出循环。

三、面向煤炭行业的合意产能利用率区间估计

1、样本与数据

煤炭行业作为我国基础性能源行业，关系着国家能源安全和经济命脉。自 2012 以来，在经济下行、市场失灵、体制扭曲、能源转型等多种因素的

共同作用下,煤炭行业产能过剩问题日益严重。近年来,通过供给侧结构性改革和经济高质量发展重大国家战略的持续推进,煤炭去产能工作也在不断深化,并取得了阶段性成就,产能利用率也得到了相应提升。然而,目前煤炭产能利用率是否已经达到合理状态,以及到底还需去多少产能等问题尚存争议^[16]。为此,本文以煤炭行业为例,检验所提出的合意工业产能利用率区间估计方法(VMD-IF方法)的有效性,并为后续煤炭去产能工作的深化和优化提供理论依据和决策参考。

值得指出的是,由于产能利用率时间序列波动幅度较小,本文以也能够有效反映产能过剩情况的产能过剩规模时间序列为对象,求出合理的产能过剩规模区间,进而根据产能利用率与产能过剩规模间的关系得到合意产能利用率区间。本文选取1989-2019年这一时间窗口进行实证研究,原因在于煤炭产能在此期间经历了产能过剩—不足—再

过剩的周期性过程^[17],从而使合意产能利用率区间估计结果更具说服力。

煤炭产能过剩规模计算方法参照Wang等的文献^[18],计算公式为

$$OC = C - P = P / CU - P \quad (5)$$

其中, OC 为煤炭产能过剩规模; C 为煤炭产能; P 为煤炭产量; CU 为煤炭产能利用率。煤炭产量数据来源于国家统计局数据库;1989-2016年的 CU 数据来源于Wang等的文献^[18],2017-2019年的 CU 数据来源于2017-2019年国民经济和社会发展统计公报。

煤炭产能过剩规模时序 $\{z_k\}$ 如图2所示。可以发现,时序呈现出显著的非线性、复杂性与波动性,这一特征与我国工业产能过剩致因多源性和复杂性相契合;在此时间窗口,最大过剩规模为16559.25万吨,最小过剩规模为1208.36万吨,平均过剩规模为6025.89万吨。

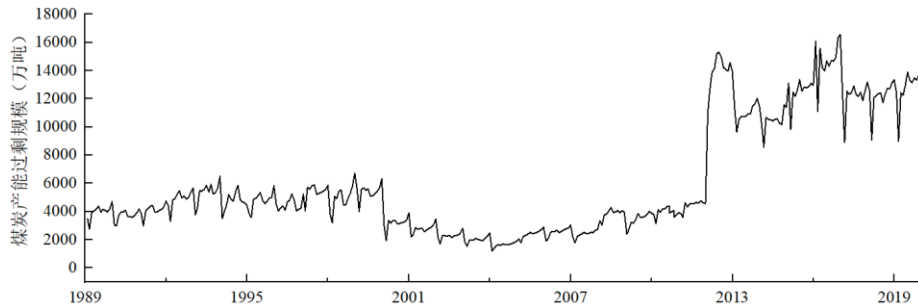


图 2: 1989-2019 年煤炭产能过剩规模

2、煤炭产能过剩规模异常值域识别结果

(1) 数据分解结果

鉴于煤炭产能过剩规模时序显著的非平稳性和非线性,采用VMD将其分解为多个IMF,以期更好地把握时序演变规律,分解结果如图3所示。从VMD分解结果和对应频谱可以发现,IMF1-IMF3的振幅依次减小,而频率依次增大,各IMF很可能隐含着不同的经济含义。因此,结合煤炭

产能过剩致因机理,探究各IMF不同规律特征背后蕴含的经济意义。首先,IMF1的发展趋势是原序的简化,其决定着原序的走向,而煤炭产能过剩的根源为体制扭曲^[19],因此可将IMF1解读为体制扭曲对产能过剩的影响。其次,IMF2呈现周期性,有着明显的“峰”和“谷”,可认为是需求变化导致的产能过剩。最后,IMF3无明显规律性,呈现出随机性,可认为是随机事件(异常温度等)造成的产能过剩。

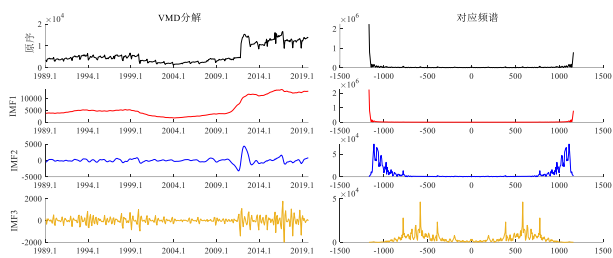


图 3: VMD 分解结果

(2) 基于 IF 的异常值域结果

分别采用 IF 方法识别煤炭产能过剩规模原序和 IMF 集合（将各 IMF 看作原序的特征）的异常

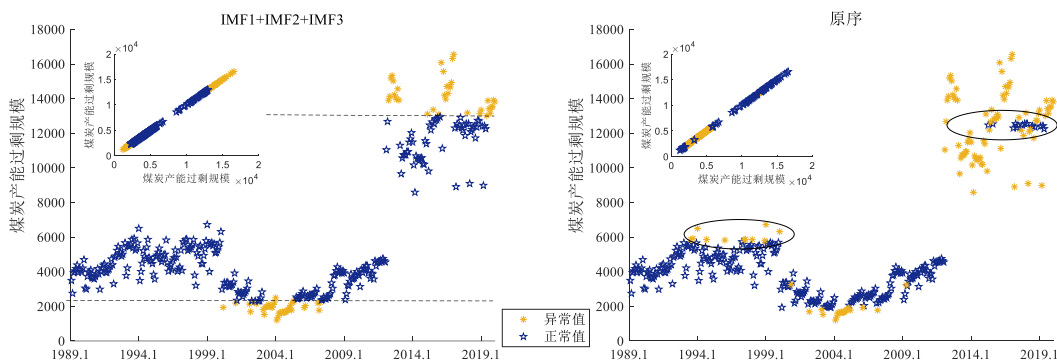


图 4: 基于 IF 的 IMF 集合和原序异常值结果

(3) 煤炭产能过剩规模异常机理分析

为进一步揭示各 IMF 对煤炭产能过剩规模异常的作用机理，采用 IF 识别各 IMF 异常值，结果如图 5 所示。可以发现：①从异常情况持续时间来看，IMF1 异常情况呈条状分布，持续时间最长，发生概率也最大；IMF2 异常情况呈块状分布，持续时间较长，发生呈现出一定的周期性；IMF3 异常情况呈现点状分布，持续时间多为 1 个月，常发生于 2 月份和 12 月份，呈现出随机性。②从异常情况与总异常情况的同步性来说，IMF1 异常情况发生时间基本同步于总序列；IMF2 大部分情况先于总异常发生；IMF3 与总异常情况基本不同步。③从对异常情况发生的贡献度来看，IMF1 异常基本能引发总异常，IMF2 次之，IMF3 基本不能引发总异常。

结合 2.2.1 中各 IMF 经济含义，获得以下结论：

①体制扭曲对煤炭产能过剩起决定性作用，且难以短时间消除，因此在行政干预时（制定产业政策等）要统筹考虑多方利益诉求，将体制扭曲扼杀于摇篮之中。②煤炭市场需求变化先于煤炭产能过剩发生变化，当煤炭需求恶化时，要警惕煤炭产能过剩（或

值，结果如图 4 所示，可以发现：①在 IMF 集合（多维特征）识别结果中，正常值与异常值混叠现象较少；而在原序识别结果中，混叠现象显著存在。这意味着引入自适应的 VMD 分解步骤能够有效降低非线性、非平稳的复杂序列分析难度，从而助力于序列异常值识别。②煤炭产能过剩规模的正常值域为 (2394.93, 12537.70) 万吨，即极小临界值为 2394.93 万吨，极大临界值为 12537.70 万吨。

短缺），尤其注意煤炭需求上升掩盖的体制扭曲导致的产能过剩（例如如图 5 中 2011 年体制扭曲异常，而由于需求的上升，产能过剩未出现异常）。③随机事件虽然对煤炭产能过剩影响不大，但近年来，随机事件频繁发生，要加强对突发事件的预测。

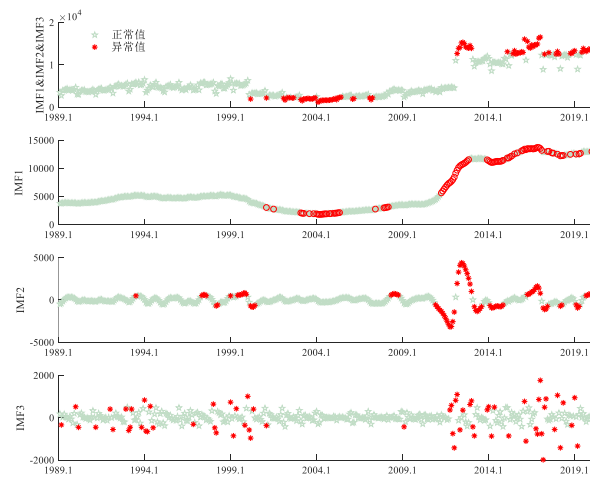


图 5: 各 IMF 异常值识别结果

3、合意产能利用率区间估计与分析

将得到的煤炭产能过剩规模月度阈值换算成年度阈值，并根据公式 (5)，得到合意煤炭产能利

用率区间为[73.13%,86.31%]¹⁶。为进一步验证本文所确定的合意煤炭产能利用率区间的有效性,结合1989-2019年煤炭产能利用率,对比分析本文确定的合意区间与我国现行经验标准区间[79%,82%]的合理性,如图7所示。其中,实线为本文所估计的合意区间,虚线为我国现行经验标准区间,带实点的曲线为历年实际产能利用率曲线。可以发现:

①1989-2000年煤炭产能利用率都在两个合意区间下限的下方,即煤炭产能处于过剩状态。回顾煤炭行业发展历程可知,1989-2000年属于煤炭行业转型发展期^[20]。这一时期内,煤炭体制从完全的计划经济体制过渡到初步的市场经济体制。体系变革以及经济快速增长使得煤炭供不应求,大量乡镇企业、村办企业进入煤炭行业。行业的无序发展和管制薄弱使得产能利用率低下。

②2001-2003年煤炭产能利用率在两个合意区间内或附近。其原因在于2001年国家发文关闭整顿小煤矿,煤炭产量得到控制,煤炭市场由长期供大于求向供求平衡转化。

③2004-2011年煤炭产能利用率变化较平稳。若以[73.13%,86.31%]为标准,其围绕区间上限略微波动,即煤炭行业处于产能略微不足的状态;而以[79%,82%]为标准,其高于区间上限一大段,即煤炭行业处于产能相当不足的状态。2004-2011年,我国工业进入重化工业阶段,对煤炭需求大幅提升。但通过历史检验可知,正是因为对当时情景判断失误,认为煤炭产能相当不足,进而鼓励投资,引发投资潮涌,导致2012年以来煤炭市场供大于求问题凸显,煤炭产能过剩日益严重。

④2012-2016年煤炭产能利用率低于两个合意

区间的下限。2012年以后,由于“黄金十年”的投资积累和产能释放,产能依旧呈扩张之势。然而在经济下行、能源转型、环境约束等多种因素的共同作用下,需求快速萎缩。煤炭产能变化与需求变化的极度不匹配引发新一轮产能过剩,产能利用率低下。

⑤2017-2019年煤炭产能利用率趋于平稳。其原因在于为帮助煤炭行业脱困,2016年以来国家出台了一系列煤炭去产能政策。以[73.13%,86.31%]为标准,目前煤炭产能利用率略低于区间下限;并通过计算得2019年后还需化解产能约15000万吨,这与煤炭工业规划设计研究院发布的去产能空间相近¹⁷。而以[79%,82%]为标准,现煤炭产能利用率低于区间下限且与之相距甚远;并通过计算得2019年后还需化解产能约35000万吨。目前,煤炭价格日趋平稳,煤炭企业盈利水平稳步增加,煤炭行业有序发展。若煤炭行业再次大规模去产能,虽然产能利用率得以提高,但是煤炭价格将会剧烈波动,必将对其下游行业发展产生不利影响。

此外,我国现行经验标准区间非常狭小,使得只有零星几年的煤炭产能利用率处于区间内或区间周围,而产能利用率易受外部随机扰动的影响,具有一定的随机性和不稳定性。因此,若以过于狭小的区间作为决策依据,政府政策措施会在产能化解和产能激励之间不断变动。政策措施的频繁变更无法对企业提供合理的信号显示机制,还会对行业造成巨大冲击,同时严重损害了政府信誉和政策公信力^[21]。综上所述,本文确定的合意煤炭产能利用率区间更加符合煤炭行业发展实际,对煤炭行业发展判断更为合理。换言之,合意煤炭产能利用率区间为[73.13%,86.31%]更为合理与科学。

¹⁶ 煤炭产能过剩规模阈值转化为产能利用率阈值时,选取的煤炭产能数据为极小临界点、极大临界点当年的产能,分别为2005年和2016年的煤炭产能。根据中煤协发布资料和已有文献研究结果,2005年煤炭产能约为210000万吨,2016约为560000万吨。

¹⁷ 煤炭工业规划设计研究院发布的《中国煤炭行业“十三五”煤控中期评估及后期展望》报告中指出,预计2019~2020年煤炭行业去产能空间为18000万吨左右。

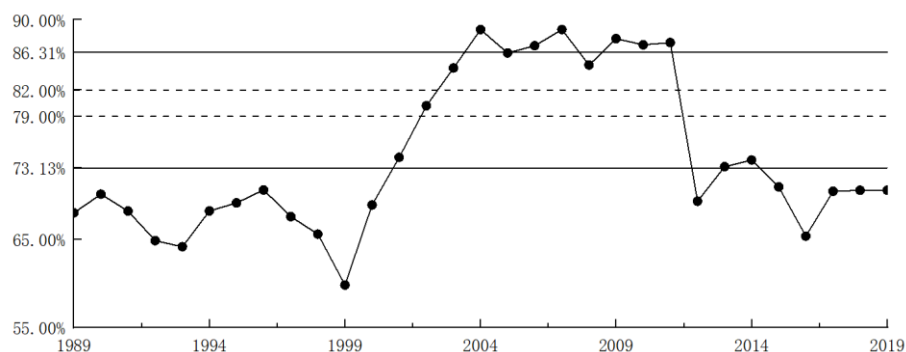


图 6: 1989-2019 年煤炭产能利用率

四、结论与启示

鉴于我国工业产能过剩复杂性、严峻性以及传统合意产能利用率区间确定方法的主观性、缺乏动态性,本文融合 VMD 和 IF 方法对合意工业产能利用率区间估计进行了探索性研究,主要研究结论如下。

首先,鉴于产能过剩时序非线性、复杂波动性、长程相关性等数据特征,提出了一种基于 VMD-IF 的合意工业产能利用率区间估计新方法。该方法引入自适应的分解步骤能够有效降低非线性、非平稳的复杂序列分析难度,并采用无监督算法自适应地确定阈值,有效克服了传统统计与经验方法的主观性和缺乏理论依据的局限性。其次,采用 VMD-IF 方法确立了合意煤炭产能利用率区间,即 73.13%~86.31%。相较于我国现行经验标准(79~82%),该区间更加符合煤炭行业发展实际,且有助于提高煤炭产能过剩调控时机和力度的精准性。最后,揭示了煤炭产能过剩成因机理,虽然体制扭曲对产能过剩起决定性作用,但需求变化对产能过剩具有先导性,且会遮掩体制扭曲的影响;并识别了当前煤炭产能过剩状态和风险水平,煤炭产能利用率趋近但仍低于合意产能利用率区间下限,这为煤炭产能过剩预警和治理提供了决策参考。

基于以上发现,为未来我国深化去产能工作、优化行业供给侧结构性改革、促进经济高质量发展,提出如下政策建议。一方面,就工业行业而言,存在异质性的行业应根据自身发展实际和时序数据特征确定相应的合意产能利用率区间,从而提高产能过剩调控策略的针对性、适用性和精准性。另一方面,具体到煤炭行业,经过多年的调控,煤炭去

产能工作现已取得了阶段性进展和实质性成效,落后产能逐步淘汰。今后去产能工作的重点应放在“提质”、“增效”的目标上,避免“一刀切”和简单关停等政策,积极推进煤炭行业进行战略性兼并重组。在控制煤炭产能总量的前提下,持续通过科技创新发展先进产能,优化产能供给体系。同时,由于需求出现异常可能是新一轮产能过剩的前兆,将其纳入预警体系,时刻警惕煤炭行业需求变化。

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基于多模态信息融合驱动的中国电力需求预测研究

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摘要：电力行业作为国民经济的基础性行业和中国实现“双碳目标”的关键行业，精准的电力需求预测是开展国家电力总体规划以及煤电退出与可再生能源投资决策的首要基础性工作。为此，本文采用多模态信息融合驱动的建模思想，构建了一种新的多源异构数据环境下基于 CNN-LSTM (Convolution Neural Network, Long Short-term Memory) 的电力需求集成预测模型。首先，使用 CNN 分别从电力需求数值型时间序列数据和文本数据（包括政策文本、新闻报道和论坛评论三种类型）中提取隐性特征；其次采用串联融合方法将时序隐性特征 (Series feature, SF) 和文本隐性特征 (Text feature, TF) 进行有机融合；最后将融合后的特征输入到 LSTM 模型中进行预测。实验结果表明，一方面，所提出的多模态信息融合预测模型在水平精度和方向精度上均优于目前广泛采用的单预测模型 (如 ARIMA、CNN、LSTM 等) 和组合预测模型 (如 EEMD-ARIMA、EEMD-LSSVM 等)；另一方面，证明了有机融合时间序列数据和文本数据能够有效提高预测性能。预测结果显示，由于中国经济结构调整和能源系统转型等多重因素的影响，未来两年中国电力需求增速逐步放缓甚至呈现下降趋势，该发现为中国电力系统低碳转型提供了重要的决策参考。

关键词：电力需求；预测；多模态信息融合；特征级融合；CNN-LSTM

Forecasting power demand in China with a CNN-LSTM model including multimodal information

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Abstract: The power industry is a basic industry in the national economy and a key industry for China to achieve the "dual carbon goals". Accurate forecasting of power demand is the primary basic work for the development of the national power master plan, coal power withdrawal and renewable energy investment decisions. Therefore, using the modeling idea driven by multi-modal information fusion to constructs a new integrated forecasting model of power demand which based on CNN-LSTM (Convolution Neural Network, Long Short-term Memory) in multi-source heterogeneous data environment. Firstly, CNN is used to extract implicit features from power demand numerical time series data and text data (including policy text, news report and forum comment); Secondly, series feature (SF) and text feature (TF) are organically fused by series fusion method; Finally, the fused features are input into the LSTM model for prediction. The experimental results show that, on the one hand, the proposed multi-modal information fusion prediction model is superior to the widely used single prediction model (e.g. ARIMA, CNN, LSSVM) and combined prediction model (e.g. EEMD-ARIMA, EEMD-LSSVM) in terms of level accuracy and directional accuracy; on the other hand, it proves that the organic fusion of time series data and text data can effectively improve forecasting performance. The forecast results show that due to the influence of multiple factors such as China's economic restructuring and energy system transformation, China's power demand growth will gradually slow down or even show a downward trend in the next two years. This finding provides an important decision-making reference for the low-carbon transformation of China's power system.

Keywords: power demand; forecasting; multimodal information fusion; feature fusion; CNN-LSTM

一、引言

科学精准的电力需求预测是国家电力结构、电力空间布局优化和电力企业投资决策的首要基础性工作。特别是在中国当前积极推进能源系统转型以实现 2030 碳达峰和 2060 碳中和这样一个极具挑战性的战略目标背景下,准确研判中国未来的电力需求对于煤电退出路径和可再生能源发展规划具有积极的现实意义^[1,2]。诸多事实表明,过高或过低的电力需求预测将会对社会和经济发展带来严重的不利影响:当高估电力需求时,这将延缓煤电退出甚至刺激电力企业投资从而加剧电力行业的产能过剩;当低估电力需求时,则可能诱发激进的煤电退出措施,这不仅会抑制区域经济发展,还可能引发严重的民生问题¹⁸。因此,为推动能源结构转型并保证国家电力供给安全,确保煤电退出与可再生能源发展的协同开展,亟需开展国家电力需求方面的精准预测研究。

但是电力需求的波动受到经济发展、政府政策、电力企业投资、技术水平、能源供应、下游行业需求等多方面不确定因素的影响,是一个具有随机波动特性的复杂动态过程^[3,4]。近年来大量富有挑战精神的学者们围绕着电力负荷预测^[5]、电力价格预测^[6]、电力系统规划^[7]、电力企业投资^[8]等问题开展了诸多富有成效的研究,提出或改进了许多的预测理论、方法和模型。毋庸置疑,这些研究完善了能源管理领域的预测理论和方法,对于提高预测的精度做出了巨大的贡献。可是这些研究也存在着一些局限性。首先,在数据场景方面,现有文献大都是基于单模态信息,特别是数值型时间序列数据展开的。例如,Niu D(2021)^[9]采用单一时间序列数据基于二次分解的思想构建了月度电力需求预测组合模型,提高了中期电力需求预测方面的准确性;Obst D(2019)^[10]利用纯文本数据探讨了如何对电力消耗进行准确预测问题。事实上,无论是时间序列数据

还是文本数据都无法为预测模型提供全面的信息。单模态数据所包含的信息有限,无法全面的刻画电力需求的驱动因素、驱动机理和反映的问题,制约了预测的精度和稳定性。其次,就研究方法而言,现有文献主要是面向单源数据场景采用单模型或者组合模型的方法。例如 Han L(2019)^[11]、Wang D(2018)^[12]面向时间序列数据分别采用改进的 LSTM 和集成经验模态分解(EEMD)-最小二乘支持向量机(LSSVM)-差分整合移动平均自回归模型(ARIMA)对风电功率和煤炭产能过剩规模进行了预测,并取得了不错的效果。显然这些方法难以适用于多源异构数据场景下的预测问题。尽管也有少量文献探讨了基于多模态信息融合预测的方法,然而这些研究方法大多面向受新闻标题影响较大的金融市场,并不适合受多种因素影响的能源管理领域。

鉴于此,本文旨在多源异构数据环境下,探讨基于多模态信息融合驱动的电力需求预测模型。本文的贡献主要体现在以下三个方面:第一,在数据场景方面,不同于现有文献,本文整合了数值型时间序列数据和多类型文本数据(包括政策文本、新闻报道和论坛评论)。这种多模态数据的融合可以充分发挥多源异构数据的信息优势,减少单一模态数据因信息不足带来的影响,为模型决策提供更多信息。第二,面向多源异构数据场景,构建了基于多模态信息融合驱动的 CNN-LSTM 集成模型及相应算法,并用于中国电力需求预测。实验结果表明,该模型明显优于目前广泛采用的单一预测模型和组合预测模型。第三,在实践方面,揭示了未来两年(2021 年 10 月至 2023 年 9 月)中国电力需求的演变规律和发展趋势,发现受节能减排、供给侧结构性改革、新冠肺炎疫情等多重影响,中国电力需求增速放缓甚至呈现下降趋势。这为中国电力系统转型路径规划提供了新的决策依据。

二、文献综述

龙江等二十余个省区采取了拉闸限电措施。这不仅导致众多的钢铁、化工等企业的停工停产,而且影响部分居民正常的用电需求,造成严重的不便影响。

¹⁸例如,2021 年 9 月份,由于全国性煤炭紧缺、燃煤成本与基准电价严重倒挂、联络线净受能力下降等因素影响导致电煤供给短缺明显,从而使得电力供应不足。为了保证国家电力供需平衡和电网安全,中国江苏、浙江、山东、安徽、黑

目前，面向单模态信息的研究文献较多，诸多学者探讨了基于单一时间序列数据或文本数据的预测方法或模型。

现有基于时间序列数据的预测模型主要包括单模型和组合模型。早期的单预测模型主要是基于经典的计量模型，常用的有 ARIMA 模型、灰色模型等。例如 Mitkov A(2019)^[13] 针对电力能源消耗历史数据的线性特性使用 ARIMA 模型构建预测模型并对未来能源需求进行了预测。但在非线性序列上囿于其高复杂性，计量模型预测性能表现不佳^[14]。而人工智能模型具有良好的自学习和组织能力，在非线性预测方面具有很大优势^[15]，常用的有支持向量机(SVM)、人工神经网络(ANN)等。Al-Musaylh(2018)^[16] 利用改进的 SVM 对电力负荷进行预测，但当数据量较少时会出现过拟合问题^[17]。可以看出，以上单预测模型各有优缺点，而组合模型因为可以实现单模型的优势互补、弥补不足，吸引了越来越多研究者的关注。组合模型可以有效利用各个单模型的信息和优势，提高预测精度。目前，组合模型既包含经典的不同计量模型的组合，也有计量模型与机器学习模型的组合。例如 de Oliveira(2018)^[18] 使用 ARIMA-ES 组合模型对不同国家每月电力需求做出了预测；Fan D(2021)^[19] 利用 ARIMA 过滤时间序列数据的线性趋势，并将残差值传递给 LSTM 模型，构

建了 ARIMA-LSTM 集成预测模型并准确有效的预测油井产量。

对于文本数据的研究来说，文本的非结构化特征限制了基于数值数据的传统计量模型的应用。随着机器学习的发展，许多深度方法和模型被用来提取文本信息，例如 CNN^[20]，RNN (Recurrent neural network)^[21]。因为文本在有效描述不确定性和不规则时间的影响方面的作用，在经济管理领域，基于文本数据的预测受到广大研究者的重视。例如，学者们利用财经新闻和原油新闻，分别进行了宏观经济预测^[22]和原油价格预测^[23]。

总而言之，时间序列数据和文本数据都包含不同的预测信息。因此，一个值得探索的思路是融合两种模态的信息，以获得更有效的信息，这可能会提高预测的准确性。

3 基于多模态信息融合驱动的预测模型
1、模型框架

为综合考虑时间序列数据的定量信息和相关文本数据的定性信息^②，充分将两种模态的信息进行融合，构建基于多模态信息融合驱动的中国电力需求集成预测模型，其框架如图 1 所示。

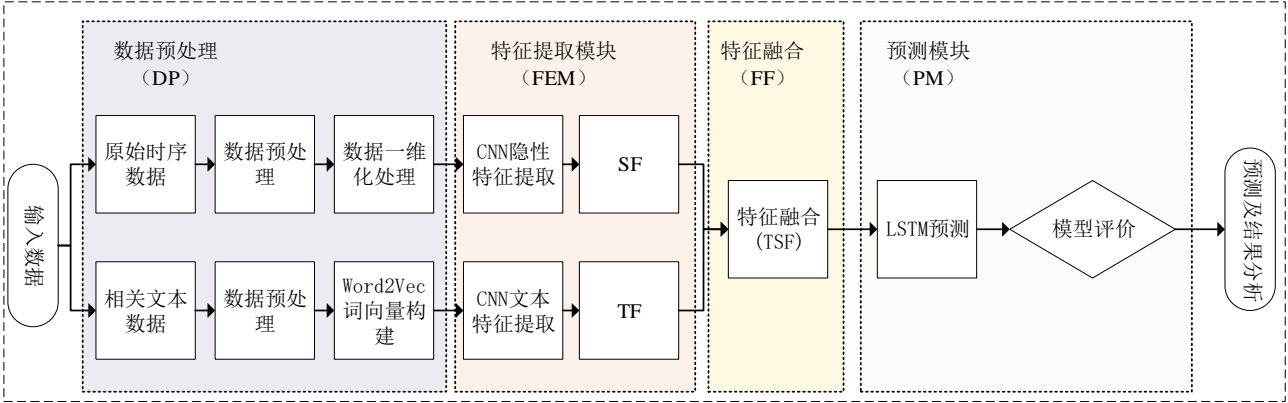


图 1 基于多模态信息融合的预测模型

②由于文本数据也是一类时间序列数据，本文为了分辨，后续谈到时序数据均指数值型时间序列数据，文本数据均为

相关的文本类信息。

2、数据预处理

(1) 时间序列数据预处理

对于时间序列数据，首先填充原始数据中的缺失值，保证数据的完整性；在此基础上，为了更好的满足卷积神经网络输入层的数据结构，采用滑动窗口技术对数据格式进行进一步处理，如图2所示。为了将数据映射在固定的范围内，本文采用了最大最小归一化的方法对输入数据进行处理，最大最小化公式如式(1)所示。

$$x = \frac{x_t - x_{\min}}{x_{\max} - x_{\min}} \quad (1)$$

(2) 文本数据预处理

使用 Word2Vec 模型^[24]进行文本表示，即文本

数据向量化 (Word Embedding)。这种文本向量化表示免去了一般特征处理的繁琐工作，可以让文本原始信息得到了最大限度的保留。模型的网络结构包括三层结构分别是输入层、投影层和输出层，其基本结构如图3所示。

该模型的训练目的就是如何让公式(2)中的值尽可能地变大：

$$\frac{1}{T} \sum_{t=1}^T \sum_{-c \leq j \leq c} \log p(w_{t+j} | w_t) \quad (2)$$

其中， $c > 0$ 表示的是窗口的大小， T 是训练文本的大小。基本的模型计算条件概率如式(3)：

$$P(w_0 | w_t) = \frac{\exp(e'(w)^T e(w_t))}{\sum_{w=-l}^l \exp(e'(w)^T e(w_t))} \quad (3)$$

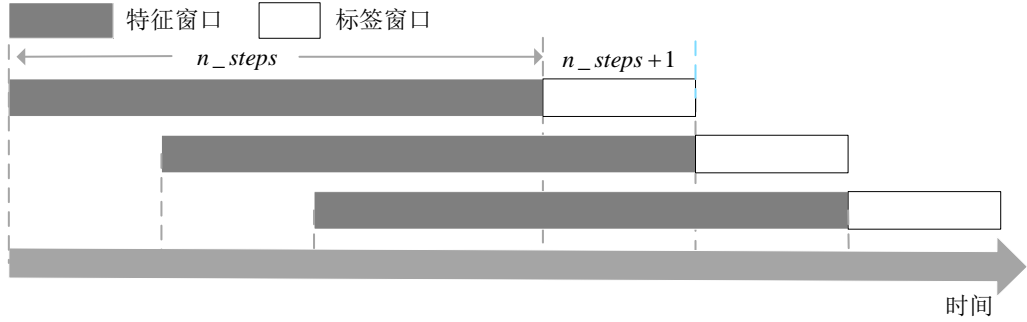


图2 滑动窗口划分数据示意图

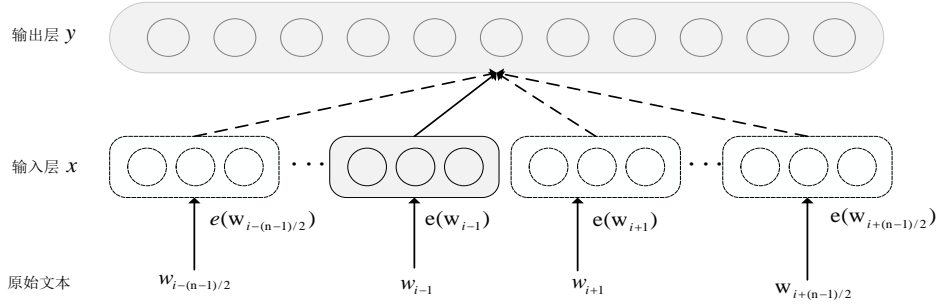


图3 Word2Vec 结构图

3、特征提取

特征提取是为了从预处理后的数据中训练出可以描述研究对象的初始属性。本文选取了两种不同模态的数据集：电力需求时间序列数据和文本数据（包括政策文本、新闻报道和论坛评论）。由于两种数据的结构特性不一致，所以需要经过不同的步骤对样本数据进行特征提取。

（1）基于 CNN 时间序列数据特征提取

目前广泛使用人工提取的方式对时序数据进行特征提取，但这种方式存在成本高、主观性强以及考虑不周全的缺点。而深度学习算法可以自适应学习和构建非线性的复杂模型，从原始数据中不断加强学习调整自身网络结构并发现潜在的特征。其中，卷积神经网络因其灵活的结构和无需设计特征的输入受到广大研究者的青睐^[25,26]。

使用卷积神经网络提取时间序列数据特征的整个过程如下：

步骤 1：卷积层对输入的数据进行特征提取。

卷积核参数用 W 表示， B 表示偏置矩阵， h 表示卷积核的高度， k 表示卷积核的宽度。由于时序数据输入是一维数据，所以 k 对应均为 1，卷积后的结果如下：

$$c_i = f(W \otimes X_{i:i+h-1} + B) \quad (4)$$

式中， \otimes 表示卷积运算， $i:i+h-1$ 表示对第 i 个到 $i+h-1$ 个数据进行卷积运算， c_i 表示上述进

行卷积得到的特征图。

步骤 2：为了加快收敛速度，在卷积层之后加入 ReLU 函数作为激活函数，公式如下：

$$f(x) = \max(x, 0) \quad (5)$$

步骤 3：在卷积层之后设置一个池化层，目的是对特征图进行降维，防止维数灾难。池化操作可以在保留特征图有用信息的同时有效地减少模型地参数数量。本研究中对卷积操作后的特征图采用 max-pooling 策略进行池化操作，公式如下：

$$z_i = \max\{c_i\} \quad (6)$$

其中 c_i 表示评论文本经卷积操作形成的特征图， $0 < i < M$ ， M 是一个卷积层中的卷积核个数。

步骤 4：加入一个连接展平层，将池化以后的特征图进行一维化，形成最终的时序数据的隐性特征 SF。

（2）文本数据特征提取

传统的方法在对文本数据进行特征提取时，会表现出文本特征维数大、处理效率低等问题。所以本研究中使用基于卷积神经网络的文本特征提取方法^[27]。一方面由于 CNN 在特征提取方面强大的能力，另一方面与上述提取到时序数据特征在结构上保持一致性。提取文本特征的过程如图 4 所示。CNN 中的卷积和池化被认为是一个特征提取器，在这里我们并未将其输入到全连接层，而是通过展平层后直接将其输出为本文所需要的文本特征（TF）。

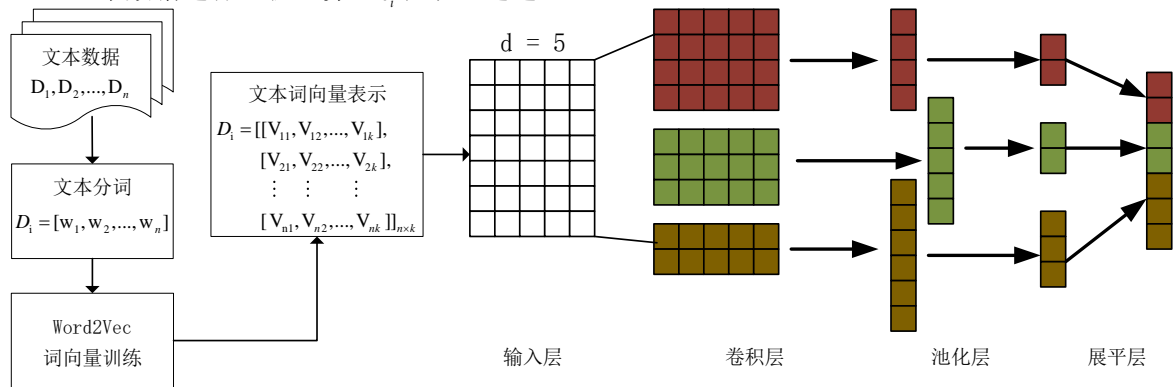


图 4 文本特征提取示意图

4、特征级融合

在得到两个模态数据的隐性特征后,通过特征级融合方法将两种特征进行融合。目前特征融合的方法有特征向量按照人工规则线性融合、按照矩阵向量相似度进行融合和直接拼接特征向量三种方法。由于本研究使用的原始数据的异构性,所以选择直接拼接向量的融合方式来保留原始的数据

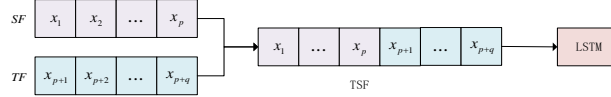


图5 特征级融合示意图

5、基于 LSTM 的预测模型构建与评价

(1) 预测模块

预测模块使用长短期记忆神经网络^[30],将融合后的特征 TSF 作为网络输入。选择 LSTM 作为预测模型有以下两个原因: LSTM 适合及逆行时间拓展,具有长期记忆功能;使用 CNN 提取的是局部特征,利用 LSTM 的长期记忆性解决 CNN 局部处理的问题。LSTM 是为了解决长期记忆问题而提出的一种网络结构。LSTM 加入了记忆细胞状态 (cell state) 和三个门阀结构:遗忘门(forget gate)、输入门(input gate)、输出门(output gate),其模型结构如图6所示:

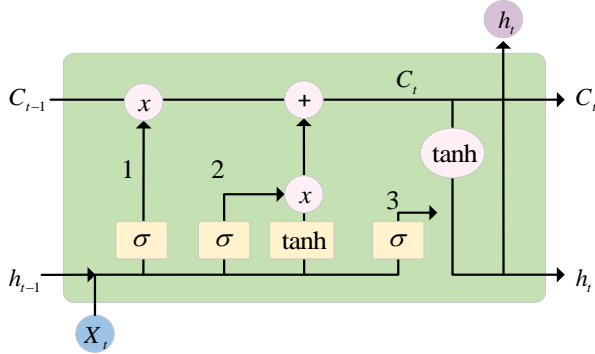


图6 LSTM 隐含层结构

当每一个隐含层接收到信息时,首先由遗忘门决定丢弃什么信息。输入 h_{t-1} 和 x_t 输入到一个激活函数,得到遗忘门的输出 f_t ,其数学表达式如下

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f) \quad (7)$$

其中 σ 为 *sigmoid* 激活函数, W_f 与 b_f 是系数矩阵。下一步是输入门决定要让多少新的信息加入到细胞状态中。输入门由两部分组成,一个使用

信息。直接拼接向量指的是串联融合^[28],将每个时序数据隐性特征和文本数据隐性特征首尾相连,获得融合特征。融合方式如图5所示。并且在实际网络构建时使用密集卷积网络(DenseNet)^[29]中介绍的 concatenate 操作,将特征提取后得到的平铺向量进行串联聚合。

sigmoid 激活函数决定哪些信息需要更新,另一个 *tanh* 激活函数创建一个新的向量,最后将两部分进行联合对细胞状态进行更新。

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \quad (8)$$

$$\bar{C}_t = \tanh(W_c \cdot [h_{t-1}, x_t] + b_c) \quad (9)$$

$$C_t = f_t * C_{t-1} + i_t * \bar{C}_t \quad (10)$$

其中 i_t 和 \bar{C}_t 是输入门更新的两种信息, W_i 、 b_i 、 W_c 、 b_c 是系数矩阵, C_t 是更新后的细胞状态。最后通过输出门决定输出,由两部分组成,第一部分由上一节点的隐藏状态 h_{t-1} 和节点序列数据通过 *sigmoid* 激活函数的输出,第二部分是隐藏状态 C_t 通过 *tanh* 激活函数的输出。

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \quad (11)$$

$$h_t = o_t * \tanh(C_t) \quad (12)$$

(2) 模型评价

为了综合对预测性能进行评价,采用均方根误差 (RMSE)、平均绝对百分比误差 (MAPE),两个指标评价预测的准确性;采用 D_{stat} 指标评价其方向精度。上述三个指标的计算方法如式(13)所示:

$$RMSE = \sqrt{\frac{1}{N} \sum_{t=1}^N (\hat{x}_t - x_t)^2};$$

$$MAPE = \frac{100\%}{N} \sum_{t=1}^N \left| \frac{\hat{x}_t - x_t}{x_t} \right|;$$

$$D_{stat} = \frac{1}{N} \sum_{t=1}^N a_t \times 100\%;$$

(13)

其中: x_t 为实际值, \hat{x}_t 为预测值, N 为测试集的样本数。如果, $(x_{t+1} - x_t)(\hat{x}_{t+1} - x_t) \geq 0$, 则 $a_t = 1$; 否则, $a_t = 0$ 。显然, $RMSE, MAPE$ 的值越小模型的水平预测精度越高, 预测模型的性能越好; D_{stat} 的值越大模型的方向预测精度越好。

四、实证结果与分析

1、数据准备

(1) 数据来源

本文中的多源异构数据包括电力需求时间序列数据和多类型文本数据两个数据集。

时间序列数据中的任一观测值皆受过去观测值的影响, 可以利用其记忆性对未来的趋势进行预测。全社会用电量包括三产及居民用电量, 所以可以使用全国全社会用电量对中国的电力需求进行衡量。时间序列数据从国家能源局和中国电力企业联合会获取, 一共涵盖了从 2003 年 1 月到 2021 年 9 月共计 255 个以月度为单位的全社会用电量时间序列数据。对数据进行可视化发现: 随着中国经济的不断发展, 其全社会用电量整体呈现上升趋势; 同时夏季和冬季用电高峰期表现出其具有季节波动性; 另外增长趋势受到控煤控碳措施的影响, 电力需求增速逐渐趋于平缓。

对于文本数据, 为综合考虑政治、经济、社会、技术等多方的影响因素, 本文选取了政策文本、新闻报道和论坛评论三种类型的文本数据。立足于中国现行体制和行政体系, 电力行业等能源行业的特质决定了它具有非完全市场化的特性, 一定程度上受到政府干预。政府政策直接、准确的表达了政府的导向, 可以很大程度从中了解市场未来发展趋势。其次, 在中国情境下, 新闻报道更多的是对政策的一种解读。最后, 论坛评论数据虽然对电力需求的总体走势不会产生较大冲击, 但是会从侧面对其产生影响。政府政策主要来自于国务院政策文件库和北大法宝。新闻报道来源于中国重要报纸全文数据库, 包括人民日报、光明日报等中央综合媒体以及中国能源报、中国煤电报等全国性专业报刊。论坛评论数据爬取自中国互联网最大的专业知识分享社区平台——知乎。以上三类数据包含从 2000 年 1

月至 2021 年 10 月的一共 9272 条数据。

(2) 数据预处理

本文在处理时间序列数据时, 设置时间窗口参数 n_steps 。使用前 n_steps 期的数据作为时间序列数据输入的样本长度, 使用 $n_steps + 1$ 月份的值作为标签。对于文本数据, 本文使用获取到全部的文本数据训练 Word2Vec 模型。通过多次实验结果对比, 设置向量维度参数值为 200, 滑动窗口参数值为 10, 得到包含上下文语义信息的特征词向量。考虑到文本数据对时间序列数据影响的延迟效应^[31], 本文中设置了 lag_period 作为文本的延迟期数。标签对应示意图如图 7 所示。

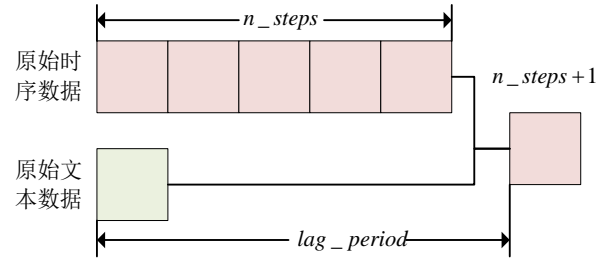


图 7 多源数据标签对应示意图

2、模型实验参数设置

本文中模型结构由特征提取模块的两个输入层、两个不同结构的 CNN 网络层、特征融合层、预测模块的 LSTM 网络层以及输出层组成 (最终模型示意图见附录 B 中图 B.1)。经过文献查阅和实验分析后, 我们发现对本文预测模型性能影响较大的参数有: 数据预处理中的时间窗口大小、文本滞后期数、时序 CNN 卷积和池化宽度、卷积层中卷积核的数量 (包括时序 CNN 和文本 CNN)、LSTM 隐藏层单元个数这六个参数。参考已有的参数调节方法^[32], 本文使用验证集方法 (The Validation Set Approach) 进行参数调节。六个参数对模型的影响见图 8~12。

为了更直观的了解时间窗口大小 (n_steps) 和文本滞后期数 (lag_period) 对模型的影响, 将两者的取值设置为一个整体, 如表 1 所示。根据原始时间序列数据可以发现其存在季节周期性, 所以 n_steps 的取值设置了 (6, 9, 12, 15, 18, 21, 24), 同时 lag_period 的期取值设置了 (6, 12, 18, 24, 30, 36), 最终包含 42 个组合结果。时

间窗口及滞后期数对模型的影响如图 8 所示。可见当取值为 (18, 24) 时，在验证集上平均相对百分比误差最小。

提取时序特征的 CNN 卷积层和池化层的宽度及预测模型平均相对百分比误差、均方根误差如图 9 所示。本文中的 CNN 网络结构为 Inception 结构，将传统的网络深度转换为网络宽度来提取数据的深度特征。但因为原始时序数据的输入长度不会太长，并且网络层数过多会导致学到的特征较为复杂，从而出现梯度消失和梯度爆炸等问题，所以将网络宽度取值设置为 (1, 2, 3)。本文认为卷积层和池化层的宽度为 2 时卷积提取到的有效隐性特征可能更多。

将提取时序数据和文本数据的 CNN 卷积层卷积核的输出数量设置为 (3, 4, 5, 6)，两个参数对模型的影响如图 10 和 11 所示。从图中可以看出，当卷

积核的数量分别为 4 和 3 时，模型的均方根误差和平均相对百分比误差都为最小。本文认为卷积核数量较少时，模型提取特征能力较弱。而卷积核数量较多时，模型提取特征的能力较强。但是滤波器过多会导致模型参数增加，进而增加了过拟合的风险，同时也会延长训练时间。因此，最终将模型的时序 CNN 的每一个卷积层的卷积核数量设置为 4，文本 CNN 的每一个卷积层的滤波器数量设置为 3。

LSTM 的隐藏层单元个数设置为 (4 8 12 16 32 48 64)，结果如图 12 所示。当输出维度为 8 时，模型的 RMSE 和 MAPE 均达到最小值。本文认为输出维度较大同样会增加过拟合的风险并导致模型训练时间变长，因此本文将模型 LSTM 的输出维度个数设置为 8。

根据以上一系列实验得到预测模型的关键超参数的最佳取值，如表 2 所示。

表 1 时间窗口及滞后期数取值对应表

<i>n_steps</i>	6	6	6	6	6	6	9	9	9	...
<i>lag_period</i>	6	12	18	24	30	36	6	12	18	...

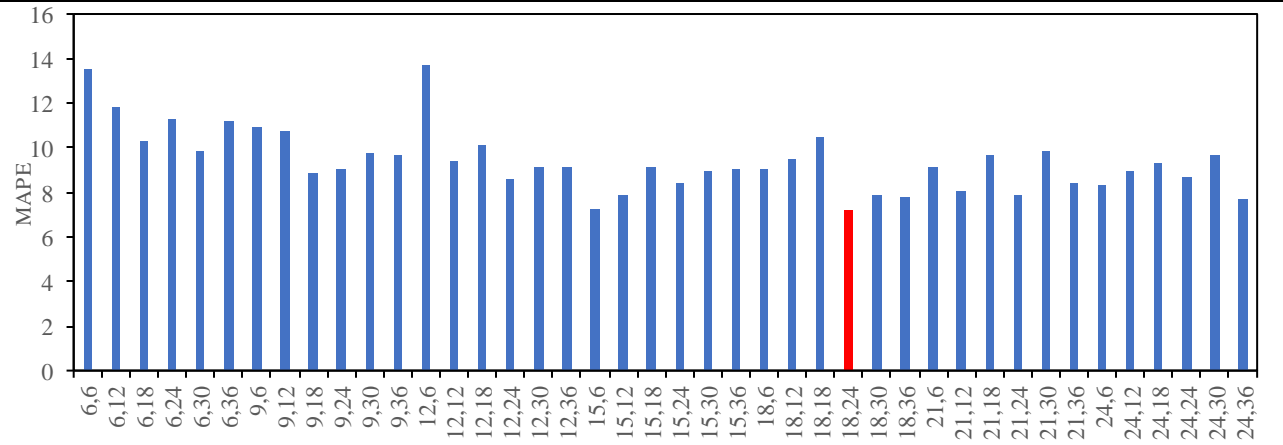


图 8 时间窗口及滞后期数对模型的影响

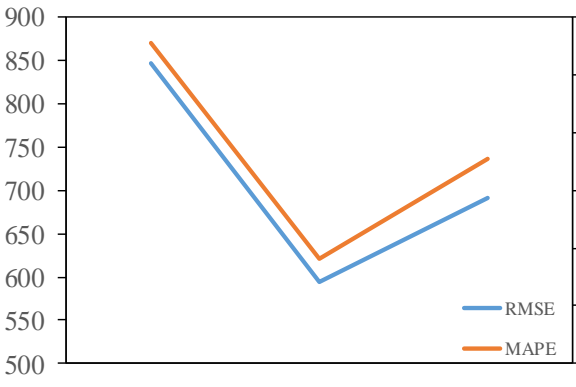


图9 时序CNN卷积层核池化层宽度对模型的影响

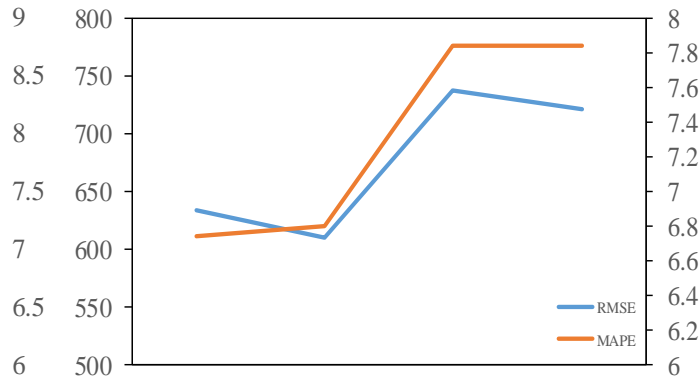


图10 时序CNN卷积核数量对模型的影响

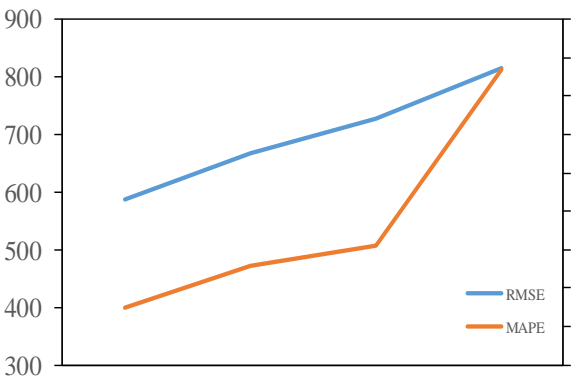


图11 文本CNN卷积核数量对模型的影响

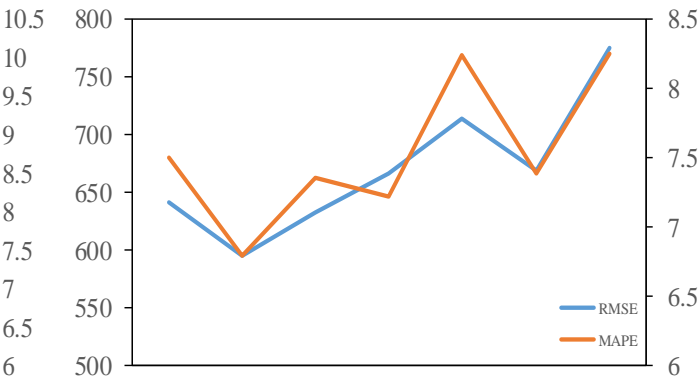


图12 LSTM隐藏神经元个数对模型的影响

表2 模型超参数取值

过程		参数	值
特征提取	时序 CNN	n_steps	18
		lag_period	24
		卷积和池化宽度	2
	文本 CNN	卷积核数量	4
		卷积核数量	3
预测模块	LSTM 隐藏神经元个数		8

3、实验结果和分析

（1）模型对比实验

为了验证模型的有效性，本文选取一系列广泛使用的经典时间序列预测模型进行对比，并使用相关评价指标评估预测效果。从对比的模型选择上来说，我们考虑了单模型（经典方法：ARIMA 和 LSSVM；深度学习方法：CNN 和 LSTM）和组合模型（EEMD-ARIMA，EEMD-LSSVM，EEMD-ARIMA-LSSVM）。预测性能对比结果如附录 A 中表 A.1 和 A.2 所示²⁰。选取

的三个评价标准在统计学上证明了本文所提出的预测模型显著优于其他模型。在 8 个模型中，本文模型不仅具有最高的预测精度（MAPE 和 RMSE 的值最低），而且在方向预测能力上也取得了最优（ D_{stat} 值最高）。总体而言，本文提出的面向多源异构数据环境的 CNN-LSTM 集成电力需求预测模型明显提高了预测精度，表明融合多源数据可以有效提高模型的预测精度。

（2）预测结果及分析

③在表 A.1，A.2 和表 3 中，实际值和预测值都表示全社会用电量，单位为亿千瓦时。

采用训练好的 CNN-LSTM 模型预测未来一段时间内中国电力需求规模和发展趋势，为政府决策者和电力企业投资者提供决策依据。表 3 和图 14 展示了 2021 年 10 月-2023 年 9 月电力需求的具体数值和发展趋势。根据预测结果可知，2021 年 10 月-2023 年 9 月中国电力需求会有一个阶段性的调整，电力需求增速放缓甚至呈现下降趋势。

对 2019 年 10 月-2021 年 9 月的文本数据进行分析，发现国家全面推进供给侧结构性改革、节能减排、控煤控碳以及能源转型的方针政策。另外，

这段时间内新冠疫情给国际和国内经济带来的负面影响，对电力需求都产生了一定的抑制作用。这与本文的预测结果相吻合。

需要指出的是，从长远来说，随着供给侧结构性改革的推进以及疫情得到有效的控制，加之经济发展的必然性，未来的电力需求应该是呈现上升趋势的。但是受到环保政策以及新能源发展的压力，这种趋势相比改革开放以来的增速来说是平缓的，不会出现大幅度增长。

表 3 中国 2021 年 10 月至 2023 年 9 月电力需求预测结果

时间	2021.10	2021.11	2021.12	2022.01	2022.02	2022.03	2022.04	2022.05	2022.06	2022.07	2022.08	2022.09
预测值	6838.77	7248.35	7388.42	7399.20	7096.37	7091.37	7180.61	7349.72	7308.66	7682.42	7737.63	6838.77
时间	2022.10	2022.11	2022.12	2023.01	2023.02	2023.03	2023.04	2023.05	2023.06	2023.07	2023.08	2023.09
预测值	7365.10	7421.46	7733.07	7770.29	7375.76	7065.84	7355.65	7179.91	7554.73	7677.98	6484.32	6125.33

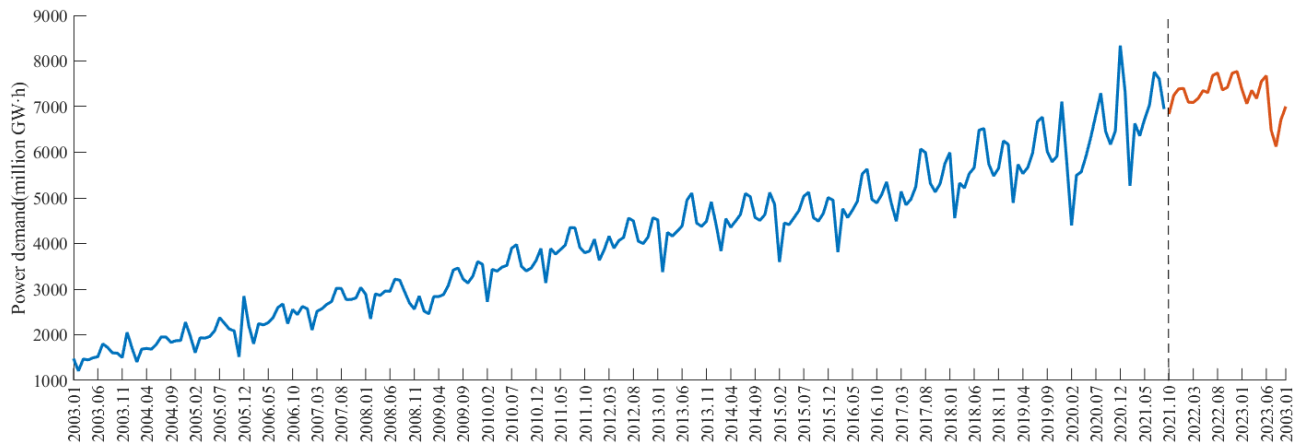


图 13 电力需求预测结果

五、结论及政策建议

1、结论

鉴于中国电力精准规划的重要性及电力需求变化高度不确定性和复杂性的新形势,本文有机融合时间序列数据和多类型文本数据(政策文本、新闻报道和论坛评论),构建了基于 CNN-LSTM 深度神经网络的中国电力需求预测模型,通过实证分析验证了模型的有效性,并使用该模型对中国未来电力需求进行预测。主要结论如下

第一,基于多模态信息融合驱动的建模思想,构建了一种新的多源异构数据环境下的 CNN-LSTM 的电力需求集成预测模型。在多源异构数据环境下采用多模态信息融合驱动构建的预测模型,充分发挥了时间序列数据和文本数据两种模态数据的信息互补作用。实验结果也验证了该模型在方向精度和水平精度上优于目前广泛采用的时间序列预测模型。本文所构建的多源异构场景下的预测模型,不仅能够更好地全面描述中国电力需求的复杂动态变化特征及未来发展态势,也为复杂动态变化环境下的多源异构数据构建逻辑与模型构建方法提供了参考与借鉴。

第二,揭示了中国电力需求的未来演变规律和发展趋势。从预测结果来看,2021 年 10 月-2023 年 9 月中国电力月度需求将在 6125 亿~7770 亿 kWh 之间波动,呈现下降趋势;2021,2022,2023 年度需求分别为 83124、89135、84637(单位:亿 kWh,平均折算获得),呈现稳中有降的趋势。这与中国大力实施能源转型、节能减排及中国当前面临的复杂多变的经济情况相吻合。这意味着这段时间内中国经济平稳运行略有震荡、能耗双控也取得一定成效,也是电力行业转型升级一个机会窗口。并且为电网公司及相关部门分析月度负荷、经济发展趋势、投资决策提供了依据与参考。

2、政策建议

以上研究不仅为中国电力需求预测提供了可靠的模型框架,也为中国电力系统规划工作提供了重要的参考。基于以上研究结论,本文提出以下政策建议。

第一,本文的预测结果表明,未来一段时间内中国电力需求总体呈现出整肃放缓甚至下降趋势,有利于政府推进电力系统转型工作。具体而言,由于经济增速放缓和经济结构转型,中国高速增长的电力需求得到有效的抑制。对于中国电力系统而言,应充分利用这个机会窗口推动电力系统转型工作,一方面要积极推进落后煤电产能的退出,提高电力行业整体效率;另一方面应加大可再生能源发电技术的投资,保证行业转型质量,在兼顾国民经济和社会发展的前提下,保证电力系统低碳转型的成本最小化。

第二,在保证国家信息安全的前提下,政府应持续加大和扩充电力等其它能源行业数据等信息的披露力度和公开渠道,帮助电力企业等主体获取全面的行业信息。本文研究结果表明,融合多源异构数据有助于提高预测精度,能更好的研判电力行业未来的发展趋势,为电力企业提供更全面的决策信息参考。因此政府应逐步有序、分级分类的推进相关行业信息的开放程度。并且在大数据时代,政府应该大力推动政务信息化工作,完善政务信息化体系和建设,同时健全保障机制和法律法规,全面提升和保障电力企业等利益主体对行业数据和信息的可得性。

第三,政府应该严控电力装机规模和完善电力行业体制机制以防止电力产能过剩的进一步加剧,保障电力行业健康发展和成功转型。中国电力企业联合会发布的数据显示,截至 2020 年底,全国新增发电装机容量 19087 万千瓦,同比增加 8587 万千瓦,增速大幅提升。而本文预测结果显示,2021 年后两年内,中国电力需求增速总体放缓甚至出现下降趋势,这与现在电力行业装机增速和发展趋势不一致,可能导致电力行业产能过剩进一步加剧。目前,中国的煤电产能过剩问题形式依旧严峻,为确保国家能源安全,防止电力产能过剩进一步加剧,政府应一方面严格控制电力装机审批工作,防止从源头造成过剩产能的出现;另一方面应坚定淘汰煤电落后产能,避免为弥补阶段性的电力短缺而造成长期性的产能过剩问题。

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附录 A 实证结果

表 A.1 本文模型与单模型预测性能比较

时间	实际值	ARIMA		LSSVM		CNN		LSTM	
		预测值	误差%	预测值	误差%	预测值	误差%	预测值	误差%
2020.01	5805.4	6686.51	15.18	6303.48	8.58	6364.36	9.63	6559.93	13.00
2020.02	4397.6	5888.40	33.90	6317.30	43.65	6258.91	42.33	6420.33	46.00
2020.03	5492.7	5378.79	2.07	6337.93	15.39	6096.50	10.99	5978.23	8.84
2020.04	5571.9	6130.06	10.02	6341.50	13.81	6499.99	16.66	5823.90	4.52
2020.05	5926	5642.25	4.79	6366.26	7.43	6438.10	8.64	5789.79	2.30
2020.06	6350	5420.78	14.63	6384.27	0.54	5987.82	5.70	6071.27	4.39
2020.07	6824	5793.89	15.10	6393.62	6.31	5698.07	16.50	5787.49	15.19
2020.08	7294	6346.35	12.99	6418.84	12.00	5799.59	20.49	5739.85	21.31
2020.09	6454	6807.83	5.48	6438.88	0.23	5943.00	7.92	6320.82	2.06
2020.10	6172	6509.41	5.47	6461.25	4.69	6339.15	2.71	6437.76	4.31
2020.11	6467	6591.73	1.93	6468.38	0.02	6651.81	2.86	6561.05	1.45
2020.12	8338	6744.38	19.11	6383.94	23.44	6852.33	17.82	6659.51	20.13
2021.01	7324	7620.61	4.05	6488.92	11.40	6864.91	6.27	7085.02	3.26
2021.02	5264	6798.31	29.15	6506.35	23.60	6847.15	30.08	7208.47	36.94
2021.03	6631	6113.17	7.81	6511.18	1.81	6880.12	3.76	6802.39	2.58
2021.04	6361	7443.47	17.02	6513.74	2.40	7582.49	19.20	6735.14	5.88
2021.05	6724	6670.52	0.80	6517.69	3.07	7706.12	14.61	6732.11	0.12
2021.06	7033	6492.74	7.68	6527.44	7.19	7225.73	2.74	7157.50	1.77
2021.07	7758	6542.57	15.67	6522.53	15.93	6890.31	11.18	6837.64	11.86
2021.08	7607	7232.30	4.93	6525.35	14.22	6776.52	10.92	6625.10	12.91
2021.09	6947	7217.93	3.90	6526.70	6.05	6790.92	2.25	7140.62	2.79
MAPE			11.03		10.56		12.54		10.55
RMSE			842.01		865.70		930.12		908.48
D_{stat}			60%		70%		75%		75%

表 A.2 本文模型与组合模型预测性能比较

时间	实际值	EEMD-ARIMA		EEMD-LSSVM		EEMD-LSSVM-ARIMA		本文模型	
		预测值	误差%	预测值	误差%	预测值	误差%	预测值	误差%
2020.01	5805.4	6834.61	17.73	6643.43	14.44	6645.55	14.47	6168.57	6.26
2020.02	4397.6	6070.29	38.04	6314.98	43.60	6278.51	42.77	5285.23	20.18
2020.03	5492.7	5397.74	1.73	6315.07	14.97	6282.10	14.37	6014.66	9.50
2020.04	5571.9	6002.77	7.73	6349.36	13.95	6342.00	13.82	6098.95	9.46
2020.05	5926	5711.23	3.62	6375.61	7.59	6315.15	6.57	5888.11	0.64
2020.06	6350	5687.60	10.43	6397.79	0.75	6445.95	1.51	6160.39	2.99
2020.07	6824	5805.99	14.92	6422.59	5.88	6350.41	6.94	6895.72	1.05
2020.08	7294	6273.73	13.99	6443.16	11.66	6456.95	11.48	6452.28	11.54
2020.09	6454	6667.74	3.31	6436.13	0.28	6531.86	1.21	6472.00	0.28
2020.10	6172	6465.43	4.75	6427.16	4.13	6393.21	3.58	5897.42	4.45
2020.11	6467	6569.36	1.58	6385.34	1.26	6321.70	2.25	6601.59	2.08
2020.12	8338	6641.73	20.34	6315.42	24.26	6281.29	24.67	6463.47	22.48
2021.01	7324	7486.50	2.22	6209.43	15.22	6113.34	16.53	6074.90	17.05
2021.02	5264	6912.50	31.32	6059.20	15.11	5752.77	9.29	5777.34	9.75
2021.03	6631	6193.11	6.60	5870.04	11.48	5728.05	13.62	6667.97	0.56
2021.04	6361	7087.32	11.42	5625.60	11.56	5423.63	14.74	6404.41	0.68
2021.05	6724	6738.70	0.22	5343.02	20.54	5131.24	23.69	6823.90	1.49
2021.06	7033	6585.18	6.37	5026.29	28.53	4774.25	32.12	6965.07	0.97
2021.07	7758	6432.09	17.09	4681.86	39.65	4480.44	42.25	7507.18	3.23
2021.08	7607	7162.68	5.84	4319.45	43.22	4025.57	47.08	7363.85	3.20
2021.09	6947	7180.50	3.36	3949.61	43.15	3675.70	47.09	7008.75	0.89
MAPE			10.60		17.68		18.57		6.12
RMSE			853.78		1529.01		1635.32		609.30
D_{stat}			60%		70%		70%		90%

附录 B CNN-LSTM 模型图

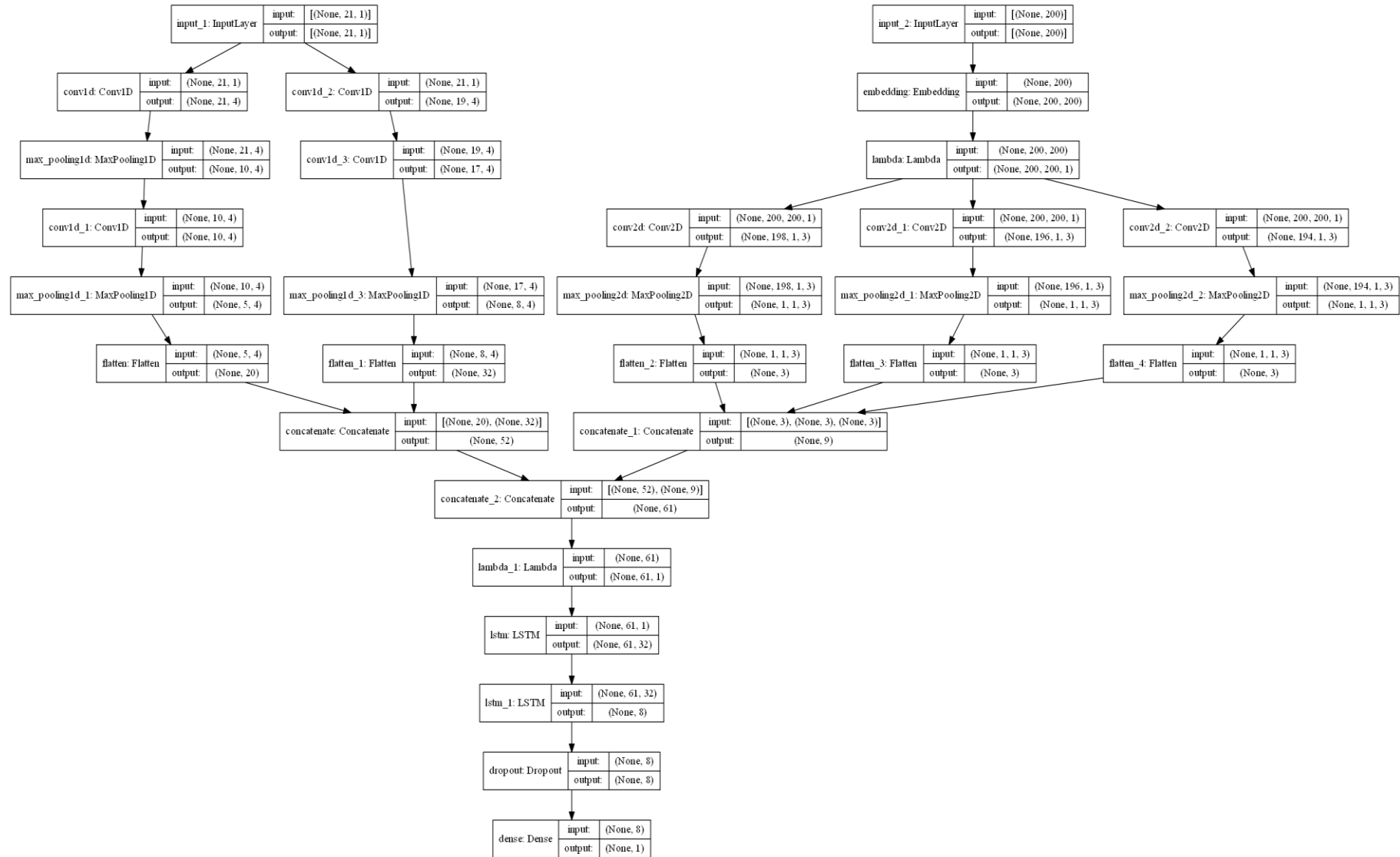


图 B.1 CNN-LSTM 模型

采煤机械化如何帮助中国煤炭工业实现安全与效益的共赢？ - 以国有重点煤矿为例

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摘要：中国采煤机械化从零起步，实现了跟踪模仿到并行引领的跨越。与此同时中国原煤产量连续三十余年居于世界首位，煤矿百万吨死亡率达到了世界产煤中等发达国家水平，煤炭工业成为了中国大踏步赶超时代的典型样本。本文以国有重点煤矿为主要研究对象，首次对采煤机械化的安全贡献和经济贡献进行了全过程分析。通过对 1966-2019 年间采煤机械化率及百万吨死亡率的门限回归分析，发现在采煤机械化早期并不存在安全红利，正是老一辈领导人的高瞻远瞩，以及集中力量办大事的社会主义制度优越性，成就了煤炭安全开采的质变。通过对 1978-2019 年国有重点煤矿经营数据的随机森林分析，发现采煤机械化率对于百万吨死亡率下降的贡献最大，其重要性得分远高于其他因素。通过对 1978-2019 年国有重点煤矿经营数据的脉冲响应分析，发现采煤机械化率对于全员效率及利润率的影响都是由负转正的，由此证明采煤机械化的发展可以逐渐带来经济红利，并最终实现安全与效益的共赢。无论是安全红利，还是经济红利，本质上都来源于中国特色社会主义的制度红利。采煤机械化已经发展到智能化阶段，本文进一步分析了“碳达峰”及“人口老龄化”背景下推进采煤智能化的意义及策略。

关键词：采煤机械化，百万吨死亡率，原煤全员效率，安全红利，经济红利

How does coal mining mechanization help China's coal industry achieve a win-win situation in terms of safety and efficiency? - Take state-owned key coal mines as an example

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Abstract: China's coal mining mechanization started from scratch, and realized the leap from tracking and imitation to parallel leadership. At the same time, China's raw coal output has ranked first in the world for more than 30 consecutive years, and the million-ton mortality rate of coal mines has reached the level of the world's middle-developed coal-producing countries. The coal industry has become a typical example of China's strides to catch up with the times. This paper takes the state-owned key coal mines as the main research object, and for the first time analyzes the whole process of the safety and economic contributions of coal mining mechanization. Through the threshold regression analysis of the coal mining mechanization rate and the mortality rate of one million tons from 1966 to 2019, it is found that there is no safety dividend in the early stage of coal mining mechanization. The superiority of the socialist system has achieved a qualitative change in the safe mining of coal. Through random forest analysis of the operating data of key state-owned coal mines from 1978 to 2019, it was found that the coal mining mechanization rate contributed the most to the reduction in the mortality rate of millions of tons, and its importance score was much higher than other factors. Through the impulse response analysis of the operating data of key state-owned coal mines from 1978 to 2019, it is found that the impact of coal mining mechanization rate on the efficiency of all employees and profit margins has changed from negative to positive, which proves that the development of coal mining mechanization can gradually bring economic benefits Dividends, and ultimately achieve a win-win situation of safety and efficiency. Whether it is a security dividend or an economic dividend, it is essentially derived from the institutional dividend of socialism with Chinese characteristics. Coal mining

mechanization has developed to the stage of intelligence. This paper further analyzes the significance and strategies of promoting intelligent coal mining under the background of "carbon peaking" and "population aging".

Key Words: Mechanization of coal mining, death rate of millions of tons, efficiency of raw coal staff, safety dividend, economic dividend

一、引言与文献综述

中国仍是发展中国家,推动现代化建设,保障能源供给是长期战略任务(李克强,2019)^[1]。新中国成立初期曾面临过非常严重的能源短缺问题,根据原煤炭工业部部长肖寒的回忆,1968年春节前夕北京市煤气供应不足,都煮不熟饺子,开滦矿务局春节不放假,坚持生产支援北京,此举得到了周恩来总理的称赞,他说“开滦工人出了力,救了急,立了功”(武晓娟,2019)^[2]。煤炭在中国一次能源储量中占比约为95%,是储藏最丰富的能源(自然资源部,2019)^[3]。2020年中国原油对外依存度为71%,天然气对外依存度为43%,原煤的对外依存度仅为7%。《中华人民共和国经济和社会发展第十四个五年规划和2035年远景目标纲要》中提出了“实现煤炭供应安全兜底、油气核心需求依靠自保、电力供应稳定可靠”为主要内容的国家能源安全战略,同时提出加强矿山深部开采与重大灾害防治等领域先进技术装备创新应用,推进危险岗位机器人替代,明确了矿山开采提升安全生产水平的工作方向。煤矿智能化对于提升煤矿安全生产水平、保障煤炭稳定供应具有重要意义(王国法,2020)^[4]。事故调查表明,井下作业越多,发生事故的概率越大,事故伤亡也越多。目前从事采煤、掘进等关键岗位的人员占比仍达60%以上,是最迫切开展机器换人的高危行业(丁百川,2017)^[5]。根据中国煤炭科工集团首席科学家王国法院士的评估,煤矿智能化建设比现有机械化煤矿可能增加30%以上的投入,但能实现更高的效率和安全效益(贺春禄,2020)^[6]。煤炭智能化是煤矿综合机械化发展的新阶段,在煤价长期低迷的背景下,煤矿智能化改造面临着严峻的成本和资金压力。如何算好煤炭智能化的盈亏账?这里需要站在中国煤炭机械化发展历程的视角上,分析中国煤矿生产机械化是否可以实现安全 and 经济效益的双赢。

采煤机械化作为煤炭科学产能的关键评价指标,推动了煤炭生产领域的能源革命。采煤机械化率又称采煤机械化程度,是指机械化采煤工作面的产量占回采产量的百分比(中国煤炭工业协会,2012)^[7]。机械化采煤的优越性集中表现在“一少、两高、三低”,即冒顶事故减少,产量高、效率高,材料损耗低、吨煤成本低(于欢和武晓娟,2017)^[8]。近30年煤矿事故特征的特征分析表明,在导致中国煤矿事故的直接原因中,人因所占比重高达85%以上(陈红和祁慧,2013)^[9]。而减少人员数量是从根源上治理人因事故的措施,即“无人就是安全”(孙继平,2011)^[10]。

虽然有政府的政策导向,但机械化的投资主体是煤炭企业。煤炭企业在“利润安全双重任务权衡”局面下,产量和安全会形成竞争关系,从而造成生产与安全投入决策方面的偏离(徐建博和钱永坤,2021)^[11]。企业核算机械化采煤经济效益的方式主要有两种:第一种是通过计算综采设备投资回收期来判别;第二种是通过“保本产量”来评价综采工艺的使用效果(陶树人,1993)^[12]。因为安全收益具有巨额性、隐蔽性、滞后性、外部性的特点,加之安全事故具有或然性,容易导致煤炭企业不愿意进行长期的安全投入(汤凌霄和郭熙保,2006)^[13]。

通过以上文献的分析,可以得到以下几点启示:

(1) 煤炭是保障能源供应的基础能源,因此煤炭的开采关系到中国能源的安全,仍将是国家投资的重点领域;(2) 采煤机械化是一个系统工程,现有文献往往只聚焦于采煤机械化的某一个发展阶段,缺乏对其进行全周期的分析;(3) 煤炭机械化的价值不仅在于增加产量,其在煤质提升、安全生产保障和矿工健康防护方面都发挥着重要作用。因此,本研究试图填补现有研究空白,分析机械化率带来的经济与安全红利。

二、研究设计与数据处理

为了从全周期分析机械化对于中国煤炭工业发展的贡献,结合数据可得性,本文选取了国有重点煤矿 1966~2019 年的经营数据进行分析,时间周期基本涵盖了中国采煤机械化的主要发展阶段。本文有两个主要研究任务:第一个是分析采煤机械化率对死亡人数的影响,衡量其对安全生产的贡献;第二个是分析采煤机械化率对国有重点煤矿原煤全员效率及利润率的影响,判断机械化率的提升是否可以为煤炭企业带来经济效益。因而本文首先通过 Granger 因果检验,分析采煤机械化率对国有重点煤矿百万吨死亡率、利润率及原煤全员效率的影响,对论文的研究框架进行初步验证。其次,在机械化率对于百万吨死亡率影响的分析中,本文通过门限回归分析机械化率所带来的安全红利大小及生成条件,随后运用随机森林模型对影响百万吨死

亡率的 11 个因素按照重要性进行排序,进一步明确了采煤机械化率对百万吨死亡率降低的贡献。最后,在机械化率对国有重点煤矿经济影响的分析中,考虑到煤炭企业的经营受煤价影响较为明显,本文引入煤价作为解释变量,分三个阶段,运用贝叶斯向量自回归模型(Bayes Vector Autoregression Model,BVAR)分析机械化率变动对原煤全员效率及利润的影响。

本文将国有重点煤矿的百万吨死亡率作为安全红利指标,将国有重点煤矿的利润率及原煤全员效率作为经济红利指标,将国有重点煤矿采煤机械化率作为机械化程度指标。门限模型样本的时间跨度为 1966-2019 年,随机森林模型样本的时间跨度为 1978—2019 年,VAR 模型样本的时间跨度为 1978-2019 年,具体的指标说明见表 1。

表 1 论文主要变量说明

变量名称	变量符号	变量定义与单位	数据来源
煤矿安全程度	<i>Mr</i>	煤炭百万吨死亡率(人/百万吨)	《中国煤炭工业年鉴》
煤矿机械化程度	<i>Cmmr</i>	采煤机械化率(%)	《中国煤炭工业年鉴》
煤矿设备量	<i>MM</i>	煤矿机械设备产量(万吨)	《中国机械工业年鉴》
产量水平	<i>Q</i>	原煤产量数据(亿吨)	《中国煤炭工业年鉴》
	<i>Qrate</i>	原煤产量增长率指数(上年=100)	
工资水平	<i>Pay</i>	采矿业在岗职工平均工资(万元/年)	《中国统计年鉴》
矿工素质指数	<i>Quality</i>	采矿业在岗职工平均工资/全行业在岗职工平均工资	《中国统计年鉴》
行业集中度	<i>CR</i>	国有大型企业原煤产量/全国原煤产(%)	《中国统计年鉴》
非民营化程度	<i>Unprivatization</i>	国有大型煤矿企业职工人数/全国煤矿企业职工人数(%)	《中国统计年鉴》
煤炭市场环境	<i>RPI</i>	煤炭工业品出厂价格指数(上年=100)	《中国统计年鉴》
技术要素	<i>Efficiency</i>	原煤生产人员全员效率(吨/工)	《中国煤炭工业年鉴》
运输风险	<i>Distance</i>	货物平均运输距离(公里)	《中国统计年鉴》
需求水平	<i>Demand</i>	煤炭消费量占能源消费量的比重(%)	《中国统计年鉴》
利润水平	<i>Profit</i>	利润率=国有重点煤矿企业利润/国有重点煤矿原煤产量(元/吨)	《中国煤炭工业年鉴》

注:由于《中国煤炭工业年鉴》统计口径发生变化,国有重点煤炭企业利润在 2004 年之后调整为规模以上煤炭企业。

图 1 可以清晰看到:国有重点煤矿采煤机械化率与百万吨死亡率呈现出“倒 U”型关系,并且机械

化程度越高,越收敛于拟合曲线;通过图 2 可以看出:国有重点煤矿采煤机械化率与利润率之间呈

“正 U”型关系，并且机械化程度越高，越发散。通过图 3 可以看出：原煤全员效率与采煤机械化率同

样呈“正 U”型关系，同时机械化成果越高，越收敛于拟合曲线。

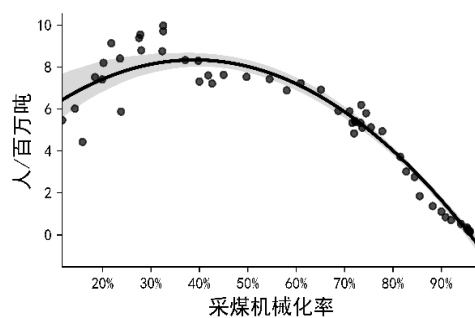


图 1 采煤机械化率与百万吨死亡率的关系

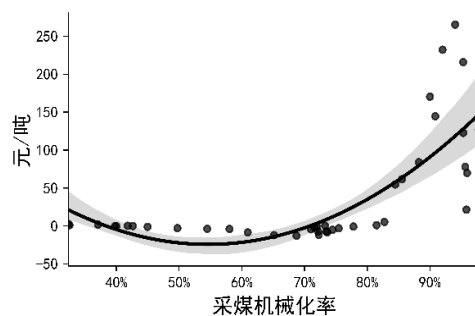


图 2 采煤机械化率与利润的关系

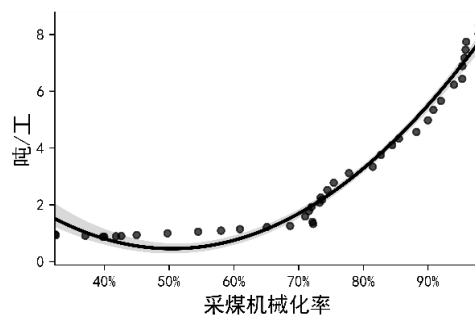


图 3 采煤机械化率与原煤全员效率

在此基础上本文分别对机械化率与百万吨死亡率及行业利润率之间的因果关系进行了 Granger

检验，检验结果如表 2 所示：

表 2 Granger 因果检验结果

原假设	<i>F-Statistic</i>	<i>Prob.</i>
机械化率非百万吨死亡率的 Granger 关系	20.8563	0.0000
百万吨死亡率非机械化率的 Granger 关系	0.5621	0.4572
机械化率非利润率的 Granger 关系	6.5618	0.0352
利润率非机械化率的 Granger 关系	2.4863	0.1752
机械化率非原煤全员效率的 Granger 关系	4.8483	0.0141
原煤全员效率非机械化率的 Granger 关系	1.6047	0.2146

表 2 的结果表明：机械化率为百万吨死亡率、利润率及原煤全员效率的 Granger 原因，并且机械化率与百万吨死亡率、利润率及原煤全员效率之间仅存在单向 Granger 因果关系，由此本文的研究框架得到了初步验证。

三、采煤机械化率的安全红利分析

1、百万吨死亡率与机械化率的门限分析

由图 1 可知，煤矿安全效益与机械化程度可能存在一种非线性阈值效应：当机械化程度超过某一个数值时，百万吨死亡率开始由升反降，而机械化程度再次大于某个数值时，这种下降趋势会显著加快。此外已有研究表明：产量会对煤矿百万吨死亡率产生显著影响(肖兴志等, 2008; 白重恩等, 2011) [14]-[15]。结合研究任务，本文将国有重点煤矿百万吨

死亡率设置为模型因变量，将国有重点煤矿机械化率和原煤产量增长率指数设为模型自变量，并运用门限回归来验证这一猜想，其基准模型如式(1)所示。

$$Mr_t = \alpha_0 + \alpha_1 Cmmr_t + \alpha_2 Qrate_t + \varepsilon_t \quad (1)$$

其中， Mr 表示煤炭百万吨死亡率， $Cmmr$ 表示煤矿机械化率， $Qrate$ 表示原煤产量指数，下标 t 表示时期。本文基于 1966-2019 年间的国有重点煤矿百万吨死亡率及国有重点煤矿采煤机械化率，分别采用“序贯检验”和“全局最优化算法”来确定最优门限数量和门限值的检验结果。其中序贯检验所使用的统计量为 $Scaled-F$ ，全局最优化算法检验所用的统计量为 $WDmax$ 。

表 3 国有重点煤矿百万吨死亡率门限值检验

门限变量	门限值的选择			
	序贯检验		全局最优化检验	
	门限值	$Scaled-F$	门限值	$WDmax$
采煤机械化率	37.0631	56.4591***	37.0632	80.5463***
($Cmmr$)	74.4243		74.4241	

注：*、**、***表示统计结果在 10%、5%和 1%置信水平下显著。以下各表同。

表 3 显示国有重点煤矿的百万吨死亡率与采煤机械化率呈显著的双门限关系，两种检验方法所得出的结论一致，取整后门限值分别为 37 和 74。对照图 1，两个门限值恰好对应了拟合曲线“正相关-弱负相关-强正相关”关系的拐点，散点图与模型拟合结果相一致。在模型(1)的基础上，设置采煤机械化率为门限变量，将模型调整为如下形式的双门限回归模型。

$$Mr_t = \alpha_0 + \alpha_{11} Cmmr_t \square I(Cmmr < \xi_1) + \alpha_{21} Qrate_t \square I(Cmmr < \xi_1) + \alpha_{12} Cmmr_t \square I(\xi_1 \leq Cmmr < \xi_2) + \alpha_{22} Qrate_t \square I(\xi_1 \leq Cmmr < \xi_2) + \alpha_{13} Cmmr_t \square I(Cmmr \geq \xi_2) + \alpha_{23} Qrate_t \square I(Cmmr \geq \xi_2) + \varepsilon_t \quad \dots(2)$$

式(2)中， ξ_1 、 ξ_2 均表示门限值，根据表 5 可

知 $\xi_1=37\%$ ， $\xi_2=74\%$ ， $I(\square)$ 为示性函数，目的在于根据门限值进行样本分段，其余符号含义与式(1)相同。为确保模型能够正确反映各变量之间的关系，避免伪回归问题的产生，本文首先采用时间序列 ADF 检验和 PP 检验法对变量的平稳性进行逐一验证。并运用 Johansen 协整分析对各变量之间的协整关系进行验证，表 4 报告了上述的检验结果，各差分变量均为一阶单整序列，协整检验均在 1%的显著性水平下拒绝了不存在协整关系的原假设，表明各变量之间存在显著的协整关系，回归分析的结果具有可靠性。

表 4 模型变量平稳性检验

变量	统计量				结论
	(C,t,q)	ADF	(C,t,q)	PP	
Mr	(C, t, 1)	-2.8109	(C, t, 0)	-2.8722	非平稳
ΔMr	(0, 0, 1)	-7.7352***	(0, 0, 1)	-7.9637***	平稳
$Cmmr$	(C, 0, 3)	-1.9665	(C, t, 0)	-1.4043	非平稳
$\Delta Cmmr$	(C, t, 1)	-8.4873***	(C, 0, 1)	-8.3541***	平稳
$Qrate$	(0,0,1)	-0.2651	(0,0,0)	0.0912	非平稳
$\Delta Qrate$	(C, t, 0)	-8.4862***	(C, 0, 1)	-25.1612***	平稳
Trace			52.2302***		
Max - Eigen			31.9048***		

表 5 报告了在双重门限值的设定下，利用样本本期数据建立门限回归模型的结果。从回归结果来看，二者呈显著的双门限关系：当 $Cmmr \leq 37\%$ ， $Cmmr$ 系数为 0.073， $Qrate$ 系数为 1.64，意味着采煤机械化没有达到门限水平时，难以发挥对死亡人数的抑制作用，同时产能越大，百万吨死亡率越高；当 $37\% < Cmmr \leq 74\%$ ， $Cmmr$ 系数为-0.062， $Qrate$ 系数为-3.852，采煤机械化率与百万吨死亡率弱负相

关，同时产能越大，百万吨死亡率越低，这说明采煤机械化提升了煤炭的安全产能；当 $Cmmr \geq 74\%$ ， $Cmmr$ 系数为-0.132， $Qrate$ 系数为-1.194，采煤机械化率与百万吨死亡率强负相关，同时产能越大，百万吨死亡率越低，说明采煤机械化进一步提升了煤炭安全产能。其中状态一到状态二的门限效应最为显著，状态二到状态三的门限效应较弱，这与图 5 曲线走势一致。

表 5 国有重点煤矿百万吨死亡率双门限回归结果

变量	状态 1	状态 2	状态 3
	$(Cmmr \leq \xi_1)$	$(\xi_1 \leq Cmmr < \xi_2)$	$(Cmmr \geq \xi_2)$
$Cmmr$	0.0731*** (0.0155)	-0.0617*** (0.0056)	-0.1321*** (0.0116)
$Qrate$	1.6402* (0.8278)	-3.8521*** (1.4075)	-1.1943 (1.0287)
Intercept	2.9801***	6.7958***	12.752***
差值	状态 1—状态 2		状态 2—状态 3
$Cmmr$	0.1353		0.0707
Adj R^2	0.9632		

注：系数下括号内为标准误。

图 4 为上述门限模型的拟合效果图，多数样本点都在 95%的置信区间内，拟合效果较为理想。采煤机械化率与百万吨死亡率呈现出明显的三阶

段线性关系，在采煤机械化率的阈值点 37%及 74%，拟合线段都呈现出明显的斜率变化。

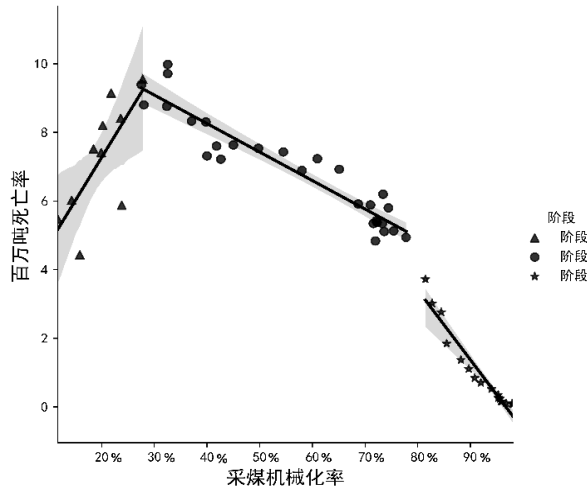


图4 双门限模型拟合效果图

从门限值对应的年份来看,采煤机械化率的两个门限值大致对应于1977及2000,这与中国煤炭工业发展的历史阶段相一致。根据前文所述,中国煤矿的综采技术在20世纪70年代起步,后在周恩来、邓小平等领导同志的关心下,加大了综采设备的引进及自主研发力度,中国的煤炭综采实现了从无到有,并得到了初步推广。1977年-1999年,国有重点煤矿采煤机械化率从32.52%提升至73.41%,百万吨死亡率由9.98下降到6.20。2001年中国成立了国家安全生产监督管理局,并在2005年升级为国家安全生产监督管理总局,国家自2001年起每年划拨国债资金、预算内资金30亿元,支持煤矿补还安全欠账,进行安全改造,2004年起又建立了煤矿安全费用制度,保障了煤矿安全生产的长效投入。2000年-2019年,国有重点煤矿采煤机械化率从74.43%提升至98.03%,百万吨死亡率由5.80下降到0.08。

2、机械化率安全红利的随机森林分析

(1) 随机森林模型的基本理论

为了综合比较采煤机械化率对百万吨死亡率的贡献,本文通过对煤炭万吨死亡率影响因素的文献梳理,归纳得出了11个对煤炭安全效益产生重要影响的影响因素,并运用随机森林模型探究各个因素对煤炭安全效益的影响力大小。这11个因素分别为:采煤机械化率,产量水平,煤矿机械设备投入量,原煤全员效率,运输风险,工资水平,行业集中度,需求水平,非民营化程度,矿工素质指

数及煤炭市场环境(肖兴志等,2011;张超林等,2021)^{[16]-[17]}。具体指标说明见表1,数据时间范围为1978-2019。随机森林是常用的机器学习中的非参数集成模型,可用于探索性特征选择、离散因变量的分类和连续因变量的预测任务。相较于传统计量模型,随机森林能够很好地拟合变量间的复杂非线性关系,并且无需考虑内生性等线性系统中存在的问题;相较于一般的机器学习模型,随机森林模型通过引入Bagging机制大大减少了模型的预测方差,模型的泛化能力强,可以在不做特征选择的情况下,处理高维数据,并按照残差平方和减少的贡献大小自动对投入要素排序。因此随机森林具有很高的预测准确率,对异常值和噪声具有很好的容忍度,且不容易出现过拟合(Ishwaran et al., 2008; 方匡南等, 2011)^{[18]-[19]}。由于本文所考察的目标变量煤矿安全效益为连续型特征,因而组成随机森林模型的基学习器为回归树模型,其本质为CART决策树。回归树模型属于规则学习算法,即按照一定的规则,基于数据特征递归产生一个自顶向下生长的树结构,每一个非叶子节点会将数据集进行一次划分,通过控制树的生长深度与叶子节点中所包含的最小样本量等,最终将特征的种类、数值对目标变量的影响在统计意义上相同的样本点划分至同一叶子节点当中,之后计算该叶子节点所包含的样本对应目标变量的平均值,平均值即为该叶子节点的输出变量。为方便表述,记第*i*个样本为 $(y_i, x_{i1}, x_{i2}, \dots, x_{iJ})$,其中 y_i 是目标变量,即煤矿安全效益; $x_{i1}, x_{i2}, \dots, x_{iJ}$ 为输入变量,即表1所述的11个影响因素。回归树的生长过程应用贪心算法,即在每个非叶子节点对数据集进行二分类数据分割,对于第*j*个输入变量 x_j ,如果已知一个阈值分割点 γ ,则可将数据集按照 x_j 大于或者小于阈值分成两个子集合 D_1 和 D_2 :

$$D_1(j, \gamma) = \{y_i, x_{i1}, x_{i2}, \dots, x_{iJ} \mid x_j \leq \gamma\} \quad (3)$$

$$D_2(j, \gamma) = \{y_i, x_{i1}, x_{i2}, \dots, x_{iJ} \mid x_j > \gamma\} \quad (4)$$

假设两个子集合分别包含了 m_{D1} 和 m_{D2} 个样本观测值,则针对每个子集合,可得到目标变量的平均值:

$$\bar{y}_{D1} = \text{Avg}(y_i | y_i \in D_1(j, \gamma)) \quad (5)$$

$$\bar{y}_{D2} = \text{Avg}(y_i | y_i \in D_2(j, \gamma)) \quad (6)$$

回归树模型通过求解最小化残差平方和损失函数的最小值,得到最佳的分割变量 x_j 及分割点 γ ,其表达式如式(7)所示:

$$\min_{j, \gamma} \left[\min_{\bar{y}_{D1}} \sum_{y_i \in D_1} (y_i - \bar{y}_{D1})^2 + \min_{\bar{y}_{D2}} \sum_{y_i \in D_2} (y_i - \bar{y}_{D2})^2 \right] \quad (7)$$

(7)式的最优化过程是通过遍历所有特征变量以及每个变量的分割点来实现的。具体而言,算法从特征 x_1 开始,如果其观测值有 m 个,则共有 $m-1$ 种分割方式可以将样本集按照 x_1 分成两个子集,通过循环遍历选择分割点来计算(5)、(6)式的结果并将它们中的最小值和对应分割点的位置保存下来,以此类推,直至遍历所有 J 个输入变量,得到 J 个最小值及其对应的分割点位置信息;从 J 个最小值中再次选择其中的最小值,其对应的特征变量及分割点即为所求。该算法执行过程中确定的第一个最佳分割特征 x_j 为回归树的根节点,根节点所对应的特征是对最终输出结果影响最大的一个。第一次样本空间划分完成后,数据集已被分裂成两个子集 D_1 和 D_2 ,之后再次在 D_1 中应用上述搜索过程寻找最佳的分割变量 x_k ($k \in \{1, 2, \dots, J\}, k \neq j$) 和最佳的阈值分割点,将集合 D_1 再次分裂成两个子集合 D_3 和 D_4 , x_k 即为回归树的一个中间节点,这一优化过程与(7)式类似,其表达式如式(8)所示:

$$\min_{j, \gamma} \left[\min_{\bar{y}_{D3}} \sum_{y_i \in D_3} (y_i - \bar{y}_{D3})^2 + \min_{\bar{y}_{D4}} \sum_{y_i \in D_4} (y_i - \bar{y}_{D4})^2 \right] \quad (8)$$

据此继续对 D_2 、 D_3 、 D_4 重复上述分割步骤,直到达到某个预设的条件时回归树停止生长。回归树模型会因生长深度过大或叶子节点中所包含的最小样本量过小等因素而导致过拟合,因而需要在其生长过程中进行数次惩罚,这通常称为回归树的剪枝过程。一般而言,单棵树的预测精度欠佳,可将树模型按照一定的方式进行整合来增强模型的预测能力,整合后的模型称为集成模型(Ensemble model),常见的集成方法有袋装法(Bagging)、提升法(Boosting)等。随机森林应用 Bagging 思想,采用多棵决策树投票机制,完成目标变量的分类或预测任务。对于本文所研究的预测任务而言,算法

对数据集进行 N 次自助采样,每次采样均可以独立地训练出一个基学习器(回归树),之后计算 N 个基学习器目标变量预测值的平均数即为最终模型的输出结果。随机森林的优势在于它的二重随机性:组成随机森林的每个基学习器的训练数据由 Bootstrap 随机采样产生,并且在训练过程中仅考虑了部分随机选择的特征(占比为全部特征的三分之二)作为候选的节点分裂变量,这种设计会极大的减少估计的方差,防止过拟合,随机森林的组成结构如图5所示。此外,随机森林在估计的过程中会按照各变量对残差平方和减少的贡献程度来进行特征重要性的排序。

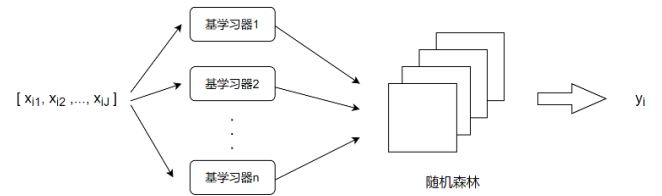


图5 随机森林模型示意图

(2) 随机森林模型的构建

本文构建了基于回归树的随机森林模型对影响煤矿安全效益的各个因素进行了实证研究。随机森林模型的拟合误差会因基学习器的个数、树模型的最大深度和叶子节点所包含的最小样本量的不同而有所差异,因而本文应用网格搜索程序(Grid Search)来确定这一水平所对应的临界点,网格搜索程序通过循环遍历待调整超参数候选值所有可能的组合并以交叉验证结果作为依据得到模型最优的超参数取值。交叉验证即针对每一种超参数的取值组合,对训练样本集随机划分为 K 组,之后按顺序将其中的一组作为验证集,余下的 $K-1$ 组作为训练集,这一过程对原始训练集进行了二次划分,得到了 K 组训练集和验证集的组合;交叉验证程序循环遍历每一种组合,在训练集中训练模型,在验证集中返回模型的预测得分;遍历结束后,将 K 组预测得分求算术平均,进而得到目标超参数取值组合的最终分数。交叉验证机制的设计能够有效地避免过拟合,提升超参数选择过程的稳健性。本文结合数据集的规模,选择每个超参数组合进行 5 折交

叉验证。图 6 描述了网格搜索程序的执行过程：横轴代表了基学习器的个数，纵轴代表了树模型的最大深度，竖轴代表了树模型叶子节点的最小样本量；每个散点表示每一种可能的超参数组合，散点的颜色代表了对应超参数组合的预测得分，其颜色越浅，得分越小。本文应用均方误差的相反数作为模型预测的评估指标。从图 7 中可以看出：模型的预测误差实际在很小的范围内波动，并且具有显著的周期性，第 113 个超参数组合达到了均方误差的最小值，该序号对应的各个超参数取值如表 6 所示。

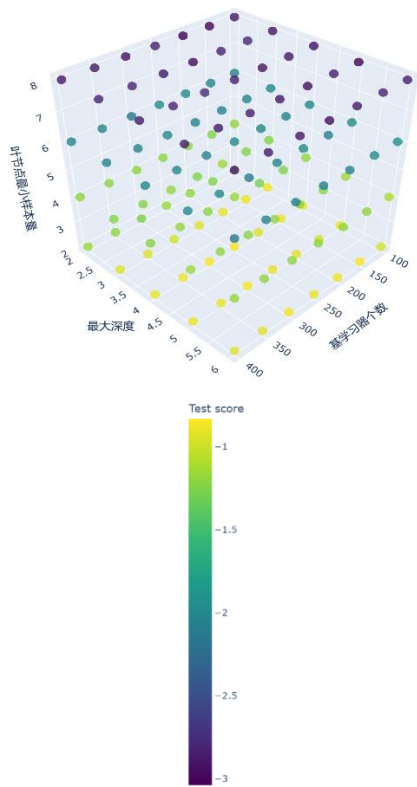


图 6 网格搜索程序

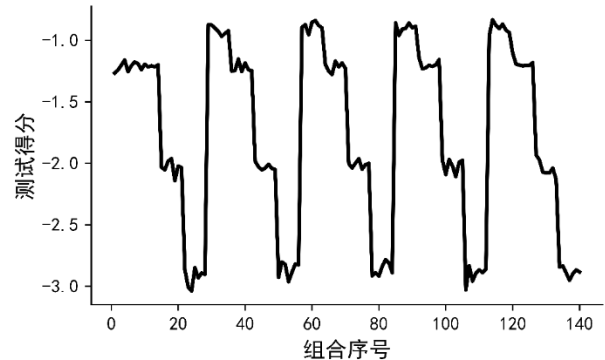


图 7 不同参数组合下的测试得分

表 6 模型超参数选择结果

超参数名称	数值
基学习器的个数	150
树模型的最大深度	6
叶节点包含的最小样本量	2

(3) 随机森林模型特征重要性排序

随机森林模型在估计的过程中会按照各变量对残差平方和减少的贡献程度来进行特征重要性的排序，该方法的基本思想为将待计量重要程度的变量进行白噪声处理，得到以白噪声为基础的对比模型，通过计算白噪声处理前后模型预测误差的差异程度进而完成该变量重要性程度的计量。本文应用该方法将影响煤矿安全效益的因素依据重要程度进行排序，排序结果如图 8 所示。

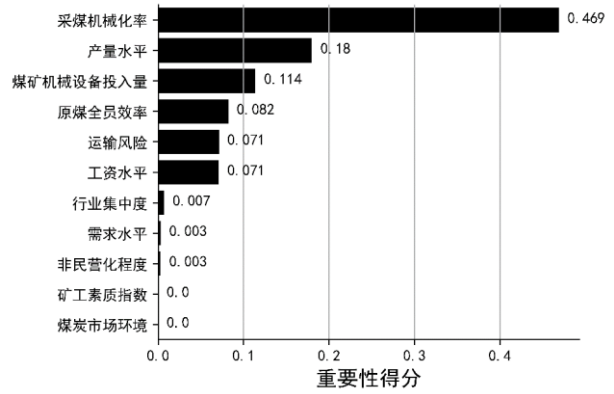


图 8 随机森林模型特征重要性得分排序

从图 8 可以看出，各特征变量的重要性得分大致可分为两类：采煤机械化率、煤炭产出水平、煤矿机械设备投入量、原煤全员效率、运输风险和工资水平对煤炭安全效益的影响效应显著大于行业集中度、需求水平、非民营化程度、矿工素质指数和煤炭市场环境，由此可以看出，煤矿企业内部生产环境主导煤矿安全效益的变化；采煤机械化率是本文所考察的因素中，对煤矿安全效益影响最大的特征，这一结果表明，机械化率的提升可以带来煤矿安全红利，实现采煤机械化、智能化是改善煤炭生产环境的首要任务。

四、采煤机械化的经济红利分析

提升采煤机械化率是煤炭开采的技术改进，可以视为对煤矿全员效率的冲击，而煤矿全员效率又

会影响煤炭企业利润，为了动态地探究行业利润与机械化率之间的关系，规避时序变量的序列相关性等问题，本文构建了 BVAR 模型来考察不同因素的变动对煤炭行业利润的影响。相较于 VAR 模型，BVAR 在参数较多且数据量相对较小的情况下有着更好地拟合效果，能够更为准确的反映变量间的相互关系。BVAR 刻画了多个模型变量间的动态影响关系，模型中的所有变量均为内生变量，脉冲冲击来自于随机误差项。借助于一个平稳的 BVAR 系统即可研究某一变量（或多个变量）前期的变化对目标变量产生影响的大小和持续时间，从而可以对比不同模型变量对煤炭行业利润的影响效应。本文建立的 BVAR 模型如式（8）所示：

$$y_t = c + Ay_{t-1} + \varepsilon_t \tag{8}$$

其中：

$y_t = (\Delta \ln Cmmr, \Delta \ln Profit, \Delta \ln Efficiency, \Delta \ln Q, \ln RPI)^T$ ，A 为滞后算子 L 的参数矩阵， ε_t 为随机扰动项；根据前文表 3 可知，采煤机械化率的变动是引起国有重点煤矿利润率及原煤全员效率变化的 Granger 原因。因此在 BVAR 模型的基础上，本文运用广义脉冲响应函数（GIRF，General impulse response function）来进一步分析采煤机械化率、原煤产量及煤炭价格指数收到冲击后，国有重点全员效率及煤矿利润率的变动变动规律。

煤炭价格指数基期为 1978 年，因此模型的整体样本区间为 1978-2019。为了刻画 VAR 模型的阶段性趋势，本论文根据中国煤炭工业发展历程将样本区间划分为 3 段：1978-1993 为第一阶段，1994-2004 为第二阶段，2005-2019 为第三阶段。第一阶段为计划煤价阶段 BVAR 模型，国家从 1994 年开始完全放开煤价，此前实行的是煤炭统购统销或价格双轨制（王震，2018）^[20]；第二阶段为采煤机械化率停滞阶段 BVAR 模型，该时期国有重点煤矿采煤机械化率基本处于停滞状态，这是因为国有煤矿存在严重的历史欠账，主要技术装备性能较先进采煤国家落后 10 年左右（汤凌霄和郭熙保，2006）^[21]；第三阶段为采煤机械机械化稳定提升阶段 BVAR 模型，2005 年国家设立安全监察总局并实施

了安全费提取制度，此阶段中国煤炭工业即经历了黄金十年，也经历了长期的行业低谷，但采煤机械化率在持续提升。

根据多信息准则，本文选择了滞后一期的 BVAR 模型。脉冲响应分析需要验证各变量在三个阶段的平稳性，结果如表 7 所示：

表 7 各阶段 BVAR 模型平稳性检验表		
特征根 (1978-1993)	特征根 (1994-2004)	特征根 (2005-2019)
0.9537	0.9281	0.9013
0.3085	0.2779	0.2507
0.0302	0.1775	0.2512
0.0208	0.0268	0.0211
0.0206	0.0011	0.0032

验证结果表明，三阶段的 BVAR 模型的特征根均在单位圆之内，表明各时期的 BVAR 模型是平稳的，适合进行脉冲响应分析。

1、计划煤价阶段脉冲响应分析结果

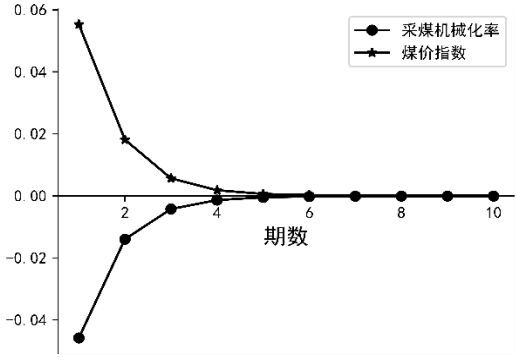


图 9 煤矿利润率响应图（1978-1993）

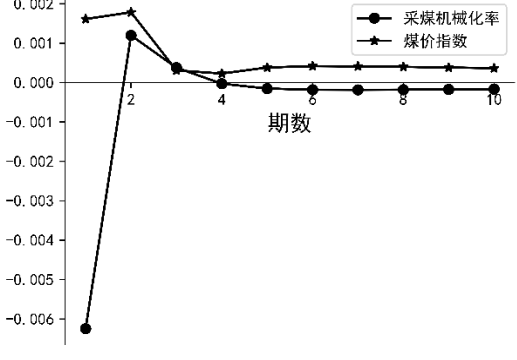


图 10 原煤全员效率响应图（1978-1993）

从图 9 可以看出：采煤机械化率对煤矿利润率形成负向影响，煤价指数对煤矿利润率形成正向影

响,二者的影响呈现出对称关系并逐期减弱,从第5期开始影响都趋于消失。从图10可以看出:采煤机械化率对于原煤全员效率的影响在第一期为负,第二期转为正,总体以负向影响为主,煤价指数对于原煤全员效率的影响持续为正,二者的影响从第4期起趋于消失。由此可以得出结论:在计划煤价时期采煤机械化率的提升不仅没有带来经济红利,还抑制了国有重点煤矿利润率及原煤全员效率。本文认为有三个原因造成了这一现象:(1)采煤机械化没有形成规模经济,1978-1993年间国有重点煤矿的机械化率长期在50%以下,难以发挥规模优势;(2)煤矿冗员问题严重,拖累了生产效率。据测算1992-1997每年分流10万人的基础上,国有重点煤矿仍然存在100万人的富余劳动力(刘传庚,2001)[22]。(3)采煤机械化投入具有巨额性的特征,该阶段国家对煤价进行严格管控,造成煤价难以反映生产成本,两种因素相叠加压缩了企业的利润空间。

2、采煤机械化率停滞阶段脉冲响应分析结果

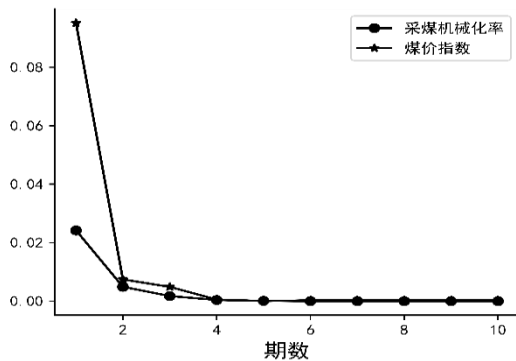


图 11 煤矿利润率响应图 (1994-2004)

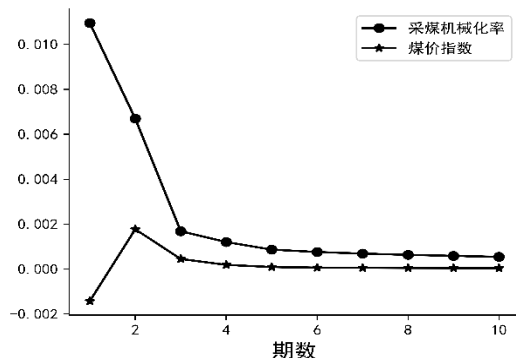


图 12 原煤全员效率响应图 (1994-2004)

从图11可以看出:该阶段采煤机械化率与煤价指数对于国有重点煤矿利润率均存在正向影响,在第1期煤价影响显著高于采煤机械化率的影响,

之后趋于一致,二者的影响都从第4期开始趋于消失。值得注意的是,对比图9与图11可以发现,采煤机械化率对利润率的影响在该阶段实现了逆转。从图12可以看出:煤价指数对原煤全员效率的影响由负转正,同时采煤机械化率对原煤全员效率存在正向影响,其影响程度显著高于煤价。第一阶段与第二阶段对比结果表明:计划煤价时期所存在的制约问题得以改善,国有重点煤矿开始从机械化率过程中获得全员效率的提升与利润红利。

3、采煤机械化率持续提升阶段脉冲响应分析结果

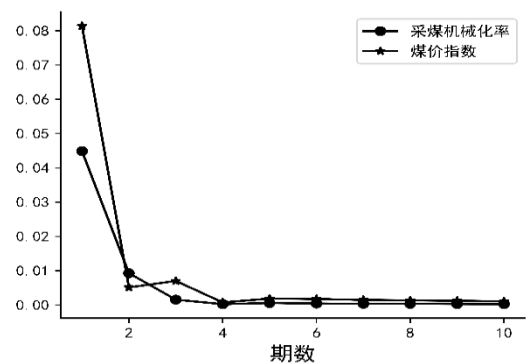


图 13 煤矿利润率响应图 (2005-2019)

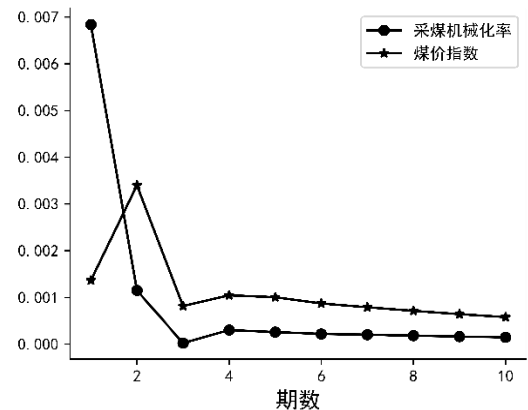


图 14 原煤全员效率响应图 (2005-2019)

从图13可以看出:该阶段采煤机械化率与煤价指数对国有重点煤矿利润率均存在正向影响,虽然煤价影响仍然高于采煤机械化率的影响,但跟前两个期对比可知:二者在第1期的影响强度差距在缩小,同时采煤机械化率的影响强度得到了显著提升。从图14可以看出:该阶段采煤机械化率与煤价指数对原煤全员效率均存在正向影响,并且从第1期影响来看,采煤机械化率的影响显著高于煤价影响。这给当期煤炭工业的发展提供了有益启发:采

煤机械化可以通过控制全员效率来平抑煤价波动的影响。随着采煤机械化和智能化水平的提高,煤炭企业可以根据价格波动,通过调控开机率来精准控制产能,未来有望做到按需生产。

五、结论与讨论

根据前文的分析,本文可以得出如下几个结论:

(1) 门限模型的分析表明:采煤机械化对于国有重点煤矿安全水平的影响并不是简单的线性关系,而是一个量变到质变的过程。因此采煤机械化是一项长期工程,不能期望短期收益。在采煤机械化初期即没有经济效益,也没有安全效益,经济指标和安全指标甚至会持续恶化。1977年前后,国有重点煤矿开始享受采煤机械化带来的可持续性安全红利:原煤产量上升,同时百万吨死亡率下降。并且在2000年前后,安全红利得到进一步增强。与百万吨死亡率的降低一样,新发尘肺病例数的降低需要机械化的长期积累。“机器换人,自动化减人”逐渐将矿工从危险的工作环境中解放出来,有效降低他们的接尘机会。此外矿山机械设备在不断强化健康防护功能,通过设备的功能设计实现对矿工健康的主动防护。采煤机械化的以上两项功能,将有效驱动煤矿职业病防治效果的质变,实现矿工职业健康水平的根本改善。

(2) 随机森林模型的分析表明:采煤机械化率对于国有重点煤矿的安全生产水平提升具有不可替代的作用,其重要性在所有因素中排名第一。除了降低死亡率,采煤机械化还具有健康防护和劳动保护的功能

(3) VAR模型的脉冲响应分析表明:采煤机械化达到一定的程度后,才能获得经济红利。采煤机械化投入回收周期较长,不能获得立竿见影的经济效益。煤炭是保障能源供应的基础能源,采煤智能化关系到中国未来的能源安全。在行业不景气的情况下,完全依靠企业的利润积累进行采煤智能化改造是不现实的。因此需要政策性银行等机构,帮助煤炭企业进行智能化改造的政策性融资。

经过70余年的发展,中国采煤机械化在一穷

二白的基础上起步,如今终成煤炭智能化开采的引领者。中国共产党及历代领导集体用实际行动诠释了什么叫做守正笃行,久久为功。由此中国逐渐解决了经济发展中的能源瓶颈问题,成为世界能源强国以及能源革命的重要推动者。只有中国特色的社会主义制度才能真正做到坚持人民至上,不计较短期利益,攻坚克难,坚持对采煤机械化这种投资额大,回收期长,收益率低的项目进行长期投资。因此无论是安全红利,还是经济红利,本质上都来源于中国特色社会主义的制度红利。在新时代的背景下采煤机械化仍然具有时代价值:它有利于国家能源安全,有利于2030年碳达峰目标的实现,有利于煤炭企业的战略转型,有利于矿工权益的维护,同时有利于煤炭行业积极应对人口老龄化,是需要坚持推进的战略性工程。

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Electrification transition and carbon emissions reduction of urban transportation systems from a double substitution perspective

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Abstract: The urban transportation sector has been one of the major contributors to carbon emissions due to motorization and urbanization. Urban transportation electrification transition is crucial to achieve the target of “carbon peak.” In this paper, we proposed the “double substitution” of vehicles and travel modes, and introduced multi-level perspective (MLP) to analyze the mechanism of urban transportation electrification transition. Furthermore, we established the multi-level perspective system dynamics (MLP-SD) model with three subsystems to simulate the change in travel mode, electrification transition process, and carbon emissions reduction effect of the urban transportation system in Shenzhen in single and comprehensive policy scenarios. The results show that: (1) The electrification transition process of urban transportation systems can be divided into four phases and the substitution processes of travel mode and vehicle are not synchronous, with a significant delay in each phase of substitution of the travel mode compared to that of the vehicle. (2) With the electrification transition, Shenzhen gradually forms a diversified green travel mode dominated by rail transit. (3) In different policy scenarios, the carbon emissions change trend of the urban transportation system is similar, showing an inverted “V” shape with the “carbon peak” around 2030, and the emission reduction effect in integrated policy scenarios (IP) is superior to that of single policy scenarios. (4) In the short term, reducing the carbon emission coefficient of fuel and electricity through technological progress can achieve carbon mitigation in urban transportation systems. In the long term, optimizing the travel mode is the most effective method.

Keywords: Urban transportation; Electrification; Carbon peak; Multi-level perspective; System dynamics

1. Introduction

Greenhouse gas (GHG) emissions and climate change have drawn extensive attention worldwide recently, with carbon emissions from human activities as the major contributor^[1,2]. As one of the main carbon emission sectors, transportation accounts for 37% (7.1 Gt) of CO₂ emissions from end-use sectors in 2020^[3], and will reach 50% by 2030 and 80% by 2050^[4]. In China, the transportation sector has the fastest growth in carbon emissions^[5], and contributes approximately 10% of the country's total emissions^[6]. The Chinese government has committed to reaching carbon peak by 2030^[7]. According to the Energy Research Institute of the National Development and Reform Commission (NDRC), carbon emissions from China's transportation sector will peak shortly after 2030, later than that of construction and industry^[8]. Thus, the transportation sector faces severer challenges and is crucial for China to achieve the goal of carbon peak^[9].

Urban transportation is one of the major contributors to transportation carbon emissions, accounting for approximately 20% (188 Mt) of the total transportation carbon emissions in China in 2016^[10,11]. With urbanization and motorization, the proportion of carbon emissions from urban transportation will continue to rise. It is predicted that before 2030, urban transportation carbon emissions will increase at an annual growth rate of 1.7%, higher in developing countries and countries in economic transition, reaching 3.4% and 2.2% respectively^[12]. For these reasons, it is necessary to determine the CO₂ emissions mitigation pathway in the urban transportation sector in China.

Many large cities worldwide are challenged by similar pressures. Various emissions reduction practices in the transportation sector have been implemented, such as the fuel tax in many cities in Europe^[13]; light-duty fuel efficiency standards in New York^[14]; low emission vehicles and the congestion

pricing system in London^[15,16]; free public transport in Brussels^[17]; and private car ownership and use management constraint policy in Hong Kong and Singapore^[18]. Some scholars have focused on emission reduction measures in the urban transportation sector from different perspectives. Intrinsically, these measures can be divided into two categories:

First is the clean vehicle strategy, which means reducing the carbon emissions of vehicle devices per kilometer using technical improvements or fuel^[19]. Some researchers have emphasized the replacement of fuel based on crude oil with renewable or low-carbon options and conducted empirical studies of the carbon mitigation effect of electric vehicles. It is believed that electric vehicles may provide insight into sustainable urban transportation transitions^[20,21]. The benefits of introducing electric vehicles in Sete Lagoas city were evaluated using AVL Cruise software, which suggests that for a complete fleet replacement of internal combustion engines (ICE) by electric vehicles, the emission reductions would vary from 3,800 tons to 5,600 tons of CO₂ per year^[22]. The second category is the travel mode shift strategy, which refers to investing in public transportation, and restricting the purchase and use of private vehicles to reduce carbon emissions. Optimization of transportation modes, especially the expansion of the public transport travel, such as providing free bus services, increasing public transportation service supply based on rail transits and buses, and enhancing service quality, has proven to be the most cost-effective means to reduce emissions and is important in developing low-carbon urban transportation^[23,24]. In addition, the government plays a crucial role in CO₂ emissions mitigation of urban transportation, and policy guidance can strengthen the effect of these measures to a large extent^[25]. The reduction in carbon emissions generated by a travel mode shift may dwarf those yielded by technological

measures as developing nations quickly move to motorization [26].

Current emissions reduction practices and research have proved the effectiveness of clean vehicle strategy and travel mode shift strategy for carbon emission reduction of urban transportation systems. Few extant studies integrated these two strategies to analyze the specific mechanism of electrification transition and carbon reduction. Moreover, the urban transportation system is complex, affected by many subsystems such as the economy, population, and environment [27]. Transition of urban transportation system also requires co-evolution and multi-dimensional interaction among technology, market, policy, culture and civil society [28]. However, existing studies rarely consider the uncertain behaviors (e.g., residents' travel preferences and policy orientation) associated with these subsystems and transition, as well as the interactions among various transportation subsystems and multiple transformation dimensions [24]. In addition, the complexity of the urban transportation system and transition also leads to the dynamic processes of electrification transition and carbon emission reduction of urban transportation systems are hardly simulated quantitatively.

This study aims to clarify the mechanism of urban transportation system electrification transition, and build a model to simulation the change in travel mode, electrification transition process and carbon emission reduction effect in different policy scenarios. To this end, Shenzhen is used as a case study. Resembling other megacities in developing countries, Shenzhen is experiencing a continuous expansion in which the population and economy are growing rapidly, resulting in a rising challenge to carbon emission mitigation from the urban transportation system [11]. It is also a city with the highest adoption rate of electric vehicles in China, and has the potential to serve as a

model for a low-carbon transportation system in China and other emerging economies [29]. Therefore, research into the urban transportation system in Shenzhen can identify solutions to reduce urban carbon emissions in transportation systems during urbanization in developing countries, which also provides a reference for the worldwide electrification transition of urban transportation systems.

To solve the gap in existing literature, this study makes three key contributions. First, we integrated clean vehicle strategy and travel mode shift strategy and proposed the double substitution of vehicles and travel modes to achieve carbon peak in the urban transportation sector, which is regarded as a vital component reflecting the electrification transition process of the urban transport system. Specifically, that is to substitute traditional fuel vehicles with electric vehicles and substitute private car travel with public transportation travel for optimization, which is of great significance in reducing carbon emissions from urban transportation and bringing forward the goal of carbon peak. Second, we introduced the multi-level perspective (MLP), a socio-technical approach that goes beyond technological fixation or behavioral change and is presented as a heuristic framework, to analyze the interactions and the mechanism of urban transportation system electrification transition. Third, we combined multi-level perspective (MLP) with system dynamics (SD) and constructed the multi-level perspective system dynamics (MLP-SD) model, which covers the interactions among various transportation subsystems and reflects the uncertain behaviors.

The rest of this paper is organized as follows: Section 2 analyzes the mechanism of urban transportation system electrification transition. Section 3 establishes the MLP-SD model of the electrification transition of urban transportation systems. Section 4 simulates the change in travel mode, electrification

transition process, and carbon reduction effect of the urban transportation system in single and integrated policy scenarios. Section 5 summarizes the main conclusions and policy implications, as well as future research opportunities.

2. Mechanism analysis

2.1. Multi-level perspective on socio-technical transitions

Transition refers to the long-term change in a system to realize a basic social function. The transition process not only includes new technologies, but also means significant changes in habits, legislations, policies, infrastructures, networks, and systems [30]. The MLP proposed by Geels is one approach of social transitions to sustainability, focusing on systems that provide societal functions or end-use services [31]. The MLP conceptualizes the transition and development of a socio-technological system (ST) as three levels, and believes that transition is a nonlinear process caused by the interaction of these levels, that is, micro-level of niches, meso-level of ST-regimes, and macro-level of landscape. Among them, the micro-level of niches is the place where radical innovations are generated and developed. The meso-level of ST-regimes accounts for the stability of existing technological developments

and occurrence of trajectories, including a series of conventions, institutions, regulations, and cognition that determine the stability of the existing system, and affect ideas and mutual behaviors as intangible elements in the ST. The macro-level of landscape refers to the external factors with slow change, which provides gradients for the trajectories [32]. As a study framework of breakthrough technological diffusion and system transition, the MLP provides both a global perspective to describe the overall process of multidimensional socio-technical transitions, and a local perspective of the dynamic role of social groups in the system and causal mechanisms in multi-level interactions [33,34]. It has been widely applied in low-carbon sustainability transitions [35-37].

2.2. Electrification transition mechanism analysis of the urban transportation system

Combining the MLP theory and the ideal transition curve proposed in the literature [38], the urban transportation system electrification transition in this study is characterized by phases, milestones, and system states. Based on the dominant transition mode, electrification transition is divided into four phases. Fig. 1 shows a dynamic process of the urban transportation system electrification transition

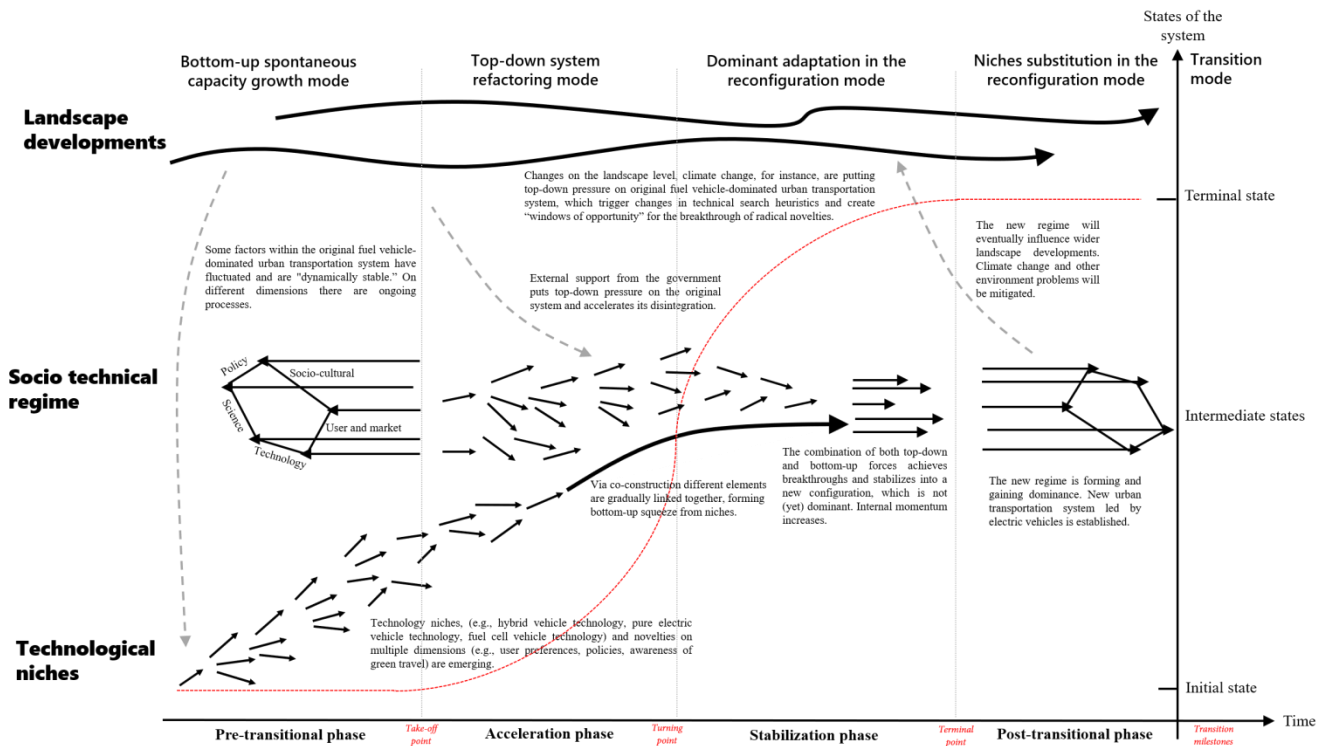


Fig. 1. A dynamic process of the urban transportation system electrification transition (adapted from [32]&[38])

From the interactions of three levels: The micro-level of niches, such as electric vehicle technology, new travel preferences and green travel awareness, are the internal driver elements for system transition. The universal lock-in and path dependency of the meso-level of regimes increase the stability of the traditional fuel-vehicle-dominated urban transportation system, further increasing the resistance to niches growth and system transition. The macro-level of landscape, such as climate change and environmental pollution, puts pressure on the original system and provides an opportunity window for the electrification niches to break through the obstacle within the original system with top-down external support from government. New technologies and user preferences are fine-tuned and absorbed along the established transition path, then remain stable and gradually gain dominance. A new regime led by electric vehicles has been established and

influences landscape developments.

From the system state of transition: In the pre-transitional phase, the urban transportation system is dynamically stable. From the “take-off point,” the electrification transition enters an acceleration period, and the basic composition of the system starts to change with the rising rate and scale. At the “turning point,” the growth reaches the maximum rate, and the conversion rate gradually decreases in the stabilization phase, during which the vehicle and travel mode substitution of the system have already occurred. At the “terminal point,” the system enters the post-transitional phase, and the electrification transition is basically completed, from where the new urban transportation system led by electric vehicles is established and becomes relatively stable again. Table 1 explains the dynamic changes and interactions among the elements in each phase of the electrification transition.

Table 1 Transition conditions, mechanisms and dominant transition modes of each phase.

Phase	Transformation conditions	Mechanisms and dominant transition modes
Pre-transitional phase	Top-down external pressure from the landscape	Climate warming and urban pollution have highlighted the problem of carbon emissions from existing fuel-vehicle-dominated urban transportation system and provided an opportunity window for the electrification transition.
	Internal pressure within the regime	Although some factors within the existing system have fluctuated, the fuel-vehicle-dominated urban transportation system remains predominant, with no response from the participants in the original system.
	Bottom-up squeeze of niches	Technology niches of electric vehicle technology and novelties on multiple dimensions (e.g., user preferences, policies, awareness of green travel) are emerging. Top-down conscious niches protection has not formed, and niches are growing spontaneously.
	Dominant transition mode	Bottom-up spontaneous capability growth mode: In the pre-transitional phase, the changes of landscape provide the opportunity window to emerge, in which the technology niches are being researched and grow spontaneously from the bottom-up.
Acceleration phase	Top-down external pressure from the government	Environmental pressures continue to increase, and the government has issued emission reduction targets and imposed taxes on fuel, providing external support for the development of technology niches of electric vehicles.
	Internal pressure within the regime	External pressure from the landscape and government have influenced the fuel-vehicle-dominated urban transportation system, decreasing its stability. The meso-level of regimes adjusts the external pressures and absorbs the innovations that appear at the micro-level of niches. Participants in the original system make non-adaptive adjustments (e.g., fuel vehicle manufacturers improve fuel efficiency and reduce emissions) to avoid obsolescence and maintain their dominant position, increasing the resistance to the electrification transition.
	Bottom-up squeeze of niches	The positive environment created by the government has formed the protection for the technology niches, allowing further growth to enter the demonstration operation stage, while the technology niches cannot be allowed to market niches due to high battery substitution costs, inadequate charging facilities, and low public acceptance.
	Dominant transition mode	Top-down system reconfiguration mode: The transition enters an accelerated period, in which the established technology niches can grow further due to the external support from government, while the current system makes non-adaptive adjustments. However, the phenomenon of universal lock-in and path dependence within the regime increases the stability of original system.
Stabilization phase	Top-down external pressure from the government	The government provides technical and financial support to accelerate the electrification substitution of fuel vehicles and the shift of technology niches to the market niches.
	Internal pressure within the regime	The original fuel-vehicle-dominated urban transportation adjusts within the system. It makes non-autonomous participatory adaptive changes to cope with the impact of external pressure (e.g., traditional fuel vehicle companies absorb the battery manufacturing industry, including power battery production and other businesses to continue their dominant position; some public transportation operators have to use energy-saving and carbon-reducing vehicles, change new vehicles to electric vehicles, and replace the existing fuel vehicles in batches). In addition, due to the low emissions and comfortable environment of electric vehicles, residents who used to travel by private cars shift to electric public transport, some of which are willing to buy electric private cars.
	Bottom-up squeeze of niches	The bottom-up squeeze of niches combines with the top-down support from government to match incremental innovations with the market demand, realizing the transition from the technological niches to the market niches, in which regional pilot programs of electric vehicles are being promoted.

Post-transitional phase	Dominant transition mode	Dominant adaptation under the reconfiguration mode: In this phase, the transition enters the stabilization period and continuously strengthens the reconfiguration mode. Under continuous pressure, fluctuations occur within the original urban transportation system regime, and the policy, market, and technology are absorbed along the established transition path. The technology niches shift to market niches.
	Top-down external pressure from the government	The government further strengthens the regulations to reduce barriers from the original urban transportation system to promote the electrification substitution of travel modes.
	Internal pressure within the regime	The gradual disintegration of the impediments has resulted in autonomous participatory responses to the development of electric vehicles by most actors in the existing fuel-vehicle-dominated system (e.g., rising cities implement the public transport electrification transition, the share of public transport travel has raised, achieving a shift in travel mode from private cars to public transport). The new urban transportation system is gradually emerging and stabilizing, and the new regime is forming and gaining dominance. In this phase, the electrification transition is completed.
	Bottom-up squeeze of niches	The gradual removal of obstacles within the original system has allowed the technology niches to grow into mature market niches. With electric vehicles becoming popular in major cities, the market niches enter the mass application stage.
	Dominant transition mode	Niches substitution in the reconfiguration mode: transition enters the post phase when the electric vehicle market niches have formed and continue to expand. With the niches substitution mode strengthening, the niches are in a dominant position and destabilize the existing fuel-vehicle-dominated urban transportation system. The regime, technology, and market of the electric vehicle-dominated urban transport system has reconfigured and feed back into the landscape.

3. Model and scenarios setting

An urban transportation system is a complex system in which a slight change in social, economic or environmental aspects can lead to a dramatic change in the system, which makes it difficult to define the elements as precise mathematical expressions. SD is a method based on systems theory to simulate multiple feedback loop interaction networks and the nonlinear relations of complex systems. Literature ^[39] revealed that the SD model not only achieves the combination of quantitative and qualitative analysis to describe the uncertain behavior characteristics, but can also be used when the database is insufficient to support. Thus, the SD model is an appropriate approach to reflect the dynamic process and display the inherent behavior and interrelation within the system, which is also an effective policy analysis tool widely used in strategy planning and policy simulation ^[24,40,41].

To this end, based on the mechanism analysis of

electrification transition, this study combines the SD with MLP theories to construct the MLP-SD model for urban transportation system electrification transition, focusing on the “double substitution” of vehicles and travel modes. According to the principle of system theory, a complete urban transportation system includes not only various types of vehicles, but also urban population, economy, social environment and related policies. Considering the collectability of the data, the MLP-SD model consists of three subsystems: population and economy subsystem, urban transportation subsystem, and carbon emission subsystem, in which the urban transportation subsystem contains two parts: a private car travel section and a public transportation travel section. Fig. 2 presents the framework of the MLP-SD model.

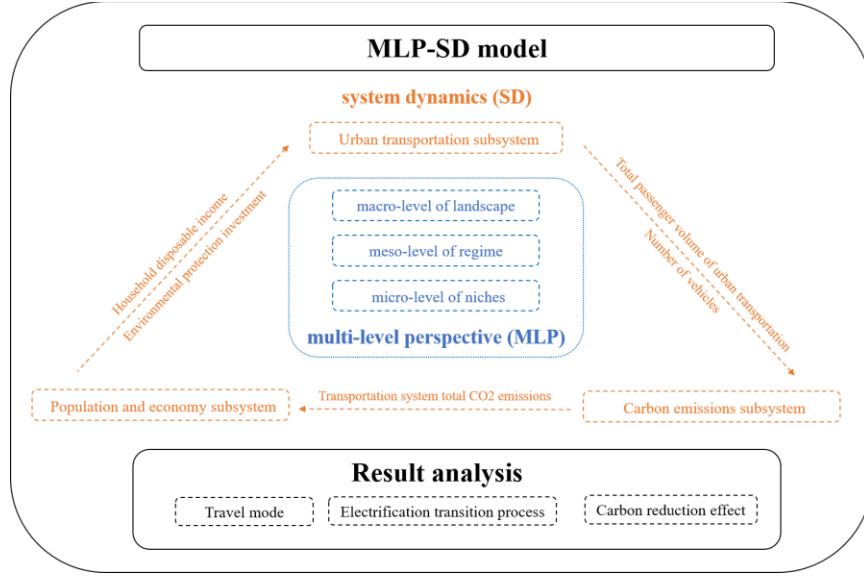


Fig. 2. Framework of the MLP-SD model

The main assumptions of the model are as follows:

- (1) The model operation range is set from 1995 to 2050. During the simulation period, the vehicles that generate carbon emissions mainly include buses, fuel private cars, electric private cars, taxis and rail transits. Green travel in this study refers to rail transits and electric vehicles travel.
- (2) Public transportation is strongly government-driven, hence the electrification substitution of buses and taxis in the MLP-SD model only considers the orderly promotion under government guidance.
- (3) In the travel mode substitution, only the

substitution of private cars, taxis, and rail transits with buses are considered, excluding the combination of travel modes.

3.1. Causal-loop diagram

The SD model provides an opportunity to use feedback loops to demonstrate the relationship between variables in the system. The "+" sign indicates that when one variable changes, the other produces a change in the same direction, while a "-" sign indicates that one variable causes the other to change in the opposite direction. Fig. 3 shows a causal-loop diagram of the MLP-SD model.

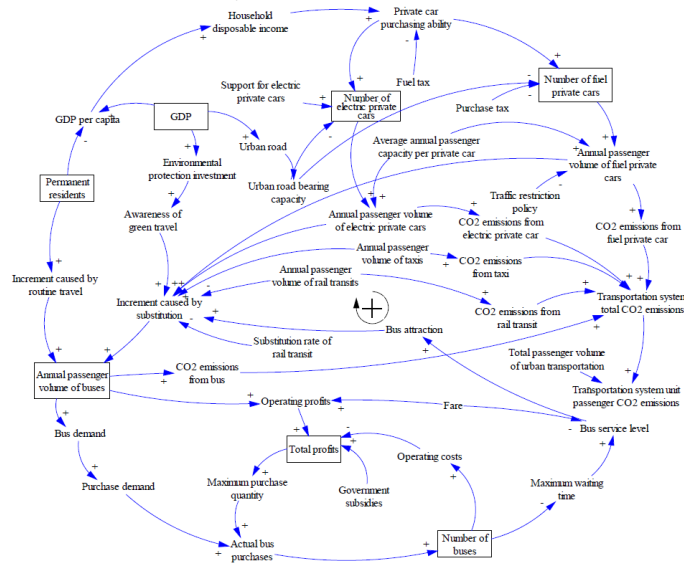




Fig. 3. Causal-loop diagram of MLP-SD model for urban transportation system electrification transition

On the one hand, with the rapid growth of GDP, household disposable income has risen, bringing a significant increase in private cars and urban transportation carbon emissions. On the other hand, owing to the pressure of traffic congestion and carbon mitigation, the electrification transition of urban transportation systems continues to advance. The “double substitution” of vehicles and travel modes leads to travel mode optimization and low-carbon transportation development.

3.2. Stock–flow diagram

Based on the causal-loop diagram, we established the stock–flow diagram of the MLP-SD model to reflect the accumulated reactions and quantitative relationships among the variables, as illustrated in Fig. 4. The causal relationship between variables is indicated by blue arrows. There are three types of variables in a stock–flow diagram: Level variable represented by the INTEG function, generally is used as an output variable to simulate a state value of the system, which is denoted with the symbol “”; Rate variable, is used to define the relationship between the increase or decrease in the level variable, which is denoted with the symbol “”; Auxiliary variable, is mainly used to establish the logical relationship between the factors of each variable and represent some parameter or values calculated mathematically.

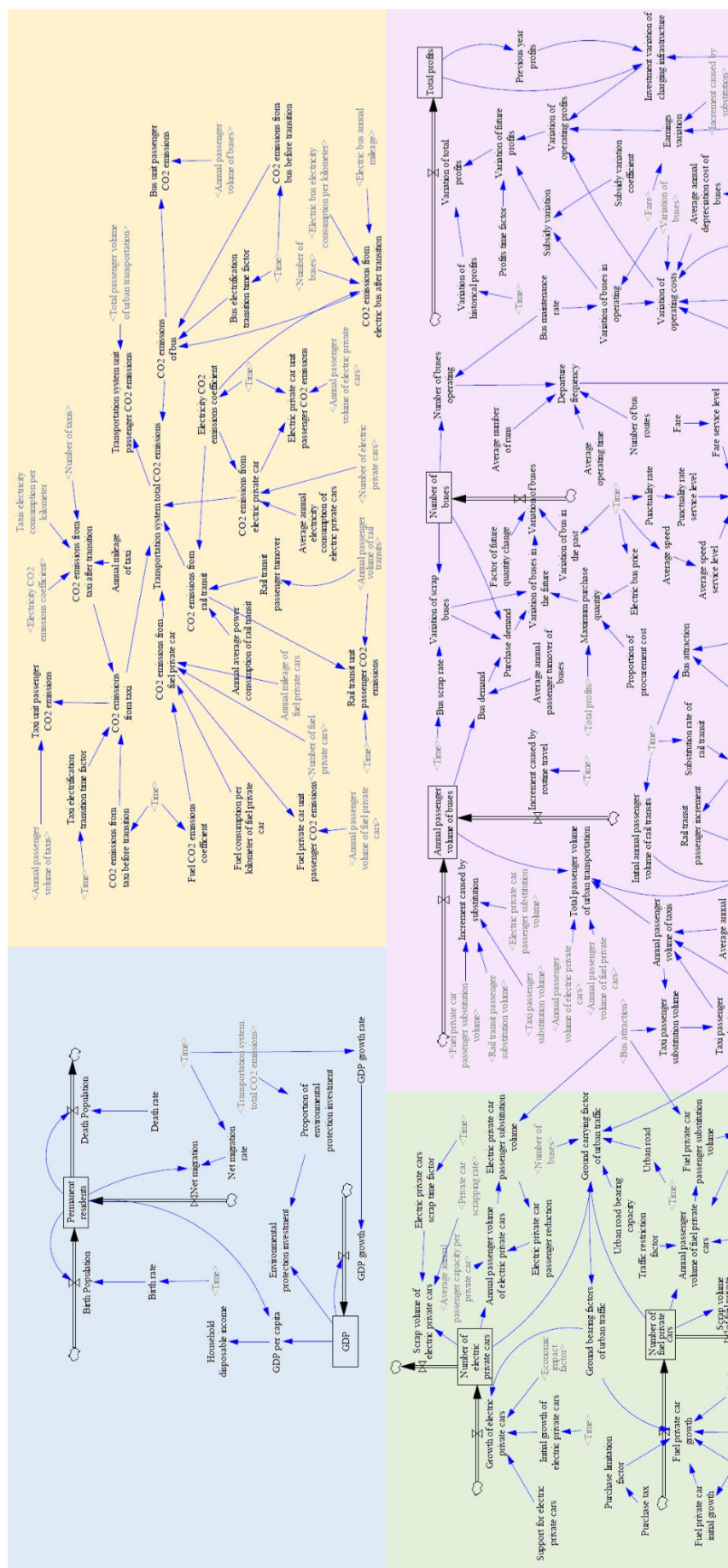
3.2.1. Population and economy subsystem

The size and structure of urban populations are vital factors that affect urban transportation [42]. Rising population puts enormous pressure on urban passenger transportation. In addition, Rapid economic development leads to an increasing number of private vehicles. It is found that the increment of private vehicles in developing countries in Asia during this period is significantly higher than that of developed countries, making the transportation mode shift from

non-motorized to motorized [43]. Therefore, the economy, especially the rapid growth of per capita GDP and household disposable income, and the massive increase in net migration, have a significant impact on the urban transportation system and carbon emissions. To this end, the population and economy subsystem stock–flow diagram is constructed to simulate the changes in variables such as “Permanent residents” and “GDP” over time.

3.2.2. Urban transportation subsystem

Urban travel modes can be mainly divided into two categories: public transportation and private car travel (owing to the relatively smaller proportion of carbon emissions, slow-moving traffic, such as bicycles, walking, and other travel modes, are not considered in this study). Private car travel mainly includes traditional fuel private cars and electric private cars. Public transportation travel includes buses, rail transits, and taxis. The scale and quantity of each travel mode have an important impact on urban transportation and carbon emissions [44]. Therefore, we constructed a stock–flow diagram of the urban transportation subsystem, including fuel private cars, electric private cars, buses, rail transits, and taxis. It is investigated that passengers who prefer private cars and taxis believe that they would shift from private cars and taxis to buses when the existing service level of buses improves to a certain extent, while rail transit diverts part of the bus travel volume due to its convenience and efficiency [27]. Therefore, a specific substitution relationship exists between the different travel modes. Bus operators are both public welfare and profitable. Although operating profits are not the focus of this study, they directly affect the number of bus purchases and level of bus service, which is an essential variable constraining the development of urban bus travel. For this reason, the profits of bus operators are included in the urban transport subsystem. The urban transportation



subsystem as the major part of the MLP-SD model mainly simulates the urban transportation electrification transition process over time.

3.2.3. Carbon emissions subsystem

The carbon emissions subsystem mainly shows the changes in total CO₂, unit passenger carbon and CO₂ emissions of various travel modes in the urban transportation system with the electrification transition. The emission coefficient method is widely used to calculate CO₂ emissions in the transportation field with the following equation [45]:

$$EM_{ij} = EC_{ij} \times EF_j \quad (1)$$

where EM_{ij} represents CO₂ emissions for energy type j by i transportation modes; EC_{ij} is the energy consumption for energy type j ; and EF_j is the carbon emission coefficient of energy type j to CO₂ emissions.

Because of the different power sources and CO₂ emission sources during the different periods of transition, the emission coefficients in the formula are also different. Furthermore, the carbon emission coefficient decreases with the maturation of technology.

The CO₂ emission sources of traditional fuel private cars, buses, and taxis are gasoline combustion, a direct emission source, while electric private cars, buses, and taxis are power generation, which is an indirect emission source. The carbon emissions in the power generation process should be included based on the power generation characteristics of specific regions in China.

3.3. Model test

3.3.1. Authenticity test

Three level variables, including permanent residents, number of fuel private cars and annual passenger volume of buses, were selected as representatives for testing. We compared the simulated and actual values between 1995 and 2020 and calculated the absolute value of the relative error. As shown in Fig. 5, the maximum error value of the three variables is 13.2%. The absolute error value of each level variable is less than 20%, which meets the requirements of the system dynamics. Consequently, the MLP-SD model can be used to simulate the Shenzhen's urban transportation system.

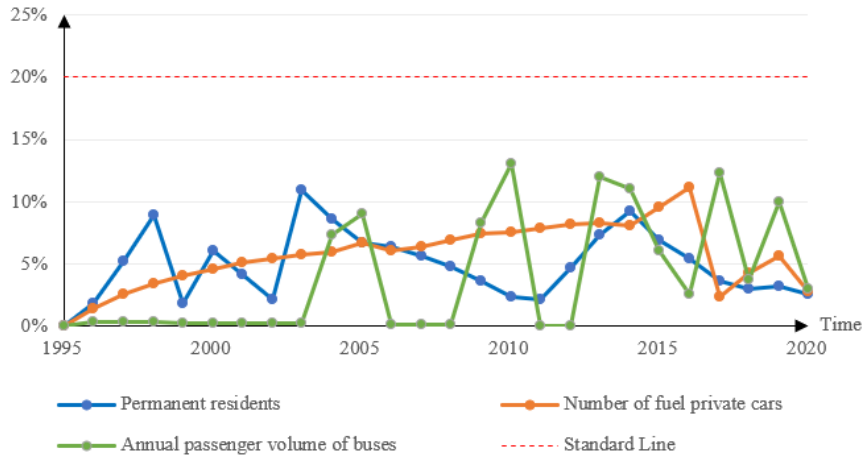


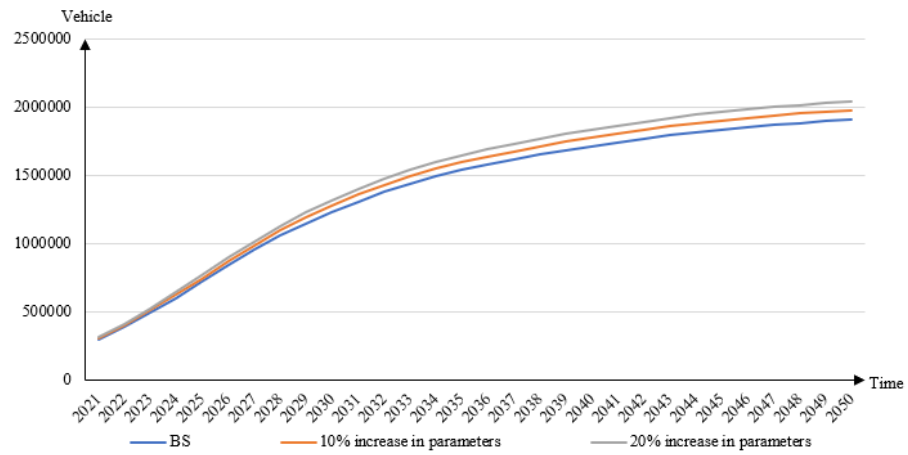
Fig. 5. Authenticity test results

3.3.2. Sensitivity test

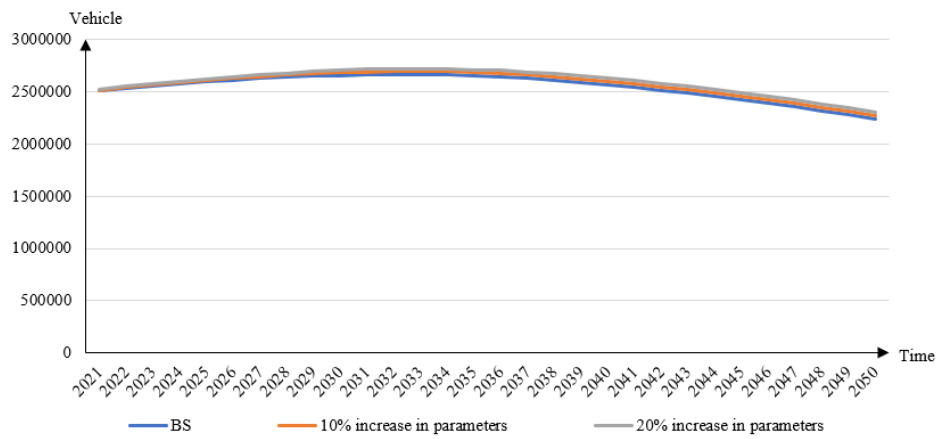
A sensitivity test was conducted to check whether the operating pattern of the model changed with changing parameter values. In this study, we selected the auxiliary variable of the urban road bearing capacity, and increased the parameter values by 10% and 20%,

based on the baseline policy scenario (BP) to test the sensitivity of the level variables, including the number of fuel private cars, electric private cars, buses, as well as the annual passenger volume of buses between 2021 and 2050. The change trends of the level variables and sensitivity test results are shown in Fig. 6 and Fig. 7,

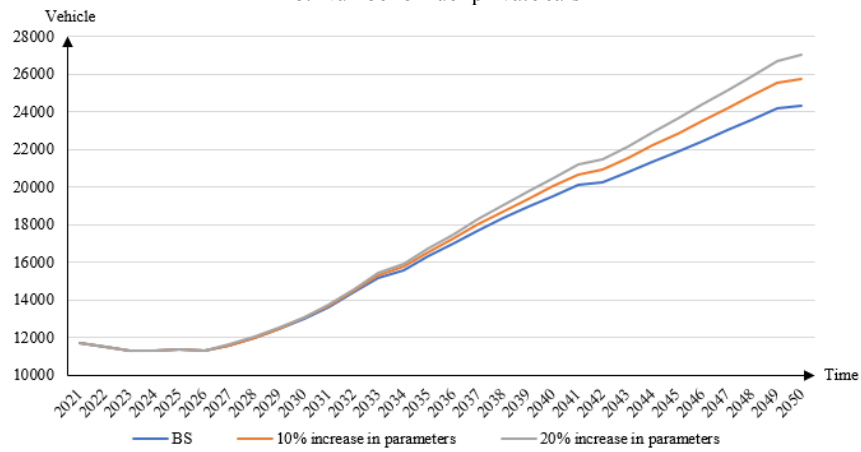
respectively.



a. Number of electric private cars



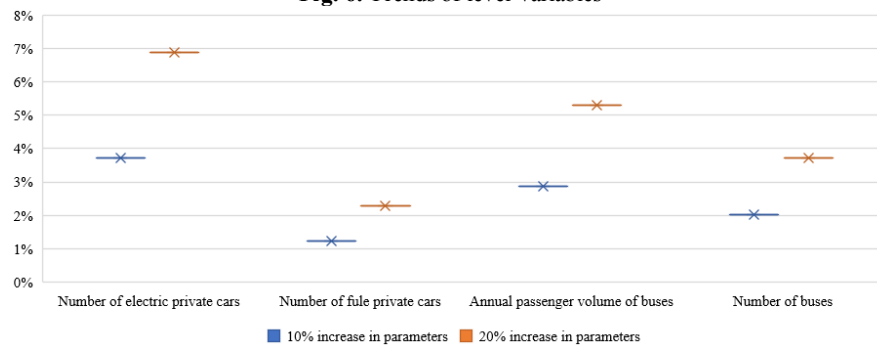
b. Number of fuel private cars



c. Number of buses



d. Annual passenger volume of buses

Fig. 6. Trends of level variables**Fig. 7.** Sensitivity test results

It is observed that when the parameter values of the auxiliary variables are changed, the trends of the level variables are consistent over time. When the parameter values change 10% and 20% respectively, the sensitivity of the level variables is lower than 4% and 7% accordingly, which fully meets the requirements of the test and shows that the operation mode of the model has no abnormal changes due to small changes in the parameters.

3.4. Policy scenarios

Based on the classification of existing policy

measures, this study established six policy scenarios, including five types of single policy scenarios: the basic policy scenario (BP), public transport priority development policy scenario (PTPD), demand-driven policy scenario (DD), administrative regulation management policy scenario (AR), technological progress policy scenario (TP), and one integrated policy scenario (IP) to simulate the urban transportation system in Shenzhen between 2021 and 2050. The specific content and parameter settings are listed in Table 2.

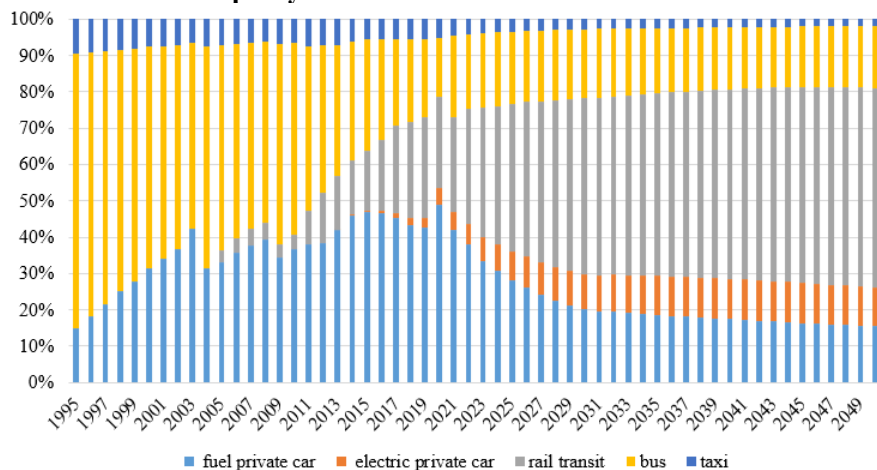
Table 2 Specific content and parameter settings in different policy scenarios.

Policy scenarios	Content	Parameter settings
BP	Set based on the existing development status in Shenzhen, and does not involve additional policy.	The same as existing parameter setting
PTPD	This scenario is based on the “70/70 target” for public transportation proposed in Shenzhen's 14th Five-Year Plan. Specifically, public transport and rail transit travel account for more than 70% of the motorized travel and public transport travel respectively in Shenzhen by 2030.	Subsidy variation coefficient changes into 1.2; Service level improvement factor increases by 20%; Increment caused by routine trips increases by 20%; Initial annual passenger volume of rail transit increases by 20%; Number of taxis increases by 10%.
DD	Control traffic demand by demand management policies: (1) Reduce the total passenger volume of urban transportation at source by establishing urban multi-centers to meet the different living needs of residents. (2) Increase residents' awareness of green travel and advocate for a travel mode change by replacing private car travel with public transportation travel. (3) Reduce the use of traditional fuel private cars by setting a fuel tax. (4) Encourage the substitution of electric private cars for fuel private cars by providing subsidies and other supportive policies.	Fuel tax changes to 20%; Support for electric private cars changes into 1.5. Environmental protection investment increases by 30%; Awareness of green travel improves by 30%; Travel frequency of private car reduces by 30%; Annual mileage of private cars reduces by 30%; Average annual electricity consumption of electric private cars reduces by 30%.
AR	Implement mandatory purchase and travel restrictions on private fuel cars to achieve carbon emission reduction targets.	Purchase tax increases to 0.2; Traffic restriction factor changes into 0.8.
TP	Rely on technical measures to achieve the goal of carbon emissions reduction. In terms of fuel vehicles, implement stricter emission and fuel consumption standards to eliminate backward high-polluting vehicles; For electric vehicles, increase the proportion of renewable energy generation and reduce carbon emissions in the process of power generation.	Electricity CO ₂ emission coefficient reduces by 5%; Fuel CO ₂ emissions coefficient reduces by 5%; Fuel consumption per kilometer of fuel private car changes into 0.06.
IP	Contains a combination of all policy measures in four single scenarios of PTPD, DD, AR, and TP.	Includes all parameter settings in four single scenarios of PTPD, DD, AR, and TP.

4. Results and discussion

4.1. Travel mode

4.1.1. Travel mode in the basic policy scenario

**Fig.8.** Change of travel mode in the BP between 1995 and 2050

As presented in Fig. 8, we simulated the data of Shenzhen to obtain the transportation mode. In the BP, the rail transit share rate increases considerably, from

3.21% in 2005 to 54.97% in 2050. The absolute amount of bus travel increases, however, the large growth of private car and rail transit travel leads to its share rate

sharp decrease, followed by a slow decline and stabilization, from 75.54% in 1995 to 17.12% in 2050. The proportion of electric private cars travel shows a steady upward trend after 2011, and stabilizes at approximately 10% in 2040 with the policy support. Before 2015, as a result of the improving economy, the share rate of fuel private cars increases rapidly, from 15.02% in 1995 to 46.84% in 2015. After 2015, with the government's support for public transportation and restriction on fuel private car purchases, the share rate of fuel private cars drops to 15.41% by 2050 and that of public transport exceeds 70% after 2030, in which the share rate of rail transit and green travel accounts for 70% and 80%, respectively. The transportation of Shenzhen is gradually optimized into a diversified green travel mode dominated by rail transit.

4.1.2 The change of travel mode in different policy scenarios

The years 2030 and 2050 were selected to compare the change in travel mode in different policy scenarios (Fig. 9). Compared with the BP, the rail transit share rate in the PTPD increases and is more significant in 2050. In particular, the share rate of bus travel is relatively lower, which is affected by the large number of rail transit travel. The share rates of private cars and taxis are also low. Overall, in the PTPD, the proportion of public transportation in Shenzhen increases sharply to 75% by 2050, more than 85% of which is rail transit. Similar to the BP, the rail transit share rate in the TP in 2050 is higher than that in 2030, but is lower than other policy scenarios for the same period. As the development of rail transit cannot meet

the rising travel demand of residents in the TP, the share rate of fuel private cars remains at approximately 15.5% by 2050. In the DD, because residents' travel demand is reduced at the source, the total travel volume in 2030 and 2050 is the lowest among all policy scenarios. Furthermore, increasing awareness of green travel among residents reduces the travel frequency of fuel private cars. The share rate of fuel private car is the lowest of all single policy scenarios in 2030 and 2050, with a significant decrease from 15% in 2030 to 11% in 2050, and taxis also have the lowest share rate. In the AR, the share rate of fuel private cars decreases significantly in 2050 compared with that in the BP because the restrictions on the purchase and use of fuel private cars, and the share rate of electric private cars has the greatest increment from 2030 to 2050 in all scenarios. In the IP, the share rate of fuel private cars decreases from 11.1% in 2030 to 8.4% in 2050, and the proportion of green travel is the highest among all scenarios in 2030 and 2050, significantly exceeding 90% by 2050.

In general, with the electrification transition of the urban transportation system and the improvement of residents' awareness of green travel, the proportion of green travel increases and the share rate of fuel private cars decreases in all the scenarios in 2050 compared with that in 2030. It indicates that fuel private cars or other high-carbon emission vehicles will be rarely used in the future and the transportation mode will turn to low-carb

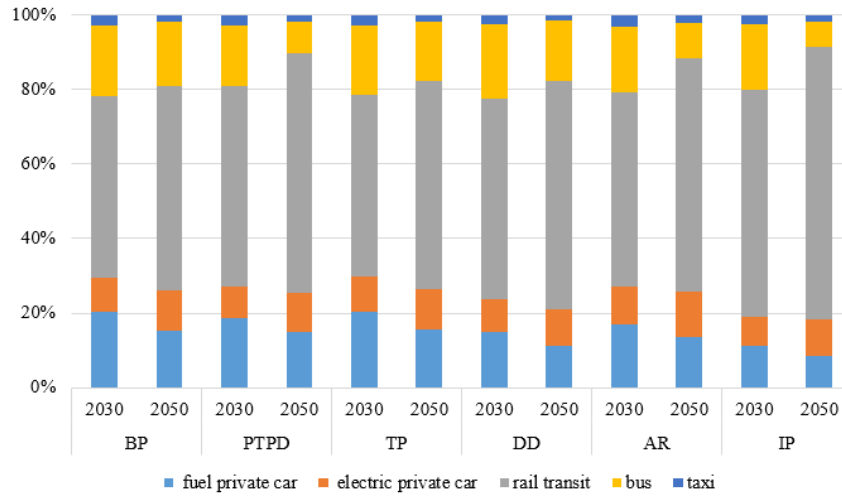


Fig. 9. Change of travel mode in different policy scenarios from 2030 to 2050

4.2. Electrification transition process

4.2.1. Electrification transition process in the baseline policy scenario

Based on the mechanism analysis, we simulated the electrification transition process of the transportation system in Shenzhen using the MLP-SD model. Because of more government-driven, the analysis focuses on the electrification transition process

of public transportation. From the perspective of “double substitution,” two indexes, substitution quantity of vehicle, which is the sum of the substitution of electric buses, taxis and rail transits, and substitution rate of travel mode, which is the ratio of public transportation travel to private car travel, are selected to reflect the process of electrification. A simulation of the electrification transition process is shown in Fig. 10

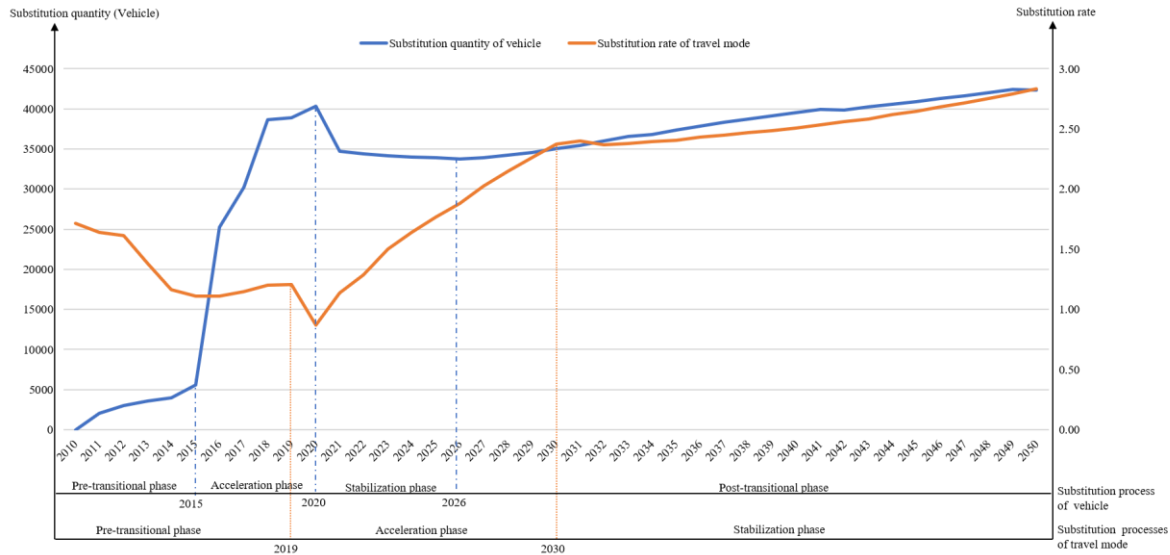


Fig. 10. Simulation of electrification transition process in the BP

(Note: The decrease in the substitution rate of travel mode in 2020 and substitution quantity of vehicle in 2021 are outliers caused by the COVID-19 pandemic, which should not be considered in the analysis of the overall transition. In 2020, COVID-19 caused a sharp decrease in travel volume, and the substitution rate of travel mode decreased accordingly. Furthermore, there was a time lag between the feedback of travel volume and demand for vehicles, hence the substitution quantity of vehicle also declined in 2021.)

Both the substitution processes of travel mode and vehicle are consistent with the transition mechanism, but are not synchronous, with a significant delay in

each phase of substitution of the travel mode compared to that of the vehicle. Specifically, the substitution process of vehicles is as follows: Before 2015, it is in

the pre-transitional phase. After 2015, it enters the acceleration phase, and the substitution quantity reaches its highest in the acceleration period in 2020, lasting for 5 years. Then, it enters the stabilization phase, and the substitution quantity of transportation fluctuates in a small range of approximately 34,000 vehicles, maintaining a dynamic stability; after 2026, it enters the post-transitional phase, and the substitution of vehicles is basically completed. The substitution quantity continues to rise at a slow growth rate, mainly because of the rising demand for public vehicles caused by the increase in permanent residents. The substitution process of travel mode is as follows: Before 2019, due to the rapid growth of private cars, the substitution rate of travel mode is low, which is the pre-transitional phase. After 2019, the transition accelerates, and the substitution rate increases rapidly. By 2030, the substitution rate reaches its highest value in the acceleration period, which lasts for 11 years. After 2030, dependence on private cars through environmental protection education and mobilization, which takes longer and is less controllable. Based on the double substitution perspective and two indicators, Shenzhen's urban public transportation electrification transition should be divided into 2015–2030 as the transition acceleration phase and beyond as the transition stabilization phase.

Based on the analysis of the electrification transition process of public transportation in Shenzhen in the BP, although the electrification transition of

although the substitution rate continues to increase, the growth rate slows down and enters the stabilization phase. This shows that both the substitution process of travel mode and vehicle reflect the electrification transition, with various transition types. The specific implementation of vehicle substitution includes bus and taxi operators, with a dominant government player and precise subjects. Moreover, vehicle substitution is more planned and compulsory, which is easier to complete, and the stabilization phase of the transition is shorter. However, urban residents are the main actors in travel mode substitution, with a large base, scattered behavior, and decision-making. First, it takes time for individuals to perceive changes in the urban public transportation system to form green travel awareness, leading to significant delays in each phase of travel mode substitution. Second, travel mode substitution is more random and spontaneous, and the government can only influence residents' travel choices to reduce their public transportation is heavily influenced by the government plan, it is still inseparable from other participants such as the passengers, operators, and residents, demonstrating that it needs time for the behavior adjustment. We also used quantitative methods to prove the multi-subject, multi-level, and multi-stage transition intuitively. The simulation results are consistent with the existing mechanism analysis of the electrification transition of urban traffic systems, which further verifies the effectiveness of the MLP-SD model.

4.2.2. Electrification transition process in different policy scenarios

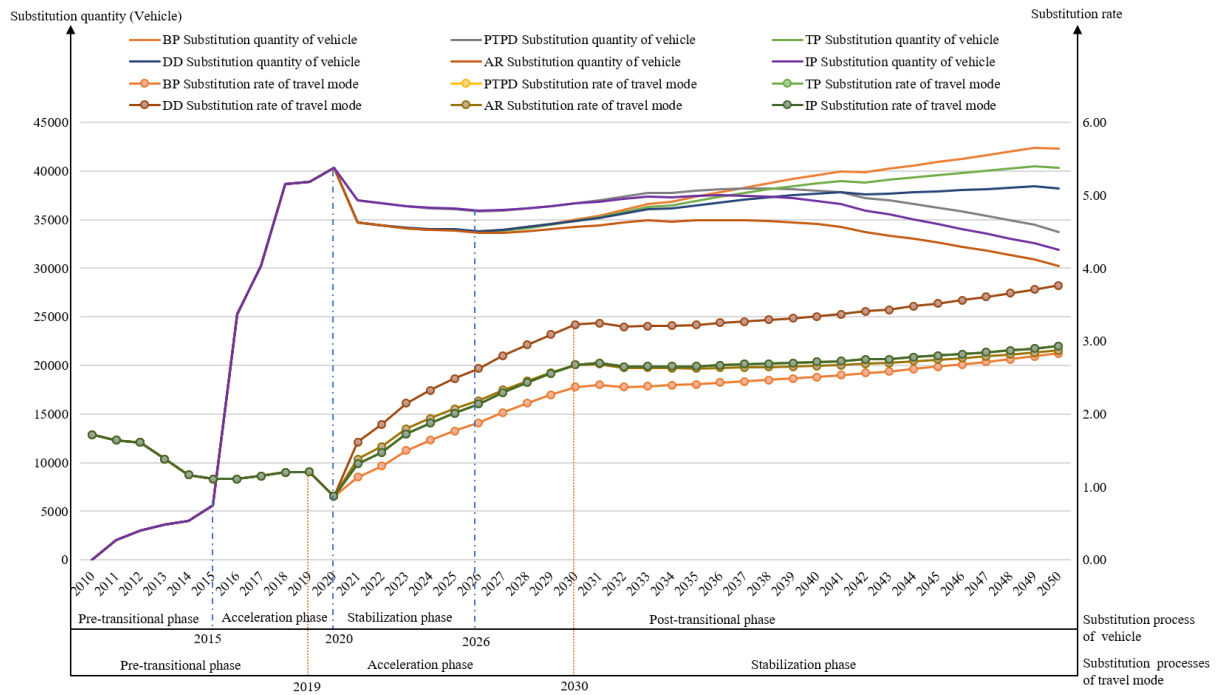


Fig. 11. Electrification transition process in different policy scenarios

(Note: Consistent with Fig. 13, the decrease in the substitution rate of travel mode in 2020 and substitution quantity of vehicle in 2021 are outliers caused by the COVID-19 pandemic, which should not be considered in the analysis of the overall transition effect.)

As discussed in Section 4.1, the travel mode change trends of private car and public transportation in the six policy scenarios are consistent, with only a slight difference in the share rate. As a result, the public transportation electrification transition process in different policy scenarios (Fig. 11) is consistent with that in the BP scenario; only the extent, trajectories, and effect of electrification transition in each phase have certain differences. In the IP, the substitution quantity is the highest during the acceleration phase, with the most significant transition effect. In the post-transitional phase, there is a different demand for substitution quantity of vehicles influenced by travel volume in different policy scenarios; therefore, the

trajectories of the vehicle substitution process are different. The substitution of travel mode is influenced by the residents' travel preference, which is higher in the DD during the acceleration phase because of a lower proportion of travel with private cars. Although the electrification transition process does not change with policy scenarios, it significantly affects the overall effect of the transition. The active policy mix results in a better performance on low-carbon development and public transport electrification in urban transportation systems.

4.3. Carbon reduction effect

4.3.1. Change trend of carbon emissions in the baseline policy scenario

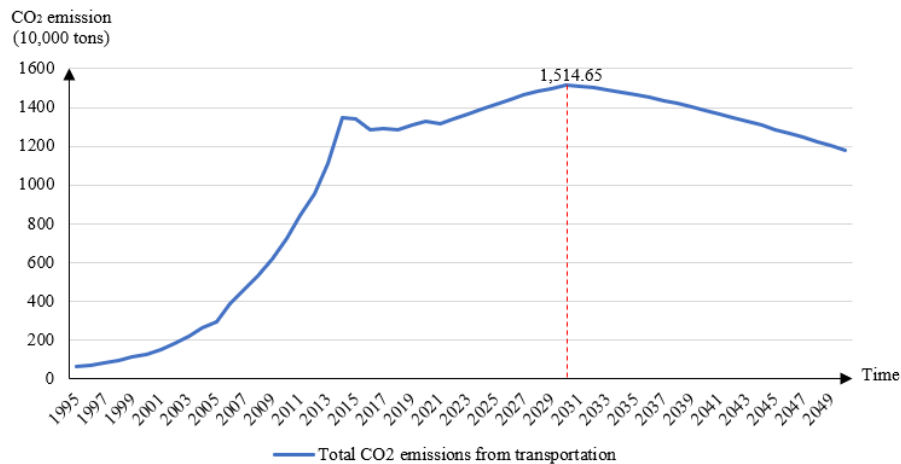


Fig. 12. Change trend of carbon emissions in the BP between 1995 and 2050

As seen from Fig. 12, in the BP, the total carbon emissions of the Shenzhen transportation system show an obvious inverted “V” with a peak value of 15.1464 Mt in 2030, which is in line with the policy goal of “striving to achieve the carbon peak by 2030,” confirming the scientific validity of the MLP-SD model. Taking the peak year 2030 as the boundary, the carbon emission change of the Shenzhen transportation system can be divided into two stages.

The first stage is from 1995 to 2030, in which carbon emissions show a significant upward trend. During the pre-transitional phase of transportation system electrification, between 1995 and 2015, carbon emissions show a rapid growth, and from 2015 to 2030, the growth rate slows down and gradually tends to peak. Considering that the urban transportation system of Shenzhen is in the construction stage during the pre-transitional phase, new buses and taxis are constantly purchased, all of which are fuel vehicles. In addition, with the rising economy, residents' per capita disposable income increases, and the purchase ability of private cars increases significantly, while the electric private cars are still immature and have not been widely marketed. Residents prefer to purchase fuel private cars, which multiplies the increasing travel volumes. During the 2015–2018 period, thanks to the government's guidance, original fuel buses and taxis were entirely

replaced with electric vehicles. The emergence and maturity of rail transits and electric private cars make travel modes abundant and low-carbon. With the decline in CO₂ emissions from individual vehicles, the overall CO₂ emissions have fallen sharply. Moreover, due to the restriction policy on fuel private cars, the new fleet is significantly reduced phasing out old models; even in 2015, the fuel private car ownership decreased, reducing and stabilizing CO₂ emissions. During the 2018–2030 period, with the increase of permanent residents, the total travel volume increases, while all new vehicles are electric vehicles, the emissions of which are significantly lower than those of the original fuel vehicles. Because of the purchase restriction policy, new fuel vehicles are controlled to within 80,000 vehicles per year. The overall carbon emissions of the transportation system show a slow upward trend, reaching a peak by 2030.

The second stage is during the 2030–2050 period, in which, with the government's strong support, the public transport share rate reaches more than 70%, and rail transit becomes the dominant travel mode. The fuel private car share rate decreases, and the growth rate of both buses and electric private cars slows down. Furthermore, owing to the improvements in technology, the emission standards of fuel vehicles are stricter, the proportion of renewable energy power generation

increases, and the carbon emissions in the power generation process is reduced. Both the carbon emission coefficients of fuel and electricity are lower, so that the overall carbon emissions of the

transportation system continue to decline slowly.

4.3.2. Carbon emissions contribution of different travel modes in the baseline policy scenario

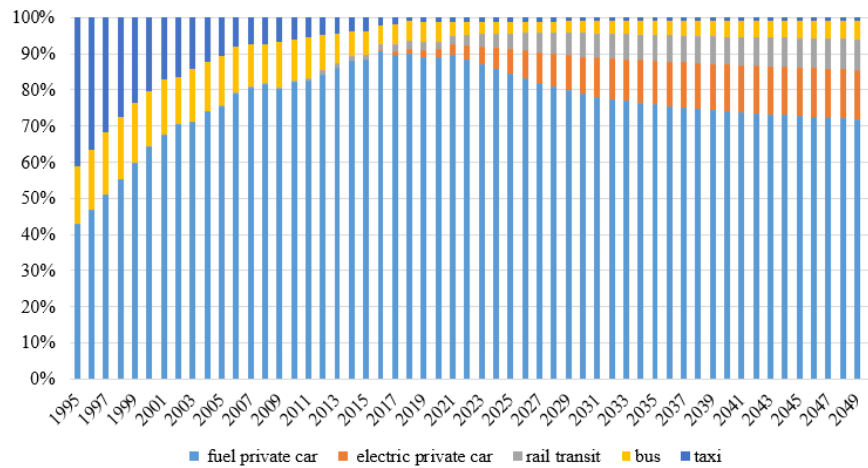


Fig. 13. Carbon emissions contribution of different travel modes in the BP between 1995 and 2050

Fig. 13 shows the carbon emission contributions of the different travel modes in the BP. Fuel private cars are the main source of carbon emissions in the urban transportation system, with the contribution rate remaining above 70% and showing a sharp rise followed by a slow decline, which is consistent with the literature [46] and further verifies the reliability of the model. Before 2016, with the rising economy, the number of fuel private cars greatly increase, and the carbon emissions shows an apparent upward trend, with the contribution rate rising rapidly from 43% in 1995 to 90% in 2016. After 2016, with the purchase restriction on the fuel private cars, the growth rate and travel volume slow down. In addition, technological improvements lead to stricter emission standards for fuel vehicles, lower carbon emission coefficients, and a slow decline in the contribution of carbon emissions to 71% by 2050. Since the emergence of rail transit in 2005, and with the government's advocacy of public for carbon mitigation. Generally, with the electrification transition of urban transportation systems, public transportation contributes approximately 13% of carbon emissions. Fuel private

travel mode, the rail transit travel volume has increased annually, and the contribution rate of carbon emissions has increased to 8%. Electric private cars are also developing rapidly, gradually becoming the main carbon emission source after fuel private cars. As a result of the popularization of private cars and the coverage expansion of rail transits and buses, travel modes are gradually diversified, and the dependence on taxis is reduced. By the end of 2018, all fuel taxis in Shenzhen were replaced by electric taxis, significantly reducing carbon emissions. Therefore, between 1995 and 2018, the carbon emissions contribution rate of taxis shows a sharp decline from 41% to 0.84%, as it has been maintained since 2018. Before electrification, the carbon emissions contribution rate of buses remains above 10%. After replacing the original fuel buses with electric ones in 2017, the contribution rate of carbon emissions only accounts for approximately 5%, reflecting the significance of electrification transition cars have become the focus of carbon emission reduction as the main cause of carbon emissions from urban transportation systems.

4.3.3. Change trends of CO₂ emissions in different policy scenarios

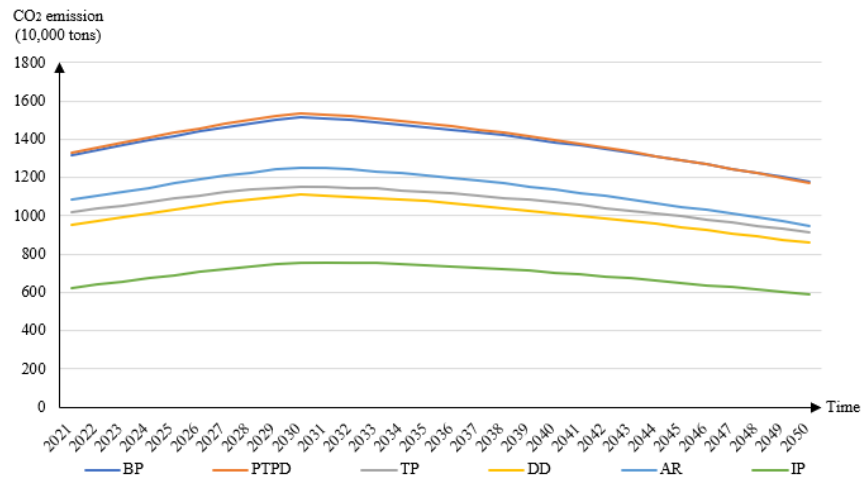


Fig. 14. Changes of CO₂ emissions of urban transportation system in different policy scenarios between 2021 and 2050

The CO₂ emissions of the urban transportation system between 2021 and 2050 in different policy scenarios are shown in Fig. 14. In all policy scenarios, carbon emissions of the urban transportation system show an inverted “V” shape change, and the peak appears in 2030 in all single policy scenarios. In the IP, the total carbon emissions of the urban transportation system are the lowest, and the peak appears in 2031.

In the PTPD, carbon emissions are generally higher than those of the BP because of the increase in total travel volume, while the reduction in carbon emissions is the highest among all scenarios. In particular, after 2047, carbon emissions in the PTPD are lower than those of the BP, which indicates that the public transportation priority development policy has a certain lag, and the vigorous development of public transportation is beneficial to carbon mitigation in the long term without the total travel volume decline. In the TP, urban transportation also realizes a reduction in carbon emissions without controlling the total travel volume. This refers to technological progress is a direct

measure to promote carbon emission reduction in transportation through stricter emission and fuel standards. In the DD, building urban multicenter meets the demands of residents, reducing the total travel volume from the source. Moreover, enhancing residents' awareness of green travel raises the proportion of green travel and reduces the use of fuel private cars. At this moment, the total emissions are the lowest among all the single policy scenarios. In addition, since fuel private cars are the main source of carbon emissions in the transportation sector, implementing administrative regulations to reduce their purchase and use is efficient. In the AR, the carbon emissions are also lower. In the IP, the lowest carbon emissions of all policy scenarios are obtained in both the short and long terms. It is suggested that an integrated approach is superior to only a travel mode shift or clean vehicle strategy in achieving carbon mitigation in urban transportation.

4.3.4. Change trends of CO₂ emissions per unit passenger in different policy scenarios

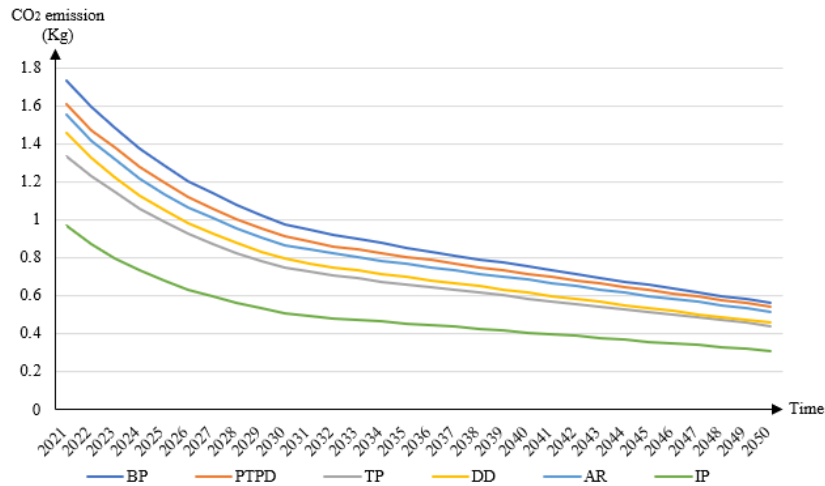


Fig. 15. Change trends of CO₂ emissions per unit of passenger in different policy scenarios between 2021 and 2050

The change trends in CO₂ emissions per unit passenger of the urban transportation system during the 2021–2050 period are shown in Fig. 15. In general, carbon emissions per unit passenger show a downward trend in all policy scenarios, with a rapid decline in the 2021–2030 period, and CO₂ emissions per unit passenger drop to 1 Kg/person in all policy scenarios by 2030. After 2030, due to the marginal diminishing effect, the decline rate of carbon emissions per unit passenger slows down, and by 2050, carbon emissions per unit passenger decrease to less than 0.6 Kg/person in all policy scenarios.

The unit passenger CO₂ emission levels in the four policy scenarios of the BP, AR, DD, and IP are ranked the same as the carbon emissions of the transportation system in the corresponding scenarios. Because CO₂ emissions per unit of passenger consider the total travel volume impact on carbon emissions, the ranking of which is better than that of the carbon emissions of the transportation system in the PT and PTPD.

In the single policy scenario, the CO₂ emissions per unit passenger of the urban transportation system is the lowest in the TP. This illustrates that reducing the carbon emission coefficient of fuel and electricity through technological progress can effectively achieve carbon reduction with the same total travel volume. In

particular, the reduction rate over time is lower than that in the DD, resulting from technological progress limitations; the carbon emission coefficient will not be reduced indefinitely, and will eventually stabilize. For this reason, to consider the carbon emission reduction effect per unit passenger of transport over a more extended period, appropriate control of total travel volume while promoting technological progress will produce more significant effects. In the PTPD, the passenger unit CO₂ emissions show a noticeable decrease compared with that in the BP, which shows that promoting public transportation is an effective measure to reduce carbon emissions per passenger when the total travel volume is large during rapid urban development.

5. Conclusions and policy implications

5.1. Conclusions

This study aims to clarify the mechanism of electrification transition, and explore a pathway for carbon peak in the field of urban transportation sector. To that end, we proposed the “double substitution”, divided the phases of electrification transition, and explained the dynamic changes and interactions among the elements in each phase. We further established the MLP-SD model to simulate the change in travel mode, electrification transition process, and carbon emissions reduction effect of the urban transportation system in

Shenzhen in different policy scenarios. The main conclusions of this study are as follows:

(1) The electrification transition of the urban transportation system is based on the “double substitution” of vehicles and travel modes. According to the dominant transition mode, the electrification transition process can be divided into four phases: pre-transitional phase, acceleration phase, stabilization phase and post-transitional phase, and the substitution processes of travel mode and vehicle are not synchronous, with a significant delay in each phase of substitution of the travel mode compared to that of the vehicle.

(2) With the electrification transition of the urban transportation system, the proportion of green travel increases and the share rate of fuel private cars decreases significantly in all the scenarios. Shenzhen gradually forms a diversified green travel mode dominated by rail transit and is constantly optimized toward low-carbon and public development.

(3) The change trend of carbon emissions in urban transportation system is similar in different policy scenarios, showing an inverted “V” shape with the “carbon peak” target around 2030. In both the short and long terms, the travel mode and carbon emission reduction effect in the IP are superior to those in the single policy scenarios.

(4) In the short term, decreasing the carbon emission coefficient of fuel and electricity through technological progress can reduce carbon emissions. In the long term, reduction in the purchase and use of private cars, especially fuel private cars, increase in the share rate of public transportation to optimize the travel mode are the priority ways to achieve carbon mitigation.

5.2. Policy implications

Based on the conclusions of this study, the following policy implications are suggested:

(1) Combining urban development and population

size formulates a reasonable electrification development plan for specific time points, vehicle types, and financial subsidy methods to ensure orderly implementation. After the substitution of vehicles, it is also necessary to maintain the continuity of the policies, including financial subsidies to the operating enterprises and positive guidance measures to the travel mode transition, to finally realize the electrification transition of the urban transportation system.

(2) Accelerate the construction of rail transit and bus hubs to expand public transport coverage and form public transport networks, reducing residents' reliance on private cars. In addition, improving the quality of public transport services and increasing the attractiveness of public transport travel to build a diversified urban system dominated by public transportation.

(3) Combine mandatory policy tools, such as restrictions on the purchase and use of fuel private cars to phase out high-polluting vehicles, with guiding policy tools, including fuel tax, subsidies for electric vehicles, and advocacy of green travel, to achieve carbon emission reduction in the transportation sector.

In addition, our study also has some limitations. The MLP-SD model constructed in this study has been tested effectively in Shenzhen and needs more sample cities for testing. Moreover, because of the data limitation, the cost benefit analysis of each policy scenario has not been considered. These issues need to be explored further in the future.

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基于二层多目标规划的中国省际非水可再生能源电力配额分配模型

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摘要：可再生能源电力的发展是中国能源结构改革的重要推动力量，制定科学的可再生能源电力配额分配方案，是实现 2030 碳达峰和 2060 碳中和目标的重要保障。立足中国当前的行业管理体制和可再生能源电力配额分配博弈过程的复杂动态性，充分考虑中央政府和地方政府利益诉求的异质性，构建了一种新的基于二层多目标非线性规划的省区间非水可再生能源电力配额分配模型。基于中国 30 个省区的相关数据资料，得到了一个兼顾成本、环境与公平的最优分配方案。结果显示，由于省区间能源替代成本和减排成本的不同，各省区对中央政府分配的指标任务的执行意愿存在较大差异。比较分析结果表明：与政府现行分配方案相比，二层优化分配方案在补贴成本方面节约了 42.22 亿元，在能源替代成本方面降低了 2595.12 亿元，在减排成本方面减少了 791.39 亿元。同时，求解得到的二层优化分配方案的基尼系数小于 0.2，属于绝对公平的范畴。该模型能够真实反映中国可再生能源电力配额分配博弈过程的复杂动态性，为政府制定非水可再生能源电力配额方案提供更加有效的决策工具和参考。

关键词：可再生能源电力；配额分配；二层多目标规划

Allocation of non-hydro renewable portfolio standard targets among China's provinces based on bi-level programming approach

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Abstract: The development of renewable energy power is a critical driving force for China's energy structure's reform. The formulation of a scientific renewable portfolio standard (RPS) quota allocation scheme is a crucial guarantee for achieving the 2030 carbon peak and the 2060 carbon neutrality goal. Based on China's current industry management system and the complex dynamics of the RPS quota allocation game process, and considering the heterogeneity of the interests of the central and local governments, a new provincial non-hydro renewable portfolio standard (NHRPS) quota allocation model based on bi-level multi-objective nonlinear programming is required. Based on data from 30 provinces and regions in China, an optimal distribution scheme that considers cost, environment, and fairness were obtained. The results show that because of the differences in energy substitution costs and emission reduction costs between provinces, the willingness of various provinces to implement the indicator tasks assigned by the central government varies. The comparative analysis results show that compared with the government's current distribution scheme, the bi-level optimized distribution scheme saves 4.222 billion yuan in subsidy costs, 259.512 billion yuan in energy substitution costs, and 79.139 billion yuan in emission reduction costs. Meanwhile, the Gini coefficient of the bi-level optimal distribution scheme is less than 0.2, which indicates absolute fairness. The NHRPS quota allocation model proposed in this study reflects the complex dynamics of China's RPS quota allocation scheme and provides a more effective decision-making tool and reference for the government to formulate an NHRPS quota scheme.

Keywords: renewable portfolio standard; quota allocation; bi-level multi-objective programming

一、引言

电力产业是国民经济发展中的重要基础产业，也是经济可持续发展的重要保障和动力源泉。人类进入工业化以来，化石能源的大量消费导致二氧化碳排放量不断增加，引起了全球变暖，推动了自然灾害的频发，成为了人类生存和发展的严重威胁^{错误！未找到引用源。}。因此，限制碳减排已成为世界各地政府的当务之急。为此，中国在 2020 年第七十五届联合国大会上向世界郑重承诺力争在 2030 年前实现碳达峰，努力争取在 2060 年前实现碳中和。为了限制温室气体排放导致的气候变化，各国政府引入了可再生能源配额制（Renewable Portfolio Standard，简称 RPS）。高效合理的可再生能源电力配额分配将影响中国的能源结构转型，也是高质量发展的前提。因此，如何制定合理的新能源电力配额方案是需要重点研究的问题。

韩国在 2012 年开始实施 RPS，但其政策执行率低于 80%。韩国电力生产商面临数百亿韩元的罚款，这导致韩国政府在 2015 年之后修改了 RPS 目标，但执行率仍低于 90%^[2]。这说明配额指标的制定将直接影响实施 RPS 的效率。总结来看，中国的政治结构和各省之间经济发展和资源分布水平的巨大差异要求制定详细的省级区域政策。2020 年 6 月，国家发展改革委和国家能源局统筹提出了各省级行政区域 2020 年可再生能源电力消纳责任权重。然而从实践来看，相关政策的实施效果并不理想。由于地方政府试图降低成本以获得更多的利益，导致许多省份的积极性不高，部分省市可再生能源电力消纳进展严重滞后。与此同时，我国可再生能源发电厂分布不均，地区之间经济社会发展水平有较大差异，且在空间上二者呈逆向分布，无法充分利用可再生能源，导致资源浪费。

近年来，许多学者针对 RPS 政策实施进行了大量的研究。从方法论来看，现有研究主要采用优化模型^[3]，忽略了可再生能源电力配额分配过程中政府利益的异质性。事实上，中央政府和地方政府作为 RPS 的制定者和执行者，有着不同的目标诉求。如果不考虑中央与地方的利益互动，可再生能源电

力配额分配就不能反映中国电力行业的实际管理体制。从研究角度来看，现有文献主要关注系统总成本最小化^[4]，没有考虑补贴成本带来的影响以及二氧化碳减排带来的环境改善。

为此，基于中国电力行业现行管理体制，构建了非水可再生能源电力配额分配模型，并得到了 30 个省区非水可再生能源电力配额最优分配方案。本研究对现有文献的贡献体现在三个方面。首先，以中央政府为上层决策者、地方政府为下层决策者，采用二层多目标优化方法构建了非水可再生能源电力配额分配模型。与之前研究中使用的单层最优分配方案(Single-level Optimal Allocation Scheme，简称 SOAS)相比^[4]，该模型能够更好地反映中国可再生能源电力配额分配博弈过程的复杂动态，为各级政府提供了更具前景的决策工具。第二，该研究首次将补贴成本纳入中央政府的可再生能源电力配额分配目标，更加符合配额工作经济效益的现实目标。第三，得到了一个统筹兼顾成本、环境和公平的 30 个省区非水可再生能源电力配额最优分配方案，通过与当前的政府分配方案 (Government Allocation Scheme，简称 GAS) 进行比较，验证了该分配方案的优越性。此外，该研究还测算了中央政府不同目标偏好情景下 30 个可再生能源发电省份非水可再生能源电力配额方案的比例和执行率，揭示出其异质性机理，这将有助于政府更加科学的优化设定配额分配方案。

二、文献综述

近年来，学术界和产业界众多研究人员都关注于 RPS 问题。在实践方面，中国的 RPS 制度和政策实施较晚^[5]，发达国家 RPS 制度的立法实践对中国具有重要的借鉴意义。目前，以美国德克萨斯州、加利福尼亚州和澳大利亚的配额制实施最早而且也是最成功的^[6]。此外，英国、丹麦、日本等国也开始引入配额制度。根据可再生能源发展目标，采用等比例法将配额指标分摊给各责任主体，如澳大利亚、英国、意大利和美国大部分州。也有少数国家或地区（例如日本）采取差异化的指标分配方式。中国幅员辽阔，不同省区在经济发展、资源禀赋、

财政实力等方面存在显著差异,因此,差异化的RPS目标分配机制可能更加符合中国国情。

学术界关于 RPS 问题的探讨大都聚焦于不同 RPS 目标对发电成本、宏观经济和碳排放的影响。例如,赵新刚等^[7]研究了配额制与发电厂商策略行为的共生演化以及配额制的相关制度准参数对发电厂商策略行为演化博弈的影响;Ritzenhofen 等^[8]通过一个动态的长期能力投资模型,模拟了可再生能源配额制、上网电价和市场溢价方案的影响;Rouhani 等^[9]利用 RPS 模型研究了设立不同的 RPS 配额指标对加利福尼亚州 2020 年社会福利、温室气体排放、市场电价、可再生能源开发决策等的影响,为政策制定提供了量化依据。在这些研究中,重点是在国家或地区实施不同的 RPS 政策的影响,但没有确定分配 RPS 指标的合理方案。与大量探讨 RPS 政策的经济或环境效应的研究成果相比,关于 RPS 目标分配方法的研究相对较少。Wang 等^[10]根据管理学原理和熵权法,制定了中国 RPS 的制度框架和省区分配方案,但没有考虑各省实际可再生能源资源禀赋和成本问题。总体而言,关于 RPS 目标分配的定量化研究尚未取得突破性进展。特别是,

由于中国省区间社会经济发展的不平衡性,仅从宏观总量来研究可再生能源电力配额问题的调控策略是远远不够的。

鉴于可再生能源电力配额分配问题的重要性,目前少量文献基于系统总成本最小化的视角探讨了可再生能源配额分配方法。然而,这些研究中忽略了配额过程中中央政府与地方政府之间利益诉求的异质性。为此,立足于中国当前的电力行业管理体制,采用二层规划的方法研究可再生能源配额问题。目前,二层规划作为一个重要的优化方法和手段已在经济管理^[11]、网络规划^[12]、工程问题^[13]、电力定价^[14]等领域得到了广泛应用。在中国当前管理体制下,可再生能源的配额过程也是一个中央政府和地方政府博弈的过程,是一种典型的主从递阶的二层规划问题。

三、模型构建

1、二层规划模型概述

中央政府与地方政府的非水可再生能源电力配额指标分配过程中如图 1 所示,中央政府是上层配额方案的决策者,地方政府是下层配额方案的执行者。

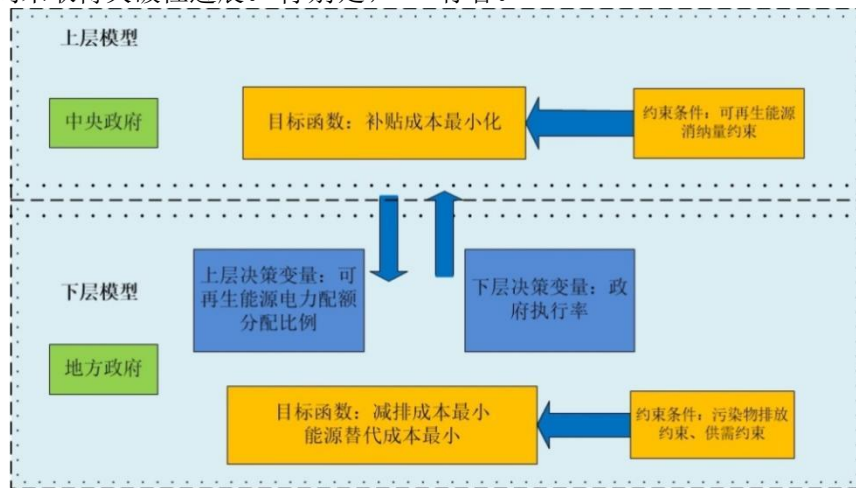


图 1 基于二层规划的可再生能源电力配额模型框架

中央政府综合考虑国家能源规划、地区可再生能源资源、地区消纳能力等制定各省区非水可再生能源电力配额指标，其目标为补贴成本的最小化。地方政府从地方发展利益最大化的角度出发，结合地方政治、经济、民生情况制定本地区的可再生能源电力配额指标规划，其目标为减排成本最小化及能源替代成本最小化，下层的决策信息传回到上层，上层对下层的政策执行率及可再生能源开发利用情况进行考核，根据考核结果不断优化自身目标，重复进行直到达到平衡。

2、上层模型

中央政府目前不仅要解决弃风弃光、补贴资金缺口等问题，还要推进对化石能源的替代，加快构建向清洁低碳模式的能源体系。我国可再生能源的发展主要依赖政府给予的发电补贴，现补贴缺口问题日益严重，已成为限制新能源发展的重要因素之一。因此，该研究将最小化的发电补贴作为中央政府的发展目标。可再生能源消纳总量达到国家目标是主要制约因素。因此，将其作为上层的约束条件。

省区可再生能源电力补贴成本估算

按照《可再生能源电价附加补助资金管理办法》规定，符合补助标准的第 i 省项目全生命周期补贴电量表达为：

$$\text{项目全生命周期补贴电量} = Y_{qi} R_i K_i \quad (1)$$

其中， Y_{qi} 是第 i 省 2020 年预计行政区域内全社会用电量， R_i 是第 i 省可再生能源电力消纳量占该省区全社会用电量的比例， K_i 是第 i 省可再生能源电力配额任务的执行率。可得全部省级区域内可再生能源电价附加补助资金的测算公式即可再生能源电力补贴成本的表达式为：

$$B = \sum_{i=1}^{30} \frac{(E_i - S_i) Y_{qi} R_i K_i}{1 + m\%} \quad (2)$$

其中， E_i 是第 i 省可再生能源上网电价， S_i 是第 i 省燃煤发电上网基准价， m 为适用增值税税率。

基于上述分析，构建上层模型如下：

$$\begin{aligned} \min B &= \sum_{i=1}^{30} \frac{(E_i - S_i) Y_{qi} R_i K_i}{1 + m\%} \\ \text{s.t.} &\begin{cases} \sum_{i=1}^{30} Y_{qi} R_i K_i / \sum_{i=1}^{30} Y_{qi} \geq W \\ Q_{ci} (1 - ar_i)^2 \leq R_i \leq Q_{ci} (1 + br_i)^2 \end{cases} \quad (3) \end{aligned}$$

其中 B 是中央政府的补贴成本； R_i 是上层中央政府的决策变量， K_i 是下层地方政府的决策变量，含义同上； W 表示全国平均配额比例； Q_{ci} 表示基准年可再生能源发电的比例； ar_i 表示规划年可再生能源发电量占全部发电量的比例下降的上限； br_i 表示规划年可再生能源发电量占全部发电量的比例上升的下限； Y_{qi} 、 S_i 、 E_i 、 m 含义同上。

3、下层模型

近年来，为积极助推大气污染防治和生态文明建设，各省纷纷提出相关政策目标，减少污染物排放，故地方政府将减排成本作为追求的目标之一。此外，地方政府在履行 RPS 政策时势必会引起对火电的挤压，由于电力行业投入了大量的生产设备，必然又会引起固定资产的闲置。所以，就会产生能源替代成本。然而在能源替代的过程中产生的成本费用绝大部分是需要地方政府承担，因此，地方政府希望能源替代成本的最小化。同时仍需满足区域的用电需求，减排约束控制在国家约束的指标下。综上，地方政府的利益诉求是希望在满足区域用电需求和污染物排放约束条件下，减排成本最小，能源替代成本最小。

(1) 减排成本估算

地方政府在控制 CO_2 排放的前提下期望降低本地区的 CO_2 减排成本，加速各区域低碳转型进程。参照文献^[15]对发电环境成本的估算，借鉴其计算方法，估算地方政府的减排成本。

$$U_e = Y_{qi} R_i K_i \mu_i \varphi_{ci} \quad (4)$$

其中可再生能源消纳量 $= Y_{qi} R_i K_i$ ， Y_{qi} 、 R_i 、 K_i 含义同上， μ_i 表示单位可再生能源发电碳排放减排的系数； φ_{ci} 表示第 i 省单位 CO_2 减排成本， φ_{ci} 是利用线性规划法对方向距离函数进行有效参数估计基础上，对 30 省份 2015 年边际减排成本进行测算得到^[16]。

(2) 能源替代成本估算

能源替代成本主要包括建设资金成本、运行维护成本和火电关停成本三个部分。地方政府为完成中央下达的配额任务,就需要建设满足发电需求的可再生能源基础设施,增强可再生能源发电能力,以达到目标要求。另外,电厂停运后,原有资产难以转移到其他行业,导致大部分或全部资产价值损失,所以电厂关停主要考虑固定资产的损失。鉴于此,将能源替代成本分为建设初期的资金投入成本、运行维护成本和资产处置导致的固定资产损失三部分。

建设资金成本如下:

$$C_j = w_i \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) \quad (5)$$

其中 Y_{qi} 、 R_i 、 K_i 含义同上; w 代表可再生能源电厂单位造价; t_i 代表第 i 省可再生能源平均合理利用小时数; Y_{mi} 是第 i 省基准年可再生能源电力行业发电量。

运行维护成本如下:

$$C_w = C_{di} \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) \quad (6)$$

其中 C_d 代表可再生能源电厂维护费用。

根据国家税务总局发布的《关于做好已取消的企业所得税审批项目后续管理工作的通知》,固定资产可回收率 (R_r) 取 3%, r 则表示火电行业固定资产损失率。

$$r = 1 - R_r \quad (7)$$

将关停的装机容量近似等于可再生能源新增装机容量, v 表示火力发电厂单位造价,火电关停成本可表示为:

$$C_h = rv \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) \quad (8)$$

基于上文分析,能源替代总成本包含建设资金成本、运行维护成本、火电关停成本三部分。即:

$$\begin{aligned} \min C = & w_i \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) + C_{di} \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) \\ & + rv \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) \end{aligned} \quad (9)$$

从地方政府的角度来看,实施可再生能源配额制后,各省排放的 CO_2 要满足不超过规划年内相应 CO_2 排放量的约束。另外,通过技术上的柔性系数表示对系统运行的柔性贡献^[17]。

基于上述分析,构建下层模型如下:

$$\begin{aligned} \min U_e &= Y_{qi} R_i K_i \mu_i \varphi_{ci} \\ \min C &= w_i \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) + C_{di} \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) + rv \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) \quad (10) \\ s.t. & \begin{cases} (Y_{qi} - Y_{qi} R_i K_i) \times \varphi_{hi} \times h \leq P_i \\ Y_{qi} R_i K_i \times f_i + Y_{qi} (1 - R_i) \times f_j \\ + D_i \times f_d \geq 0 \end{cases} \end{aligned}$$

其中 U_e 是地方政府 CO_2 的减排成本; C 代表能源替代成本; φ_{hi} 是第 i 省火电发电占比系数; h 为火电二氧化碳排放系数, P_i 为第 i 省二氧化碳排放控制指标; f_i 表示可再生能源发电的灵活性系数; f_j 表示火力发电的灵活性系数; D_i 表示第 i 省的电力需求; f_d 表示电力消耗的灵活性系数; μ_i 、 φ_{ci} 、 Y_{mi} 、 w_i 、 C_{di} 、 r 、 v 、 t_i 含义同上。

4、模型求解

二层规划问题是 NP-hard 问题,无法使用多项式求解算法。求解该问题极其复杂的一个重要原因是其本身的非凸性。因此,考虑到模型的复杂性和下层的非凸性,将采用遗传算法进行求解。

下层模型中包括 30 个省份的减排成本函数和能源替代成本函数,由于量纲相同,首先将各省的两个目标函数合为一个目标函数,下层问题的公式可转换为:

$$\begin{aligned} \min U_e &= \frac{1}{30} \sum_{i=1}^{30} Y_{qi} R_i K_i \mu_i \varphi_{ci} \\ \min C &= \frac{1}{30} \sum_{i=1}^{30} \left\{ w_i \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) + C_{di} \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) + rv \times \left(\frac{Y_{qi} R_i K_i}{t_i} - Y_{mi} \right) \right\} \quad (11) \end{aligned}$$

然后用线性加权的方法将 30 个省份的目标函

数合并成一个目标函数。下层模型可转换为：

$$\min TC(R_i, K_i) = \frac{1}{30} \sum_{i=1}^{30} \left\{ \lambda_1 (w + C_d + r_i v) \times \frac{Y_{ei} - Y_{mi}}{t} \right. \\ \left. + \lambda_2 Y_{qi} R_i K_i \mu_i \varphi_i \right\}$$

(12)

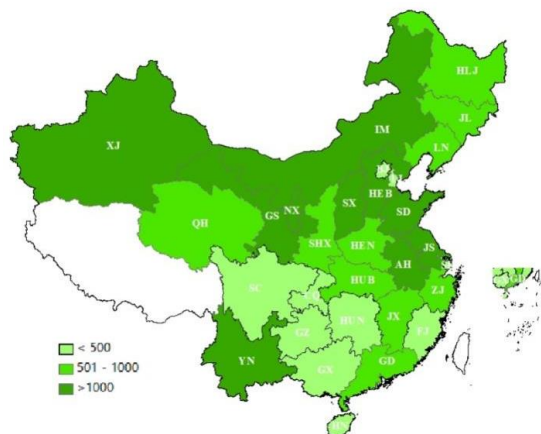


图 2 2017 年 30 个省区风力和光伏装机容量的分布图

综上，二层多目标转换成一个上下层均为单目标的二层规划，利用遗传算法进行求解。

四、数据

2017 年 30 个省区风力和光伏装机容量的分布如图 2 所示。相关参数的测量方法与数据来源见附录 A。

五、结果与讨论

1、非水可再生能源电力配额分配最优方案

设定地方政府对减排成本与能源替代成本有相同的偏好，设 $[\lambda_1, \lambda_2] = [0.5, 0.5]$ 。利用 Matlab2018a 编译算法，运用遗传算法求解上述二层规划模型，得到最优的非水可再生能源电力配额分配方案，如表 1 所示。

表 1 非水可再生能源电力配额优化方案

省份 _i	$B = 857.04, U_e = 7337.46, C = 33863.26$		
	消纳量 _i	分配比例 _i	政策执行率 _i
LN _i	296.074 _i	11.50% _i	102.81% _i
JL _i	133.931 _i	22.82% _i	72.32% _i
HLJ _i	285.138 _i	23.12% _i	94.95% _i
BJ _i	113.331 _i	11.30% _i	84.18% _i
TJ _i	88.017 _i	11.42% _i	86.06% _i
HEB _i	660.002 _i	15.48% _i	96.52% _i
SX _i	288.834 _i	10.19% _i	119.66% _i
IM _i	568.963 _i	17.54% _i	82.71% _i
QH _i	173.410 _i	30.49% _i	81.80% _i
NX _i	246.253 _i	21.00% _i	93.32% _i
SHX _i	273.369 _i	16.52% _i	80.91% _i
GS _i	221.574 _i	17.05% _i	101.00% _i
XJ _i	256.201 _i	8.52% _i	114.77% _i
SH _i	58.002 _i	3.67% _i	100.57% _i
JS _i	657.014 _i	12.04% _i	85.23% _i
FJ _i	219.145 _i	10.98% _i	79.99% _i
SD _i	566.311 _i	10.14% _i	87.86% _i
ZJ _i	409.836 _i	10.63% _i	78.90% _i

AH ₁	299.780 ₁	15.40% ₁	78.53% ₁
HUB ₁	328.734 ₁	13.82% ₁	100.51% ₁
HUN ₁	229.924 ₁	12.08% ₁	95.59% ₁
HEN ₁	209.024 ₁	8.61% ₁	73.32% ₁
JX ₁	157.495 ₁	9.45% ₁	100.97% ₁
GD ₁	269.489 ₁	4.82% ₁	78.89% ₁
GX ₁	63.078 ₁	3.45% ₁	85.51% ₁
HN ₁	25.513 ₁	5.83% ₁	113.68% ₁
CQ ₁	78.449 ₁	6.83% ₁	95.00% ₁
SC ₁	160.619 ₁	6.75% ₁	84.23% ₁
GZ ₁	101.830 ₁	7.06% ₁	90.12% ₁
YN ₁	181.482 ₁	11.87% ₁	78.16% ₁

从表 1 可以看出,由二层规划模型求解得出补贴成本为 857.04 亿元,能源替代成本为 33863.26 亿元,减排成本为 7337.46 亿元。二层优化分配方案 (Bi-level Optimization Allocation Scheme, 简称 BOAS) 对内蒙古、吉林、黑龙江、青海、宁夏、甘肃和福建等省份的非水配额指标有所增加,而对北京、天津、山西、广西、云南和河南等省份的非水配额指标有所减少。可再生能源消纳量最多的 6 个省区是河北、江苏、内蒙古、山东、浙江、湖北,分别为 660.002、657.014、568.963、566.311、409.836、328.734 (单位:亿千瓦时),分别占全国非水电可再生能源电力消纳量的 8.66%、8.62%、7.47%、7.43%、5.38%、4.31%,共占全国非水电可再生能源电力消纳量的 41.87%,可再生能源消纳量最少的 6 个省份是海南、上海、广西、重庆、天津、贵州,分别占全国目标总量的 0.33%、0.76%、0.83%、1.03%、1.15%、1.34%,共占全国非水电可再生能源电力消纳量的 5.44%。可见,少数省区承担了全国可再生能源电力消纳量的主体任务。此外,执行率超过 100% 的省区有辽宁、山西、甘肃、新疆、上海、湖北、江西、海南,这表明这些省区超额完成了上层中央政府分配的配额任务,积极性较高,执行率低于 80%

的省份有吉林、福建、浙江、安徽、河南、广东、云南,这表明这些省区没有完全执行上层中央政府分配的配额任务,可再生能源电力消纳水平较低。

为分析导致各省区电力消纳差异的主要原因,构建了政策执行率与单位减排成本的关系图。如图 3 所示,该方案政策执行率最高的 5 个省份分别是山西、新疆、海南、辽宁、甘肃,政策执行率为 119.66%、114.77%、113.68%、102.81%、101.00%;相对应的单位减排成本相对于其他省份是较低的,分别为 0.228、0.391、0.559、0.612、0.617 (单位:元/kg),政策执行率最低的 5 个省份分别为吉林、河南、云南、安徽、广东,政策执行率为 72.32%、73.32%、78.16%、78.54%、78.89%,相对应的单位减排成本相对于其他省份是较高的,分别为 1.203、3.613、1.468、1.042、1.871 (单位:元/kg)。中央政府从补贴成本优化的角度制定的分配方案并没有得到地方政府的完全执行,地方政府根据自身可承受的减排成本来执行上层中央政府的配额任务,体现出不同的消纳意愿程度。单位减排成本相对低的省区,配额政策的执行率就越高;单位减排成本相对高的省区,配额政策的执行率就越低。

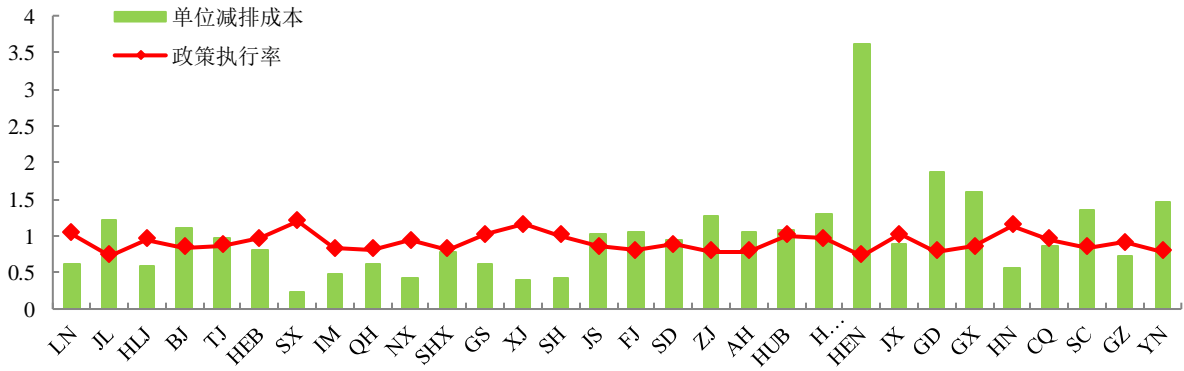


图3 单位减排成本与政策执行率关系图

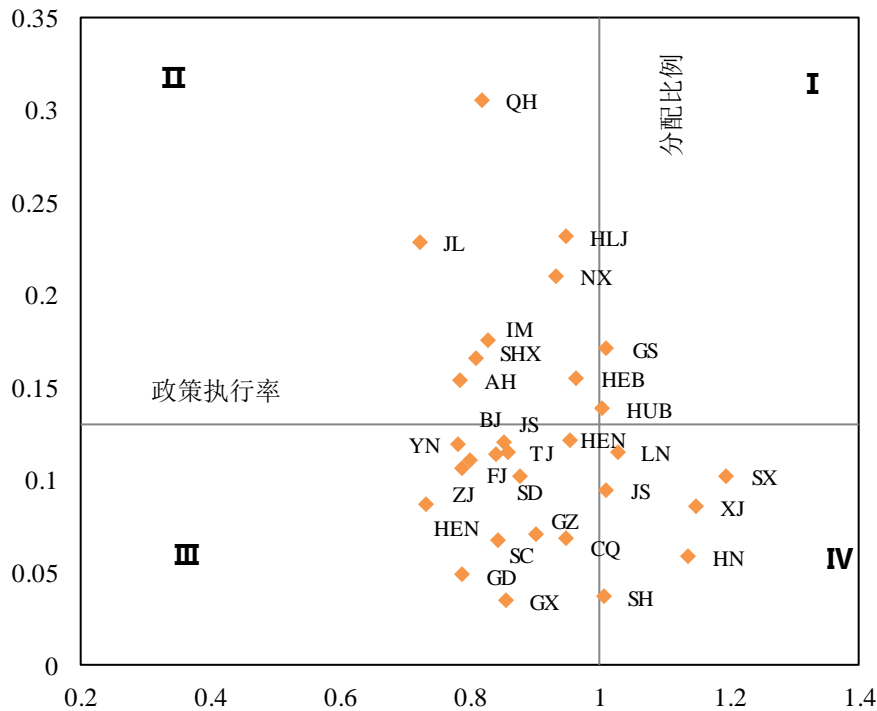


图4 基于政策执行率和分配比例的30个省区分组结果

由于30个可再生能源发电省份政策执行意愿存在差异，根据配额比例和执行率进行分组，探究原因。结果如图4所示。第一组是甘肃省和湖北省。他们承担的配额比其他省份多，执行既定任务的积极性也更高。第二组中分布的省份有内蒙古、青海、宁夏、北京等省份，他们承担了很大比例的非水可再生能源电力配额。然而，由于化石能源发电在这些省份中仍占据着比较重要的地位，能源替代可能会影响当地的经济发展，他们对可再生能源电力消

纳普遍持消极态度。14个省密集分布在第三组。这些省份虽然承担了少量的非水可再生能源电力配额任务，但不能全面执行配额任务，执行既定配额的意愿较低。因此，当中央政府监测非水可再生能源电力配额效果时，这些省份应该成为关注的焦点。第四组有上海、海南等6个省份。这些省份承担的配额比例较小，超额完成配额任务。这可能与他们的较低的减排、能源替代成本有关。

2、最优方案与政府分配方案比较

为了验证上述 BOAS 的合理有效性,考虑国家发展改革委和国家能源局制定的各省级行政区域 2020 年非水可再生能源电力配额任务,据此从补贴成本、能源替代成本、减排成本和公平性进行对比分析。

(1) 补贴成本的对比分析

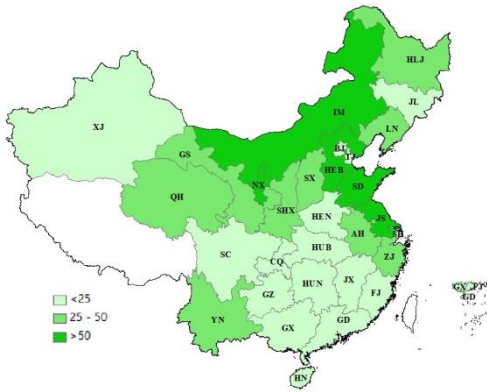
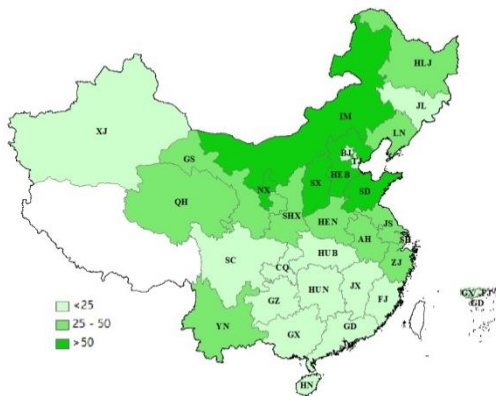


图 5 (a) 基于 BOAS 的补贴成本



(b) 基于 GAS 的补贴成本

对 BOAS 与 GAS 进行比较,结果如附录 B 所示,可以发现二层优化方案的补贴成本有明显降低 4.70%。从补贴成本的表达式来看,补贴成本的大小与该省可再生能源消纳量和燃煤发电上网基准价有关,这主要是由于二层优化分配方案平衡了各省之间的可再生能源配额任务。在考虑各地非水可再生能源的情况下,BOAS 增加了相对补贴成本较低的省份消纳量,如黑龙江、湖北等省份,减少相对补贴成本较高的省份消纳量,如云南等省份,平衡了各省之间的非水可再生能源电力配额任务,使得消纳量满足中央政府的平均配额下补贴成本有效降低。绘制 BOAS、GAS 补贴成本的分布情况,如

图 5 (a), (b) 所示。

(2) 能源替代成本的对比分析

BOAS 有效降低了能源替代的成本。在能源替代成本方面减少了 2275.12 亿元,降低了 7.61%。其中建设资金成本减少 1528.10 亿元,运行维护成本减少 15.28 亿元,火电关停成本减少 1051.74 亿元。这是因为,与 GAS 相比,二层消纳量增加的省份和地区主要是黑龙江、河北、江苏、陕西等省份。这些省份的用电量相对较大或者位于可再生能源电力发达的地区,可再生能源丰富。绘制 BOAS、GAS 能源替代成本的分布情况,如图 6 (a), (b) 所示。

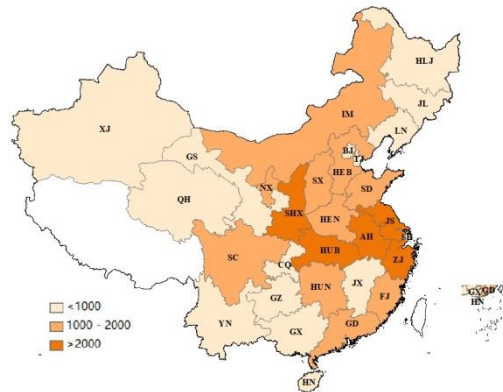
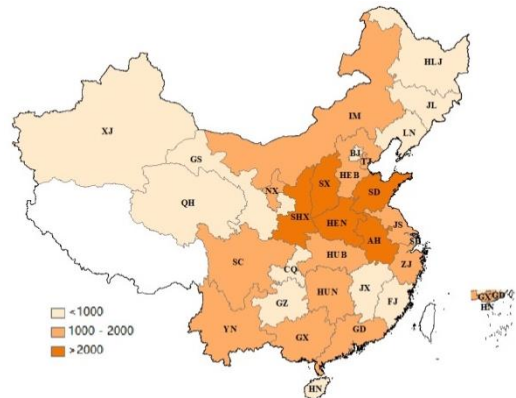


图 6 (a) 基于 BOAS 的能源替代成本



(b) 基于 GAS 的能源替代成本

(3) 减排成本的对比分析

相较于 GAS, BOAS 的二氧化碳减排成本明显降低。由附录 B 可知,BOAS 的减排成本比 GAS 减少了 791.39 亿元,降低了 9.74%。如图所示,与政府相比,BOAS 的减排成本降低显著的省份有山东、河南、云南,分别是 123.428 亿元、740.545 亿元、

164.167 亿元。其中,河南的减排成本降低幅度最大,超过其它省份和地区。主要原因是治理二氧化碳的成本在各省区之间虽然有差距,但减排成本与各省可再生能源消纳量的大小有关,河南分配的可再生能源消纳量缩减较大,因此,在满足中央政府平均消纳量的要求下,各地政府累计的减排成本显著降低。绘制 BOAS、GAS 的分布情况,如图 7 (a), (b) 所示。

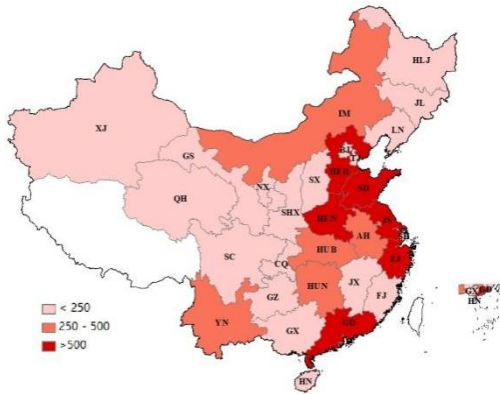


图 7 (a) 基于 BOAS 的减排成本

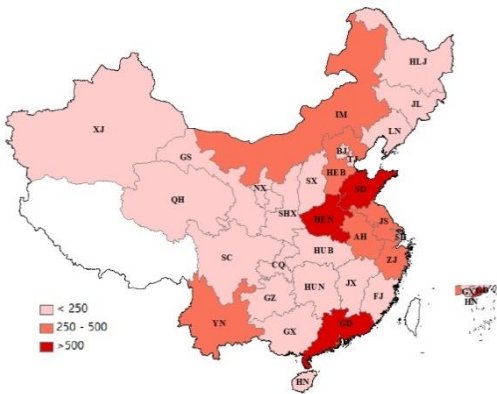


图 7 (b) 基于 GAS 的减排成本

(4) 公平性的对比分析

为了考察 BOAS 的省域公平性,应用基尼系数进行测度。基尼系数被广泛用于衡量资源分配问题的公平性,如水资源优化配置^[18]。基于中国可再生能源电力省区的特点,图 8 和图 9 分别以人均能源替代成本和人均可再生能源消纳量作为排序依据,以人口累计占比为横坐标,以累计能源替代成本占比、累计可再生能源消纳量占比为纵坐标的 BOAS、GAS 的洛伦兹曲线。

根据表 2,图 8 和图 9 可知,当以上述方法绘制洛伦兹曲线时,BOAS 的基尼系数均小于 0.2,隶属绝对平均范畴。因此,总体而言,BOAS 在降低补贴成本、减少减排成本和能源替代成本的同时,还具有很高的公平性。

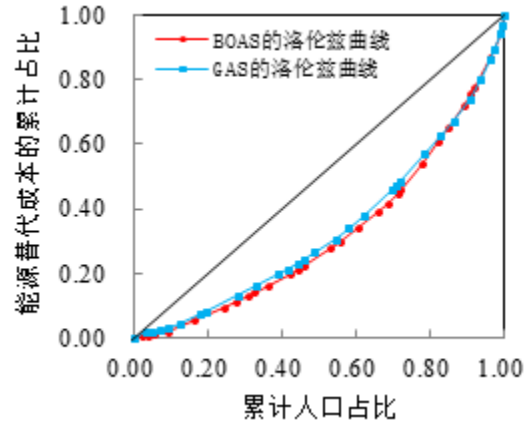


图 8 基于人均能源替代成本的洛伦兹曲线

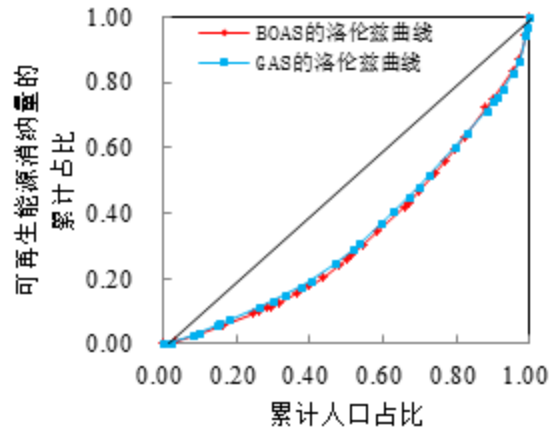


图 9 基于人均可再生能源消纳量的洛伦兹曲线

表 2 基尼系数计算结果

洛伦兹曲线排序依据 _i	非水可再生能源电力配额方案 _i	基尼系数 _i
人均能源替代成本 _i	二层优化方案 _i	0.1580 _i
	政府分配方案 _i	0.1381 _i
人均可再生能源消纳量 _i	二层优化方案 _i	0.1584 _i
	政府分配方案 _i	0.1329 _i

3、情景分析

在政策实际制定的过程中地方政府会由于一些现实原因或基于未来发展方向的考虑具有不同的目标偏好。为此，将偏好权重进一步分别设置为

$[\lambda_1, \lambda_2]=[0.3,0.7]$ 和 $[\lambda_1, \lambda_2]=[0.7,0.3]$ ，分别考察地方政府环境偏好和经济效益情景下的分配方案，结果如表 3 所示。

表 3 不同权重下各省区非水可再生能源电力配额分配指标

省份 _i	环境导向型 _i		相同偏好 _i		经济导向型 _i	
	$B=864.77, U_p=7135.92, C=34158.50$		$B=857.04, U_p=7337.46, C=33863.26$		$B=862.37, U_p=7274.57, C=33564.11$	
	分配比例 _i	政策执行率 _i	分配比例 _i	政策执行率 _i	分配比例 _i	政策执行率 _i
LN _i	12.89% _i	90.93% _i	11.50% _i	102.81% _i	15.14% _i	86.29% _i
JL _i	22.52% _i	71.92% _i	22.82% _i	72.32% _i	22.23% _i	74.65% _i
HLJ _i	22.90% _i	96.00% _i	23.12% _i	94.95% _i	24.03% _i	94.59% _i
BJ _i	9.90% _i	100.08% _i	11.30% _i	84.18% _i	9.57% _i	99.21% _i
TJ _i	8.94% _i	109.06% _i	11.42% _i	86.06% _i	10.44% _i	92.35% _i
HEB _i	14.67% _i	102.02% _i	15.48% _i	96.52% _i	14.54% _i	105.69% _i
SX _i	12.46% _i	114.66% _i	10.19% _i	119.66% _i	10.99% _i	116.35% _i
IM _i	19.44% _i	78.52% _i	17.54% _i	82.71% _i	18.59% _i	83.50% _i
QH _i	29.49% _i	86.50% _i	30.49% _i	81.80% _i	26.12% _i	82.34% _i
NX _i	23.99% _i	88.32% _i	21.00% _i	93.32% _i	24.00% _i	82.15% _i
SHX _i	15.87% _i	81.01% _i	16.52% _i	80.91% _i	15.69% _i	81.28% _i
GS _i	18.15% _i	94.57% _i	17.05% _i	101.00% _i	19.33% _i	88.55% _i
XJ _i	10.32% _i	107.77% _i	8.52% _i	114.77% _i	9.27% _i	101.55% _i
SH _i	4.53% _i	106.07% _i	3.67% _i	100.57% _i	4.13% _i	91.05% _i
JS _i	11.60% _i	80.83% _i	12.04% _i	85.23% _i	12.52% _i	80.06% _i
FJ _i	11.32% _i	73.99% _i	10.98% _i	79.99% _i	11.20% _i	79.60% _i
SD _i	10.55% _i	83.58% _i	10.14% _i	87.86% _i	11.01% _i	84.87% _i
ZJ _i	10.01% _i	76.90% _i	10.63% _i	78.90% _i	9.65% _i	71.25% _i
AH _i	15.79% _i	76.53% _i	15.40% _i	78.53% _i	14.97% _i	80.80% _i
HUB _i	11.55% _i	119.77% _i	13.82% _i	100.51% _i	12.19% _i	113.82% _i
HUN _i	11.45% _i	97.65% _i	12.08% _i	95.59% _i	12.26% _i	94.43% _i
HEN _i	7.11% _i	75.74% _i	8.61% _i	73.32% _i	8.06% _i	78.05% _i
JX _i	9.09% _i	109.71% _i	9.45% _i	100.97% _i	8.77% _i	110.64% _i
GD _i	4.51% _i	81.98% _i	4.82% _i	78.89% _i	4.50% _i	82.75% _i
GX _i	2.71% _i	96.57% _i	3.45% _i	85.51% _i	3.09% _i	93.65% _i
HN _i	8.80% _i	108.99% _i	5.83% _i	113.68% _i	5.72% _i	100.16% _i
CQ _i	7.13% _i	93.26% _i	6.83% _i	95.00% _i	6.54% _i	99.55% _i
SC _i	4.98% _i	111.23% _i	6.75% _i	84.23% _i	4.95% _i	114.86% _i
GZ _i	8.10% _i	72.67% _i	7.06% _i	90.12% _i	7.65% _i	82.35% _i
YN _i	12.07% _i	79.77% _i	11.87% _i	78.16% _i	11.44% _i	80.77% _i

图 10 和图 11 分别展示了不同情景下非水可再生能源电力配额在各省区的最优分配比例和政策执行率。可以看出,在环境导向情景下补贴成本和能源替代成本相对增加,而减排成本相对降低;在经济导向情景下减排成本和能源替代成本相对降低,而补贴成本相对提高。详细来看,与同等偏好情景相比,在环境导向情景下减排成本相

对减少 201.54 亿元,能源替代成本相对增加 295.24 亿元,补贴成本增加了 7.73 亿元。在经济导向型情景下减排成本减少了 62.89 亿元,能源替代成本相对减少了 299.15 亿元,而补贴成本增加了 5.33 亿元。这说明不同偏好情景下求解可得不同的分配方案,且偏好的目标权重越大则表现越好,模型内在一致性成立。

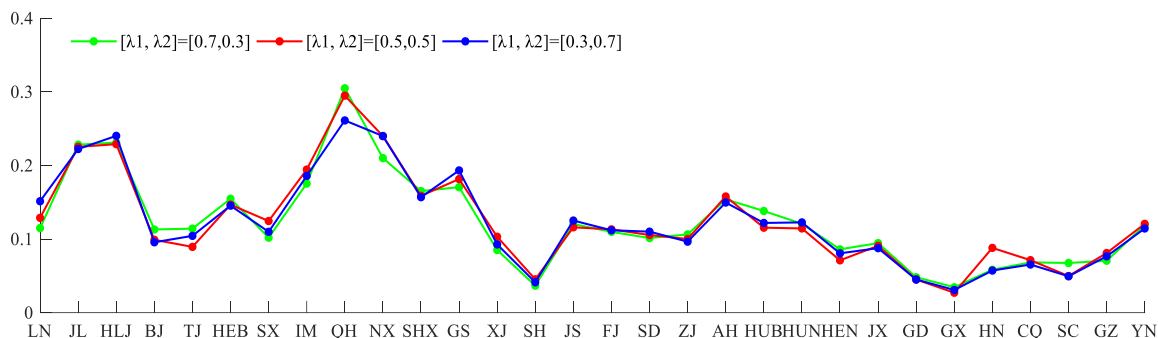


图 10 不同情景下非水可再生能源电力配额在各省的最优分配比例

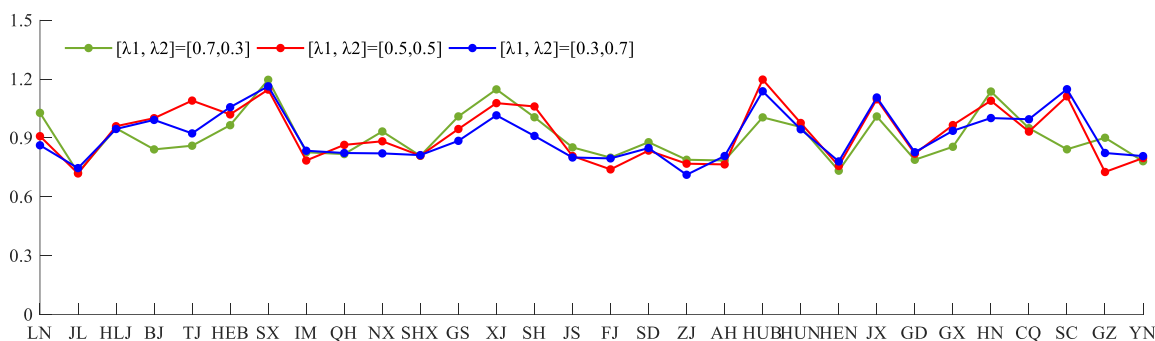


图 11 不同情景下非水可再生能源电力配额在各省的政策执行率

六、结论

鉴于当前中国可再生能源电力消纳的迫切性和实现 2030 碳达峰和 2060 碳中和的根本要求,以中央政府补贴成本最小为上层目标,以各省区减排成本和能源替代成本最小为下层目标,构建了基于二层多目标中国非水可再生能源电力配额分配模型,并得到了 30 个可再生能源发电省非水可再生能源电力配额最优分配方案。为检验优化分配方案的合理性,从补贴成本、能源替代成本、减排成本和公平性上对比分析了二层优化分配方案与政府分配方案。在此基础上通过情景分析探究了中央政府不同偏好情景下目标值和分配方案的变化规律。主要结论如下:

部分地方政府在执行中央政府的非水可再生能源电力配额方案时意愿程度较低,存在违约行为,而有些地方政府对于非水可再生能源电力配额任务积极性很高,能够超额完成既定的目标分配,这与中国实施配额政策的实际情况相符。具体而言,政策执行率最低的 5 个省份分别为吉林、河南、云南、安徽、广东,政策执行率为 72.32%、73.32%、78.16%、78.54%、78.89%,这是由于这些省份的可再生能源相对缺乏,高昂的减排成本和能源替代成本会给地方财政带来巨大的压力,从而削弱地方政府执行配额政策的积极性。配额政策执行率最高的 5 个省份分别是山西、新疆、海南、辽宁、甘肃,政策执行率为 119.66%、114.77%、113.68%、102.81%、101.00%,这些省份均为资源禀赋优良的可再生能源

源相对丰富的省份, 风力、光伏资源丰富, 减排、能源替代成本相对较低, 对于配额任务的执行意愿较为积极, 这些省份的可再生能源消纳对于非水可再生能源电力配额的总体工作效果发挥着重要作用。

与政府分配方案相比, 二层优化方案的补贴成本更低, 减排成本和能源替代成本更小, 同时具有较好的公平性, 能够更好地兼顾成本、环境和公平。具体而言, 二层优化分配方案的补贴成本比政府分配方案减少了 42.22 亿元, 降低了 4.70%, 减排成本比政府分配方案减少了 791.39 亿元, 降低了 9.74%, 能源替代成本减少了 2595.12 亿元, 降低了 7.10%。此外, 不同指标计算出的基尼系数是不同的, 二层优化方案的基尼系数都小于 0.2, 属于绝对公平的范畴。

尽管不同情景下的非水可再生能源电力配额分配方案存在一定差异性, 但变化趋势与实际情况相符, 结果表明该模型具有良好的内在一致性, 能够为政府在不同偏好下制定政策提供一定参考。具体而言, 在环境导向情景下, 单位减排成本较小的省份所分配的消纳量较多, 而单位减排成本较高的省份所分配的消纳量较少; 而在经济导向情景下, 单位能源替代成本较小的省份所分配的消纳量较多, 而单位能源替代成本较高的省份所分配的消纳量较少。

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附录 A 模型符号说明与数据来源

符号	符号含义	测量方式	数据来源
Y_{qi}	第 i 省 2020 年预计行政区域用电量	估计得出	Wang 等 ^[4]
S_i	第 i 省燃煤发电上网基准价	以各省区燃煤发电上网基准价衡量 (单位: 元)	《中国电力行业年度发展报告》
E_i	第 i 省可再生能源上网电价	以各省区可再生能源上网电价衡量 (单位: 元)	《中国电力行业年度发展报告》
m	适用增值税税率	$m = 13\%$	《国家发展改革委关于电网企业增值税税率调整相应降低一般工商业电价的通知》
W	全国平均配额比例	$W = 0.1$	《可再生能源十三五规划》
Q_{ci}	第 i 省基准年可再生能源发电的比例	可再生能源发电/总发电量	《中国电力统计年鉴》
ar_i	第 i 省规划年可再生能源发电量占全部发电量的比例下降的上限	以各省区可再生能源发电量占全部发电量的比例情况设定	《中国电力统计年鉴》
br_i	第 i 省规划年可再生能源发电量占全部发电量的比例上升的下限	以各省区可再生能源发电量占全部发电量的比例情况设定	《中国电力统计年鉴》
Y_{mi}	第 i 省基准年可再生能源装机容量	以各省区基准年可再生能源装机容量衡量 (单位: 亿千瓦)	《中国电力统计年鉴》
t_i	第 i 省可再生能源平均合理利用小时数	以各省区风光总发电量/装机容量计算得到 (单位: 小时)	中国电力企业联合会
r	火电行业固定资产损失率	$r = 97\%$	《关于做好已取消的企业所得税审批项目后续管理工作的通知》
v	火力发电厂单位造价	$v = 4500$	Wang 等 ^[4]
w_i	第 i 省可再生能源电厂单位造价	根据 2020 年风光装机容量占比计算 (单位: 元)	中国电力企业联合会
C_{di}	第 i 省可再生能源电厂维护费用	详见参考文献	Wang 等 ^[4]
h	火力发电单位二氧化碳排放系数	$h = 0.838$	中国电力企业联合会
P_i	第 i 省二氧化碳排放控制指标	按照全国二氧化碳指标分配计算	中国电力企业联合会
μ_i	表示单位可再生能源发电碳排放第 i 省减排的系数	$\mu_i = 0.838$	中国电力企业联合会
φ_{ci}	第 i 省单位 CO ₂ 减排成本	利用线性规划法对方向距离函数进行有效参数估计基础上, 对 30 省份 2015 年边际减排成本进行测算得到	赵巧芝和闫庆友 ^[16]
φ_{hi}	第 i 省火电发电占比系数	$\varphi_{hi} = 0.75$	根据 2020 年装机容量计算
f_i	可再生能源发电的灵活性系数	详见参考文献	Sullivan 等 ^[17]
f_j	火力发电的灵活性系数	详见参考文献	Sullivan 等 ^[17]
f_d	电力消耗的灵活性系数	详见参考文献	Sullivan 等 ^[17]

附录 B 配额优化方案与政府方案对比

省份	二层优化分配方案			政府分配方案		
	补贴成本	减排成本	能源替代成本	补贴成本	减排成本	能源替代成本
LN	32.778	181.120	579.481	34.665	191.551	670.792
JL	15.041	161.168	364.467	16.857	180.632	494.856
HLJ	31.794	168.695	860.313	28.970	153.712	720.380
BJ	12.637	126.407	389.376	19.918	199.245	641.047
TJ	10.920	85.412	744.238	15.558	121.687	1104.694
HEB	78.558	522.662	1668.195	65.720	437.249	1034.938
SX	42.942	65.836	1433.868	56.329	86.360	2371.757
IM	105.737	274.155	1173.814	120.237	311.753	1838.910
QH	26.902	105.646	883.988	26.966	105.897	888.534
NX	52.410	107.101	1089.507	53.478	109.283	1145.974
SHX	35.199	213.276	2400.731	31.594	191.434	2075.230
GS	39.648	136.660	102.370	37.982	130.918	4.493
XJ	22.673	100.263	128.334	24.353	107.694	358.944
SH	4.337	24.740	98.982	4.698	26.795	118.742
JS	63.376	681.064	2759.909	46.331	497.889	1564.859
FJ	20.712	232.860	1087.735	14.143	159.009	625.259
SD	52.672	525.822	1829.916	65.036	649.250	2793.664
ZJ	30.720	525.467	2300.781	27.470	469.883	1949.511
AH	30.668	312.261	2440.649	31.703	322.807	2563.266
HUB	24.408	352.338	3154.422	14.060	202.964	1512.995
HUN	10.174	297.106	1501.507	7.931	231.600	1066.207
HEN	22.586	755.299	1117.313	44.730	1495.844	3201.218
JX	11.945	139.900	663.786	11.266	131.955	588.294
GD	11.209	504.282	1385.880	13.271	597.048	1772.973
GX	4.427	100.486	344.163	10.494	238.219	1152.490
HN	1.585	14.260	315.171	1.554	13.980	307.328
CQ	7.192	67.252	517.170	3.877	36.256	256.471
SC	14.044	216.166	1217.184	14.822	228.143	1305.213
GZ	13.382	73.301	688.516	12.628	69.172	619.518
YN	26.371	266.448	621.495	42.619	430.615	1709.825
Total	857.043	7337.456	33863.259	899.262	8128.846	36458.382

Dynamic Dependence and Risk Spillover between Oil and Foreign Exchange Markets: The Factor Copula Model

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Abstract: This paper concerns the conditional dynamic dependence and risk spill over analysis of markets. Factor copula is introduced to model the foreign exchange and oil markets to more accurately reflect the dependence. For this purpose, we extract the common factors and construct dynamic factor copula model to reveal the oil price-exchange rate dependences and measure the risk spillover. The two-factor copula model is more suitable for studying the dependence of exchange rates and oil prices by statistical indicators and graphs. The Δ Conditional Value at Risk (CoVaR) is calculated for risk spillover. Overall, our findings indicate that the common factor better reflects the global economy trend. Conditional on the common factors, the oil price-exchange rate dependence in oil importers is slightly lower than in oil exporters, even though the dependence is weak in general. Affected by various factors, the risk spillover of the crude oil market to the foreign exchange market is higher than the latter to the former, indicating that the crude oil market fluctuates more significantly. The results of this analysis provide some insight into exchange rate and oil markets connectivity.

Key words: factor analysis, oil price, exchange rates, factor copula model, CoVaR

1. Introduction

The relationship between crude oil market and financial markets has crucial connections with macroeconomics. As a key macroeconomic indicator, changes in currency or exchange rates have always been widely researched in financial economics. The global financial crisis triggered by the US subprime mortgage crisis in 2007 caused a devastating disaster to the global economy, and the financial markets of various countries have had an unprecedented close connection. Particularly, the risk spillover effect between the crude oil market and the exchange market have increased. The fluctuations of sub-markets in any region can quickly spread to other markets with a high degree of relevance, causing widespread effects. The volatility of crude oil prices largely affects the US dollar and the currencies of countries with which it has bilateral oil trade relations. Therefore, an accurate model to analyze the correlation between oil price and exchange rate is helpful to improve investment decision-making and portfolio risk management.

Many common factors affecting both the oil market and exchange rate market need to be considered.

However, relevant researches did not pay attention to common factors. There are many factors affecting the crude oil market and foreign exchange market, such as oil price volatility index (OVX) (Benedetto et al., 2020), global consumer information index or a combination of the two factors, stock price index or stock market shock (Fratzscher et al., 2014), and some exogenous variables that are not easy to be measured (political environment, interest rate, financial policy, etc.). The global consumer information index and OVX is related to the whole economic expectation. Stock price index or stock market shock reflect economic health, the financial health of individual companies, and current events. It would, therefore, be useful to capture the interdependence among markets and measure risks conditioned on common factors.

Many scholars pay attention to the dependence across crude oil and foreign exchange markets. As one of the most important commodities in the global economy, crude oil is usually regarded as an international commodity and an important strategic resource (Aloui et al., 2013; Brayek et al., 2015). It

has long been highly concerned by oil-exporting and oil-importing countries. In the process of economic globalization, crude oil also has financial attributes, and crude oil futures are an important part of the international crude oil market (Nikbakh, 2010; Ji and Zhang, 2019). Nikbakh (2010) examined the long-run relationship between real oil prices and real exchange rates in OPEC member countries using a monthly panel of seven OPEC member countries. Beckmann et al. (2020) argued that there is a strong long-term time-varying relationship between oil prices and exchange rates and that they are more effective indicators of each other in the short run. Huang et al. (2020) studied the similarity or heterogeneity of the dynamic response of exchange rates to oil price shocks from a time-varying perspective, when extreme market conditions and unexpected oil price shocks occur simultaneously. Lin and Su (2020) used ARDL method and VAR model to detect the impact of oil shocks on exchange rates at different frequencies and showed that there are differences in the impact of supply and demand shocks on exchange rates in BRICS countries. Nevertheless, they didn't consider the common factors. We have found that there are many mixed factors affecting the dependence, and previous studies ignored common factors. Therefore, this paper models them after factor analysis in order to more accurately reflect the dependence across crude oil and foreign exchange markets.

There are a lot of methods that have been used to measure dependence, but copula is the most common. Although the linear correlation coefficient is the simplest and widely used method to calculate the correlation coefficient, the calculation of it needs to assume that the marginal distribution has a normal or a Gaussian distribution, while the financial return data is usually a typical asymmetrical distribution.

Therefore, in order to model the dependence between the foreign exchange market and the crude oil market, we choose the copula method. Because it allows the use of various marginal distributions without normality restrictions and incorporates more accurate information into the joint distribution (Hussain and Li, 2018). We try to introduce copula methods to model the Kendall dependence between the crude oil market and the foreign exchange market.

In this paper, factor analysis is introduced into copula model, and then dynamic copula parameter evolution is done. Factor analysis is used mainly to find the common factors that describe the relationship of the underlying variables. Here, we adopt the "scree plot" to determine the number of common factors first, that is, the "scree plot" of the eigenvalues of the rank correlation matrix of the standardized residuals (OH and Patton, 2017).

The factor copula model to investigate the degree and structure of dependence between exchange rate returns and oil futures returns. The first to propose the concept of factor copula was Ledoit and Wolf (2003). This method is called "contraction", which is used to impose some structures on large-scale estimation problems, that is, the problem of estimating the covariance matrix of a large number of stock returns. Chen and Song (2013) proposed a new factor coefficient estimation method based on copula theory and compared the advantages and disadvantages of multi factor models by different factor coefficient estimation methods. Factor copula models proposed in Krupskii and Joe (2013), which can handle multivariate data with tail dependence and tail asymmetry. In order to more accurately describe the dependency between multivariate variables, Zhang and Jiao (2012) introduced a factor copula method, which combines factor analysis with copula model to measure the dependence of daily returns of exchange

rates. In particular, the models consider the effect of common factors on variables. The traditional copula model cannot obtain the exact dependence relationship because it ignores the influence of common factors. Therefore, we plan to simulate the dependence between exchange rates and oil returns by factor copula based on the identified common factors.

Furthermore, we employ the factor copula estimation results to evaluate the risk spillover between crude oil returns and foreign exchange rates. For risk spillover, a large number of scholars have studied it and achieved fruitful research results, such as GARCH family model, VaR method, CoVaR method and TVP-SV-VAR model. VaR only reflects the risk of a single asset and ignores the relationship between the single asset and overall system risk. Adrian and Brunnermeier (2016) put forward the concept of Conditional Value at Risk (CoVaR) to portray the maximum potential loss of other assets at a given confidence level and for a certain holding period when the loss of a given asset is VaR at a specific time in the future. It is worth noting that studies such as Zhou, A. and F. Han (2017) and Lin, Juan and H. Zhao (2020) showed that ΔCoVaR is useful and enhances our understanding of risk spillover effects across financial markets. Chen, Ting and Yu (2021) and Zhao, Ru-Bo et al. (2021) then calculated the relative magnitude of the degree of risk spillover $\%\Delta\text{CoVaR}$ to eliminate the dimensional impact. In this paper, $\%\Delta\text{CoVaR}$ will be applied to make out the risk spillover of overall market risk.

Few scholars have yet used the factor copula model combined with CoVaR to study the interdependence between crude oil prices and exchange rates. Furthermore, the traditional copula-CoVaR model does not take into account the effect of common factors on intermarket dependence. Once factor

analysis is combined with copula, CoVaR can be a further step to modeling the risk situation. The remainder of the paper is structured as follows. Section 2 introduces dynamic factor copula model. Section 3 presents the data and empirical results. Finally, Section 4 concludes the paper.

2. Dynamic Factor Copula Model

This paper constructs the conditional dynamic dependence structure between exchange rate market and crude oil market by constructing a time-varying factor copula model. Then obtains the conditional value-at-risk ΔCoVaR between markets. First, we provide factor analysis on each return series to obtain the common factors, calculates the idiosyncratic factors of each return series. Then we employ ARMA-GARCH model to construct their marginal distribution at time t . Next, we adopt the optimal time-varying copula function connects the tail distributions obtained from probability integral transformation and identify the fluctuation dependence structure among markets by the factor copula model. Finally, we calculated the relative risk spillover levels of ΔCoVaR and $\%\Delta\text{CoVaR}$ based on the optimal copula function.

2.1 Extraction of Common Factors

This paper adopts an alternative method to study the interdependence between exchange market and oil market to describe the interdependence between multiple variables better. Factor analysis is mainly used for finding common factors which have potential variable relationships. This paper mainly adopts principal component analysis (commonly defined as factor analysis), these principal components can explain most of the differences in exchange rate and oil returns. Instead of directly incorporating the marginal distribution of each return series into the copula function, we use their marginal distribution on common factors. The correlation coefficients between returns mostly depend on the

common factors. Factor copula model can more accurately describe the interdependence between multiple variables. The benefits of common factors mean will only depend on the joint distribution of $Z_{1,t}, Z_{2,t}, \dots, Z_{n,t}$ (the unique part of the return series).

We adopt the “scree plot” to determine numbers of common factors (Oh and Patton, 2017). The eigenvalues of the covariance or correlation matrix are given from large to small, and the number of eigenvalues (before the inflection points of the graph) is used as the number of means common factors. Combined with “scree plot”, this paper conducts a factor analysis to return series and gets common factors $Y_{i,t}, i=1, 2, \dots, n$, combined with factor copula model put forward by Zhang and Jiao (2012). Then we construct a multi-factor model as follows:

$$x_i = Q_{i,t}^{-1} \left[F_{i,t}(r_{i,t}) \right], i=1, 2 \quad (1)$$

$$x_{i,t} = a_{i,t}Y_{1,t} + b_{i,t}Y_{2,t} + \dots + c_{i,t}Y_{n,t} + \sqrt{1 - a_{i,t}^2 - b_{i,t}^2 - c_{i,t}^2} Z_{i,t} \quad (2)$$

where $Q_{i,t}^{-1}(\cdot)$ is cumulative distribution inverse functions as return series $r_{i,t}$, $F_{i,t}$ is cumulative distribution function of each return series, $Z_{i,t}$ has dependent normal distribution, and $a_{i,t}, b_{i,t}, \dots, c_{i,t}$ is respective time-varying factor loading measuring the correlation of factors to returns. Assuming that $r_{i,t}$ (a probability is lower than threshold m) as $F_{i,t}(m)$ under the optimal copula model, if $F_{i,t}(m) = Q_{i,t}(x_i)$ or $x_i = Q_{i,t}^{-1} \left[F_{i,t}(m) \right]$, $r_{i,t} \leq m$. From formula (2), the condition is shown as follows:

$$a_{i,t}Y_{1,t} + b_{i,t}Y_{2,t} + \dots + c_{i,t}Y_{n,t} + \sqrt{1 - a_{i,t}^2 - b_{i,t}^2 - c_{i,t}^2} Z_{i,t} = Q_{i,t}^{-1} \left[F_{i,t}(m) \right] \quad (3)$$

or

$$Z_{i,t} = \frac{Q_{i,t}^{-1} \left[F_{i,t}(m) \right] - a_{i,t}Y_{1,t} - b_{i,t}Y_{2,t} - \dots - c_{i,t}Y_{n,t}}{\sqrt{1 - a_{i,t}^2 - b_{i,t}^2 - c_{i,t}^2}} \quad (4)$$

Under the condition $Y_{i,t}$ (common factors), probability of return below m is:

$$F_{i,t}(m|Y) = Q_{i,t} \left(\frac{Q_{i,t}^{-1} \left[F_{i,t}(m) \right] - a_{i,t}Y_{1,t} - b_{i,t}Y_{2,t} - \dots - c_{i,t}Y_{n,t}}{\sqrt{1 - a_{i,t}^2 - b_{i,t}^2 - c_{i,t}^2}} \right) \quad (5)$$

Therefore, set threshold as m , we can find out the probability of such a return that is lower than the expected value. In the formula (4), the dynamics of the factor copula model can be analyzed by the variation of idiosyncratic factors $Z_{i,t}$ in each return series over time.

2.2 Marginal Distribution Model

Generally, the marginal distribution series of financial asset return fitted by *ARMA-GARCH* model ignores the influence of common factors that affect the exchange rate and oil market on related structure. In this paper, factor analysis has been used to extract the common factors affecting the returns of markets. Then the corresponding marginal distribution is constructed under the condition of common factors.

First, considering that the exchange rate and oil returns exhibit autoregressive and heteroscedastic features, this paper adopts *ARMA(m, n) - GARCH(p, q)* model to filter the return series, the model is shown as follow:

$$r_{i,t} = \varphi_0 + \sum_{j=1}^m \varphi_j r_{i,t-j} + \varepsilon_{i,t} + \sum_{j=1}^n \psi_j \varepsilon_{i,t-j} = \mu_{i,t} + \varepsilon_{i,t} \quad (6)$$

$$\varepsilon_{i,t} = \sigma_{i,t} \eta_{i,t}, \eta_{i,t} : i.i.d.t_{\nu_i}(0, 1) \quad (7)$$

$$\sigma_{i,t}^2 = \omega + \sum_{j=1}^p \alpha_j \varepsilon_{i,t-j}^2 + \sum_{j=1}^q \beta_j \sigma_{i,t-j}^2 \quad (8)$$

where $\mu_{i,t} = E(r_{i,t} | F_{t-1})$, $\sigma_{i,t}^2 = Var(r_{i,t} | F_{t-1})$, $\eta_{i,t} : i.i.d.t_{\nu_i}(0, 1)$ is residual with standard Student-t distribution, and $F_{t-1} = \{x_{t-1}, x_{t-2}, \dots, x_1\}$ denotes information set (given past time).

Through the distribution function of standard residual, we can obtain the conditional marginal distribution of variables $r_{i,t}$:

$$\begin{aligned}
 F_{i,t}(x_i|F_{i,t-1};\theta_i) &= \Pr(r_{i,t} \leq x_i | F_{i,t-1}) \\
 &= \Pr\left(\frac{r_{i,t} - \mu_{i,t}}{\sigma_{i,t}} \leq \frac{x_i - \mu_{i,t}}{\sigma_{i,t}} \middle| F_{i,t-1}\right) = t_{v_i}\left(\frac{x_i - \mu_{i,t}}{\sigma_{i,t}} \middle| F_{i,t-1}\right)
 \end{aligned} \quad (9)$$

Then we can know integral transformation of conditional probability by parameter estimation:

$$u_{i,t} = F_{i,t}(r_{i,t}|F_{i,t-1};\theta_i) = t_{v_i}(z_{i,t}|F_{i,t-1}) \quad (10)$$

2.3 Time-varying Copula Dependent Parameter Model

Due to the complexity and variability of financial markets, the interdependence among markets is always dynamic. The time-varying copula will be, thus, be introduced to simulate the dynamic dependence. This time-varying function dynamically changes the dependent parameters based on the constant parameter copula function. Following the conditional copula theory (Patton, 2006, 2009, 2012), a special driven variable is employed to model the dependence parameter of copula. According to Patton (2006), Patton (2009), Patton (2012), Liu et al. (2017) and Ji et al. (2019), this paper adopts conditional copula function connect conditional marginal distribution and conditional joint distribution constructed by $Z_{1,t}$ (idiosyncratic factor of exchange rate) and $Z_{2,t}$ (idiosyncratic factor of crude oil returns):

$$\begin{aligned}
 &F_{i,t}(z_1, z_2 | F_{t-1}; \theta) \\
 &= C_t(F_{1,t}(z_1 | F_{t-1}; \theta_1), F_{2,t}(z_2 | F_{t-1}; \theta_2) | F_{t-1}; \theta_c)
 \end{aligned} \quad (11)$$

where $z_1, z_2 | F_{t-1} : F_t(\cdot, \cdot | F_{t-1})$, $z_{i,t} | F_{t-1} : F_t(\cdot, \cdot | F_{t-1})$, $i=1,2$, $C_t(\cdot, \cdot | F_{t-1})$ is the conditional copula dependence structure.

Corresponding conditional joint density function are shown as follow:

$$\begin{aligned}
 &f_t(z_1, z_2 | F_{t-1}; \theta) \\
 &= c_t(F_{1,t}(z_1 | F_{t-1}; \theta_1), F_{2,t}(z_2 | F_{t-1}; \theta_2) | F_{t-1}; \theta_c) \\
 &\cdot \prod_{i=1}^2 f_{i,t}(z_i | F_{t-1}; \theta_i)
 \end{aligned} \quad (12)$$

where $c_t(\cdot, \cdot | F_{t-1})$ is the conditional copula density function, $f_{1,t}(\cdot, \cdot | F_{t-1})$ and $f_{2,t}(\cdot, \cdot | F_{t-1})$

are the conditional marginal densities. This paper chooses *Gaussian copula*, *t-Copula*, *Rotated-Gumbel copula* and *SJC copula* models with different tail characteristics to describe the dependence structure between foreign exchange and oil markets, respectively. In these formulas, *Gumbel copula* is very sensitive to the upper tail to describe the asymmetric positive dependence, while the *rotated Gumbel copula* has the lower tail dependence (Ji et al., 2016). The *SJC copula* can better describe the asymmetry and tail correlation and can be used to capture the dependent structure of the upper tail and lower tail at the same time. In this paper, the above four types of copula functions would be extended to the corresponding time-varying copula model. Table 1 shows their expressions of driving variables and parameter-varying formulas, respectively. According to Patton (2006), $\frac{1}{m} \sum_{j=1}^m \phi^{-1}(u_{1,t-j}) \cdot \phi^{-1}(u_{2,t-j})$ and $\frac{1}{m} \sum_{j=1}^m t_n^{-1}(u_{1,t-j}) \cdot t_n^{-1}(u_{2,t-j})$ are employed as the driven variables of copula dependence parameters for the time-varying *Normal copula* (TV-N) and *time-varying copula* (TV-t), respectively. Yang and Zheng (2020) employs $\frac{1}{m} \sum_{j=1}^m |u_{1,t-j} - u_{2,t-j}|$ as the driven variable for both the time-varying *rotated Gumbel copula* (TV-RG) and time-varying *SJC copula* (TV-SJC). The evolution formulas in following table are similar to an *ARMA(1, q)* model and the right side of formulas include an auto-regressive term and a driven variable.

Based on conditional marginal distribution shown in formula (6)-(10) and above time-varying parameter of copula function, we obtain time-varying dependent parameters. Furthermore, we adopt the Kendall's Tau to measure dependent directions and intensities among variables:

$$\tau_{u,v} = \frac{2}{\pi} \arcsin \rho_{u,v} \quad (13)$$

2.4 Risking Spillover Measuring Model

Then we use the optimal time-varying copula function to further measure ΔCoVaR and $\% \Delta \text{CoVaR}$.

ΔCoVaR to describe the difference between the CoVaR conditional on an asset at risk and the CoVaR conditional on the normal state. In order to remove dimensional influence and to reflect the degree of risk spillover more intuitively, the relative

magnitude of risk spillover $\%\Delta\text{CoVaR}$ is calculated by normalizing ΔCoVaR :

$$\Delta\text{CoVaR}_{\alpha,t}^{\parallel 2} = \text{CoVaR}_{\alpha,t}^{\parallel X_2 = \text{VaR}_{\alpha,t}^2} - \text{CoVaR}_{0.5,t}^{\parallel X_2 = \text{VaR}_{0.5,t}^2} \quad (14)$$

$$\%\Delta\text{CoVaR}_{\alpha,t}^{\parallel 2} = \Delta\text{CoVaR}_{\alpha,t}^{\parallel 2} / \text{VaR}_{\alpha}^1 \quad (15)$$

Table 1 The driven variables of different types time-varying copula and their parameter evolution formulas

Formulas	Driven variables	Parameter evolution formulas
<i>Gaussian Copula</i>	$\frac{1}{m} \sum_{j=1}^m \phi^{-1}(u_{1,t-j}) \cdot \phi^{-1}(u_{2,t-j})$	$\rho_t = \Lambda \left(\omega + \beta \cdot \rho_{t-1} + \alpha \cdot \frac{1}{q} \sum_{j=1}^q \phi^{-1}(u_{1,t-j}) \cdot \phi^{-1}(u_{2,t-j}) \right)$
<i>t-Copula</i>	$\frac{1}{m} \sum_{j=1}^m t_n^{-1}(u_{1,t-j}) \cdot t_n^{-1}(u_{2,t-j})$	$\rho_t = \Lambda \left(\omega + \beta \cdot \rho_{t-1} + \alpha \cdot \frac{1}{q} \sum_{j=1}^q t_n^{-1}(u_{1,t-j}) \cdot t_n^{-1}(u_{2,t-j}) \right)$
<i>Rotated-Gumbel Copula</i>	$\frac{1}{m} \sum_{j=1}^m u_{1,t-j} - u_{2,t-j} $	$\rho_t = \Lambda \left(\omega + \beta \rho_{t-1} + \alpha \cdot \frac{1}{q} \sum_{j=1}^q u_{1,t-j} - u_{2,t-j} \right)$
<i>SJC Copula</i>	$\frac{1}{m} \sum_{j=1}^m u_{1,t-j} - u_{2,t-j} $	$\tau_t^U = \left(\Lambda(\omega_U + \beta_U \tau_{t-1}^U + \alpha_U \cdot \frac{1}{q} \sum_{j=1}^q u_{1,t-j} - u_{2,t-j}) \right)$ $\tau_t^L = \left(\Lambda(\omega_L + \beta_L \tau_{t-1}^L + \alpha_L \cdot \frac{1}{q} \sum_{j=1}^q u_{1,t-j} - u_{2,t-j}) \right)$

Notes: $\Lambda(x) = (1 - e^{-x})(1 + e^{-x})^{-1}$ is adopted to ensure ρ_t (time-varying parameter of time-varying *Gaussian copula* and time-varying *t-copula*) ranges in $(-1, 1)$; $\Lambda(x) = (1 + x^2)^{-1}$ is adopted to ensure ρ_t (time-varying parameter of time-varying *Rotated-Gumbel copula*) ranges in $(-1, 1)$; $\Lambda(x) = (1 + e^{-x})^{-1}$ is adopted to ensure τ_t (time-varying parameter of time-varying *SJC copula*) ranges in $(0, 1)$; $\phi^{-1}(\cdot)$, $t_n^{-1}(\cdot)$ are corresponding inverse functions of standardized normal distribution and t distribution.

3. Empirical Study

3.1 Data and summary statistics

In this paper, exchange rates of major global crude oil traders and major crude oil futures products (WTI and Brent) were selected to analyze the volatility dependence and risk spillover. Our sample includes the currencies of 14 major representative oil-trading countries from the countries or regions from the BP Statistical Review of World Energy 2019. Seven net oil importers are *China* (CNY), *European Union* (EUR), *United Kingdom* (GBP), *Japan* (JPY), *India* (INR), *South Africa* (ZAR) and the *United States* (USD). *Brazil* (BRL), *Canada* (CAD), *Algeria* (DZD), *Nigeria* (NGN), *Norway* (NOK), *Russia* (RUB) and *Mexico* (MXN) are selected as seven net oil exporters. The U.S. dollar index is selected for United States, and the selected bilateral exchange rates are measured by the quantity of foreign currency

per unit of the US dollar for all other non-U.S. countries. It provides a clear indication of the value of U.S. dollar in global markets. Daily observations from January 3, 2000 to December 31, 2020 are, therefore, used in our analysis. All data were extracted from the Wind database.

In this paper, the logarithmic return rate of each exchange rate and crude oil future prices is calculated and expanded 100 times to reduce calculation error:

$$r_{i,t} = 100 \times (\ln P_{i,t} - \ln P_{i,t-1}) \quad (18)$$

Table 2 summarizes the descriptive statistics of the daily returns for exchange rates and oil prices as well as the idiosyncratic factor series based on the two-factor model. Most exchange rates have positive mean values, and the highest and lowest mean values are observed for NGN (0.0244) and DZD (-0.0120) over the 2000–2020 period. Moreover, all return series show asymmetric leptokurtic features and the

Jarque–Bera statistics indicate that all the returns do not follow a normal distribution.

Table 3 presents the autoregressions and conditional heteroscedasticity tests of each return series. We then find that all return series have conditional heteroskedasticity and ARCH effects. According to the Q -statistic results, there is no autocorrelation in the idiosyncratic factor series of ZAR but there is autocorrelation in the original return series, contrary to USDX and NOK. Neither the original return series of the JPY nor the idiosyncratic factor series based on the two-factor model are autocorrelated. While the Q , Q^2 and ARCH statistics for the standardized residual series after modeling are not significant. Thus, it provides reasonable and valid evidence for filtering the return series by the ARMA-GARCH model.

3.2 Extraction and Analysis of Common Factors

This paper first extracts the common factors. Figure 1 shows the “scree plot” of the eigenvalues of the rank correlation matrix of standardized residuals. The figure shows that the first two eigenvalues are both greater than 1, so this paper only considers two common factors. To better illustrate that the two-factor model better than the three-factor model for

variation in returns, the following ARMA-GARCH models are constructed for the idiosyncratic factors based on the two-and three-factors respectively. Furthermore, this paper calculates the idiosyncratic factor Z_i reflecting each return and performs probability integral transformation on it, and then uses the time-varying copula model to analyze the dynamic dependence of oil price and exchange rate.

Figure 2 presents the variation characteristics of common factors that affect the price fluctuations of foreign exchange and crude oil markets. It is found that the trend of common factors in the sample period reflects the trend of the macro economy on the whole. In particular, there were large fluctuations from 2008 to 2010 and in 2020, which were significantly affected by the financial crisis and COVID-19. Therefore, the extracted common factor better reflects the change trend of the global economy. In most of the time, the variation of common factors fluctuates was relatively stable in the whole sample period, which had more significant fluctuation during the financial crisis and epidemic. Under the joint influence of stock index, oil supply and demand, the crude oil and exchange rate markets may also be more unstable.

Table 2 Descriptive statistics of oil and exchange rate return

	Mean	Max.	Min.	SD	Skew.	Kurt.	Jarque-Bera
CNY	-0.004	1.810	-2.031	0.128	-0.426	27.941	178021.400***
	-0.005	2.284	-1.767	0.305	0.097	2.236	1146.700***
EUR	-0.004	4.736	-4.204	0.602	0.040	3.100	2188.842***
	-0.005	4.576	-4.269	0.747	-0.050	1.512	522.240***
GBP	0.003	8.312	-4.474	0.594	0.497	10.480	25243.100***
	0.005	4.649	-3.776	0.773	-0.032	1.579	568.440***
JPY	0.000	3.710	-4.610	0.616	-0.261	4.040	3777.227***
	0.000	3.963	-6.241	0.646	-0.270	5.356	6600.600***
INR	0.009	3.251	-3.063	0.378	0.277	7.126	11637.190***
	0.011	2.916	-3.466	0.509	-0.085	1.957	877.990***
ZAR	0.015	9.807	-8.523	1.0507	0.330	4.747	5231.493***
	0.020	9.328	-10.199	1.051	0.339	5.081	5985.200***
USDX	0.000	2.495	-3.252	0.490	-0.079	1.761	711.502***
	-0.003	6.987	-5.288	0.764	0.032	3.991	3627.100***
BRL	0.0194	9.677	-11.778	1.005	0.166	11.284	29027.280***
	0.024	9.144	-11.555	1.005	-0.042	10.413	24699.000***
CAD	-0.002	3.419	-4.007	0.548	0.168	3.259	2443.361***
	-0.003	4.524	-6.344	0.672	-0.287	4.761	5237.500***
DZD	-0.012	5.602	-6.811	0.643	-0.928	37.143	266863.300***
	-0.016	6.119	-6.061	0.671	-0.344	5.807	7788.400***
NGN	0.024	26.904	-7.710	0.703	13.511	472.793	50542830.000***
	0.024	26.808	-7.612	0.706	13.505	464.786	1146.700***
NOK	0.001	6.350	-6.458	0.756	0.142	5.209	6197.673***
	0.002	8.339	-6.518	0.825	0.163	8.123	15051.000***
RUB	0.018	14.268	-15.523	0.774	0.476	63.075	906613.200***
	0.022	13.498	-14.822	0.790	0.328	46.407	490735.000***
MXN	0.013	8.114	-5.960	0.695	0.753	11.844	32470.530***
	0.014	8.227	-5.591	0.696	0.769	11.186	29041.000***
WTI	0.011	23.745	-48.080	2.623	-1.356	30.031	207141.200***
	0.032	58.985	-96.129	4.912	-1.306	38.260	335042.000***
Brent	0.013	15.448	-30.855	2.237	-0.629	12.196	34243.380***
	0.037	27.675	-51.841	3.966	-0.506	10.192	1146.700***

Note: *** denote significance at the 1% level.

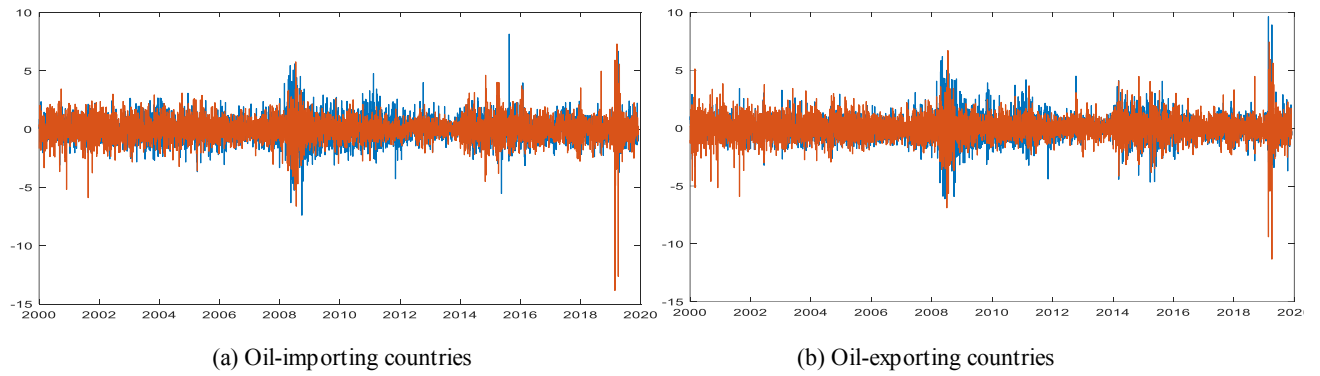
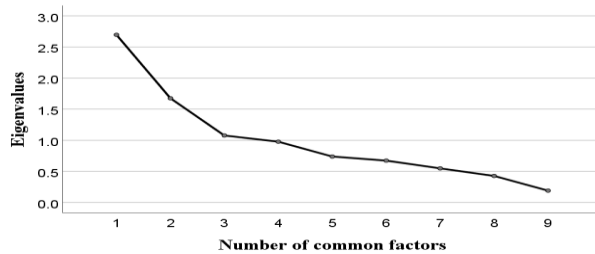


Figure 2 Dynamic variation characteristics of common factors

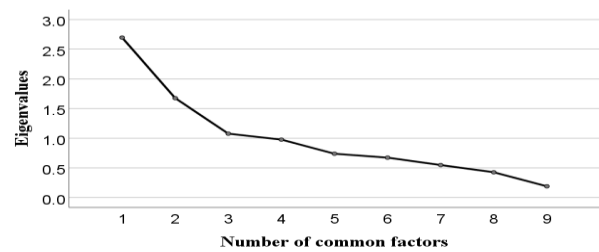
Table 3 Autocorrelation and conditional heteroscedasticity tests for daily returns.

	Q(12)	Q ² (12)	ARCH(12)		Q(12)	Q ² (12)	ARCH(12)
CNY	103.720***	220.520***	162.017***	BRL	46.942***	3010.600***	1199.059***
	59.046***	558.610***	189.140***		65.344***	2671.200***	1052.700***
EUR	24.339**	625.100***	344.356***	CAD	36.003***	4334.700***	1162.439***
	123.290***	547.270***	247.340***		49.359***	862.790***	287.600***
GBP	39.829***	563.070***	311.139***	DZD	168.630***	992.770***	695.574***
	73.169***	482.720***	207.460***		21.455*	1503.800***	566.030***
JPY	11.581	378.710***	239.852***	NGN	51.394***	34.115***	33.436***
	16.635	823.640***	307.280***		59.046***	33.882***	189.140***
INR	69.426***	2258.000***	803.131***	NOK	11.707	1102.500***	490.434***
	55.332***	826.530***	349.600***		41.560***	1123.700***	506.300***
ZAR	20.072*	1377.000***	657.387***	RUB	118.430***	2741.600***	1808.544***
	13.028	1448.100***	742.280***		84.936***	2594.000***	1636.000***
USDX	8.003	768.050***	657.387***	MXN	24.268*	3488.500***	1375.312***
	92.181***	335.220***	161.680***		29.616***	3366.100***	1299.100***
WTI	38.118***	991.070***	537.136***	Brent	25.591***	1017.300***	536.196***
	67.517***	1301.700***	723.770***		59.046***	1128.700***	189.140***

Note: *** denote significance at the 1% level. Q and Q² denote the Ljung-Box statistics for returns and squared returns, respectively. ARCH denotes the Lagrange Multiplier test for autoregressive conditional heteroscedasticity.



(a) Scree plot of oil-importing countries



(b) Scree plot of oil-exporting countries

Figure 1 Scree plots

3.3 Marginal distribution estimation

We then adopt the ARMA-GARCH model to better

fit the autocorrelation and heteroscedasticity of

respective idiosyncratic factors. Table 4 only presents the parameter estimation from the ARMA-GARCH model for the idiosyncratic factors based on the two-factor model. The empirical results such as the AIC values show that the ARMA-GARCH model based on the three-factor model are all inferior to the two-factor model for each time series. Therefore, this paper constructs a copula model based on the idiosyncratic factors extracted from the two-factor model. According to the Q statistic, the ZAR idiosyncratic factor series were fitted with AR (0)-GARCH (1,1) model and the other series were fitted with AR (1)-GARCH(1,1) model.

3.4 Time varying factor copula model estimation

This paper adopts the time-varying factor copula model conditional on the two common factors to analyze the dynamic dependence between the foreign exchange markets and the two major crude oil futures markets. Table 5 reports Kendall coefficient and AIC value of the Copula-GARCH model and the two-

factor copula model, respectively. It shows that the time-varying t copula is the best time-varying copula model to fit exchange rate and crude oil future prices of most oil-trading countries in the sample period. On the whole, the two-factor copula model is better than the Copula-GARCH model according to the AIC values from table 5.

Furthermore, it can also be seen from the graphic features that the two-factor copula model is optimal. In addition, the results of the Copula-GARCH model, the two-factor copula model and the empirical distribution model, namely the dynamic Kendall coefficient, are showed in the figure 3. It can also be seen that the two-factor copula model is closer to the result of empirical distribution fitting. Therefore, the dynamic dependence of crude oil and exchange rate based on the two-factor copula model is closer to the reality. The results are given here for only two typical oil-importing and oil-exporting countries, China and Brazil, with WTI crude oil futures prices.

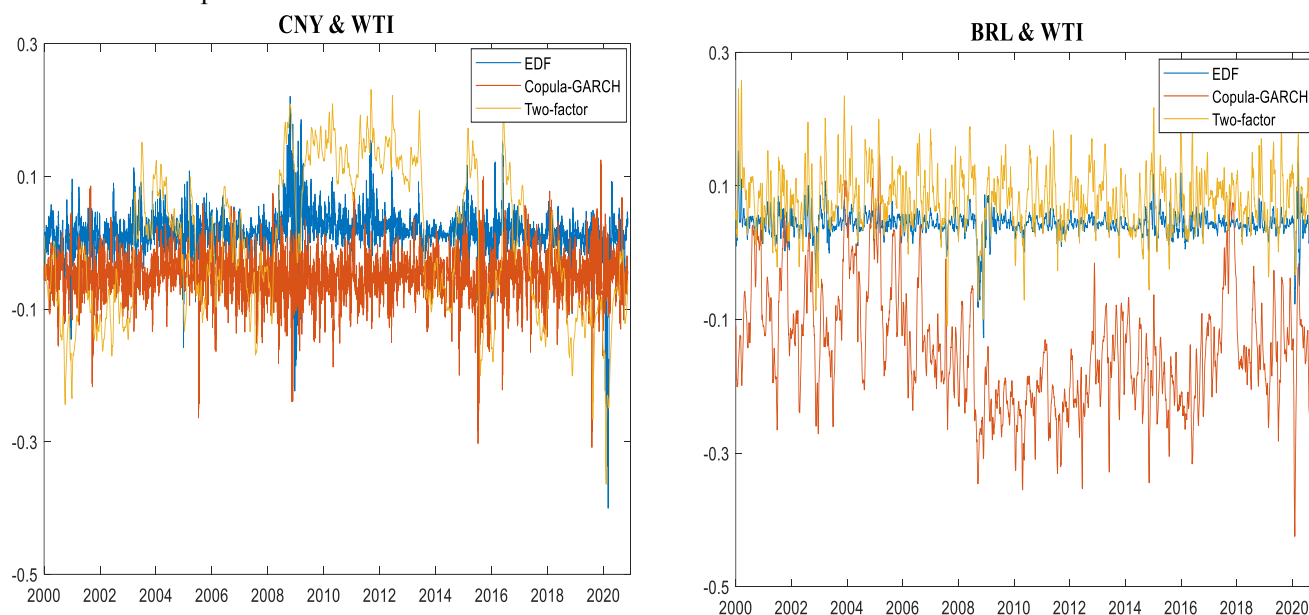


Figure 3 Dynamic Kendall coefficients of three model for typical countries

It is found that the Kendall dependence, albeit weak in general, is larger for oil exporters than the one for oil importers. This finding is similar to the overall sample of Liu et al. (2020). The positive dependence between crude oil returns and oil importers' exchange rates indicates that the rise or fall in WTI returns is linked with the depreciation or appreciation of the currencies against the USD. The higher oil prices transfer wealth from oil-importing countries to oil-exporting countries, causing the devaluation of the currencies of oil importing countries. The dependence between oil returns and exchange rates in the oil exporters is negative, indicating that currencies will appreciate against the USD because of their increasing wealth and purchasing power relatively to oil importers with the rise of oil price.

Among the sample countries, the Kendall dependence in absolute value of the main oil exporters' exchange rate changes with oil returns (CAD-OIL, NOK-OIL and RUB-OIL) is relatively large. Obviously, oil price significantly affects oil exporters' trade income and their exchange rates. However, conditional on the common factors, the dependence of CAD-OIL and NGN-OIL is enhanced, while that of NOK-OIL and RUB-OIL is weakened. It indicates that common factors have a great influence on the dependence of Canada and Nigeria on crude oil, and the high oil price is good for their economy.

It can be seen that stock price index and consumer confidence index play an important role in determining the dependent structure of foreign exchange and crude oil futures market. When these common factors change, the returns of these markets will be affected by different degrees, and this effect is related to the magnitude of their correlation with the common factors. Therefore, it is necessary to

accurately grasp the common factors to analyze the dynamic dependence structure of foreign exchange and crude oil market of oil-trading countries.

3.5 Analysis of dynamic dependence

Then, from the comparison of the results between factor copula and Copula-GARCH models, this paper analyzes the change characteristics in the correlation degree between exchange rates and oil prices.

3.5.1 Dependence in oil importers

Figure 4 depicts the dynamic Kendall dependence of oil-exchange rate pairs in oil importers along with their constant dependence considering common factors. Oil markets have been increasingly "financialization" since 2001, often attributing the global meltdown to wider phenomenon of financialization. As a financial asset, crude oil can immediately reflect the price information of other assets (Fratzscher et al., 2014). The dynamic dependence between oil returns and oil importers' exchange rates alternates positive and negative values over time. There are different variation characteristics in the dynamic dependence: the INR-OIL shows a positive dependence over the entire sample, with dynamic dependence fluctuating around 0.3. The dependence of EUR-OIL and GBP-OIL fluctuated slightly in all sample periods except the financial crisis period, suggesting that in addition to the strong influence of common factors, their own factors are also crucial. The dependence of JPY-OIL and USDX-OIL is always negative within the sample, and the rise and fall of oil price is always related to the appreciation or depreciation of currency. The exchange rate of the US dollar is in the opposite to oil price, which increased significantly and became more pronounced after the 2008 financial crisis with the financialization of the oil market. However, the exchange rates of other oil-importing countries and economies such as the UK, India and South Africa do not show a continuous negative dynamic correlation

with crude oil prices, which mainly depends on the oil demand and trade situation of specific countries.

The Kendall dependence of the exchange rates and crude oil prices based on Copula-GARCH model are the same as the results of Liu et al. (2020). The dependence between JPY and crude oil prices alternates positive and negative in the whole sample period. The dependence of the CNY-OIL pair fluctuates slightly below the zero line, and its volatility for CNY-OIL are the smallest among the sample pairs. Therefore, the appreciation effect in higher oil prices on the RMB is smaller than the depreciation effect of higher oil prices on the JPY due to the RMB basket pegged exchange rate system and government controls on energy prices. Similarly, the fluctuation between CNY and oil price is large under the common factors. Only after the “8.11” exchange rate reform in 2015, the correlation was enhanced. Therefore, the common factors have less influence on the dependence structure of exchange rates and oil prices in these countries, and their own characteristic factors play an important role in this process. As an important oil importer, China’s demand for crude oil will have a significant impact on the stability of global oil market price.

3.5.2 Dependence in oil exporters

Figure 5 depicts the dynamic Kendall of exchange rates of oil-exchange rate pair in oil exporters conditional on common factors. It can be divided into two categories according to the dependence fluctuation characteristics. The first type, including the BRL-OIL, NOK-OIL and MXN-OIL pairs, shows a relatively stable and small dependence. The second type, including the remaining oil exporters, exhibits larger dependence in absolute values and greater variations. In particular, the dynamic dependence for Canada is positive but irregular at some points in time.

This finding suggests that rising oil prices do not always contribute to the appreciation of the CAD.

There is a significant volatility in the market dependency based on the factor copula model during 2008-2010 and in 2020. It explains that common factors affecting global economic development such as financial crisis and COVID-19 played an important role in the interdependence structure of markets. Except for the DZD-OIL and NGN-OIL which have unexpected synergistic movements in crisis, all others are basically negative. The Kendall’s τ coefficient for these markets increases significantly during the crisis period but gradually decreases as the crisis effects subside. As a large oil exporter, Russia experienced little change in the dependence between the exchange rate and oil prices during crisis period. Russia has taken advantage of the economic crisis to quickly recover its national strength, which economic development has suffered less. Therefore, during the financial crisis, the pattern of dependence between exchange rates and oil prices in oil exporters is mainly influenced by common factors such as risk shocks, and their own idiosyncratic factors contribution is relatively stable throughout the sample period.

In summary, the dependence of oil returns and oil-trading exchange rates shows a negative dependence in most periods. In contrast to the Copula-GARCH model, the correlation between the two markets under the common factors both show a significant decrease, and major economic shock events such as financial crisis are an important cause for the change in dependence volatility of markets. Thus, the idiosyncratic factors of the major oil-trading countries, represented by China, can cause significant changes in the volatility between exchange rate and oil price.

Table 4 Parameter estimation of ARMA-GARCH

	ϕ_0	ϕ_1	ω	α	β	v
CNY	-0.004 (0.004)	0.069 (0.013)	0.001 (0.000)	0.036 (0.005)	0.956 (0.006)	9.578 (1.197)
EUR	0.003 (0.009)	-0.145 (0.014)	0.010 (0.003)	0.052 (0.008)	0.931 (0.013)	11.918 (1.791)
GBP	0.010 (0.010)	0.086 (0.014)	0.005 (0.002)	0.032 (0.005)	0.959 (0.007)	13.400 (2.078)
JPY	0.012 (0.010)	-0.042 (0.015)	0.006 (0.002)	0.055 (0.008)	0.929 (0.011)	7.245 (0.705)
INR	0.012 (0.007)	0.084 (0.014)	0.005 (0.001)	0.047 (0.007)	0.933 (0.011)	11.559 (1.676)
ZAR	-0.005 (0.005)	—	0.022 (0.006)	0.068 (0.011)	0.913 (0.015)	7.660 (0.732)
USDX	0.007 (0.008)	-0.106 (0.014)	0.007 (0.002)	0.039 (0.006)	0.950 (0.007)	7.386 (0.710)
BRL	0.011 (0.014)	-0.016 (0.009)	0.024 (0.006)	0.103 (0.017)	0.872 (0.021)	6.594 (0.608)
CAD	0.002 (0.005)	-0.061 (0.014)	0.007 (0.002)	0.050 (0.009)	0.934 (0.013)	7.375 (0.697)
DZD	-0.001 (0.007)	0.013 (0.041)	0.004 (0.001)	0.053 (0.009)	0.937 (0.010)	8.449 (1.015)
NGN	0.000 (0.001)	-0.094 (0.014)	0.001 (0.000)	0.260 (0.023)	0.740 (0.027)	3.001 (0.085)
NOK	0.011 (0.025)	-0.059 (0.014)	0.015 (0.006)	0.072 (0.019)	0.904 (0.027)	8.533 (1.073)
RUB	0.012 (0.007)	-0.006 (0.064)	0.005 (0.001)	0.081 (0.012)	0.908 (0.013)	7.334 (0.734)
MXN	-0.011 (0.018)	0.004 (0.051)	0.005 (0.002)	0.094 (0.017)	0.896 (0.018)	7.394 (0.774)
WTI	0.153 (0.040)	-0.039 (0.014)	0.325 (0.072)	0.074 (0.009)	0.910 (0.010)	5.448 (0.419)
Brent	0.111 (0.052)	-0.076 (0.014)	0.162 (0.048)	0.077 (0.011)	0.915 (0.012)	5.974 (0.489)

Note: The values in parentheses denote the standard errors (SE).

Table 5 Comparison of Copula-GARCH and Two-factor models

Copula-GARCH model		Two-factor copula model		
Model	Kendall	AIC	Kendall	AIC
Panel 1: Exchange rate-WTI				
CNY-WTI	-0.036	-62.258	0.011	-176.903
EUR-WTI	-0.066	-140.11	0.024	-72.748
GBP-WTI	-0.094	-201.655	0.129	-264.46
JPY-WTI	0.01	-127.041	-0.242	-1133.3
INR-WTI	-0.029	-32.531	0.236	-842.88
ZAR-WTI	-0.117	-320.095	0.095	-224.727
USDX-WTI	-0.108	-300.123	0.056	-111.725
BRL-WTI	-0.109	-289.389	0.05	-102.913
CAD-WTI	-0.215	-817.4	0.348	-1939.5
DZD-WTI	-0.077	-178.663	-0.069	-573.459
NGN-WTI	-0.01	-17.863	0.136	-632.674
NOK-WTI	-0.149	-444.214	0.056	-106.164
RUB-WTI	-0.132	-410.775	0.083	-300.759
MXN-WTI	-0.024	-33.459	-0.048	-72.053
Panel2: Exchange rate-Brent				
CNY-Brent	-0.03	-45.76	0.006	-110.192
EUR-Brent	-0.063	-19.279	0.014	-37.238
GBP-Brent	-0.091	-194.035	0.112	-301.756
JPY-Brent	0.017	-128.334	-0.246	-608.996
INR-Brent	-0.06	-163.396	0.224	-750.27
ZAR-Brent	-0.106	-281.554	0.114	-248.937
USDX-	-0.102	-272.35	0.044	-78.4
Brent				
BRL-Brent	-0.103	-224.636	0.051	-96.537
CAD-Brent	-0.207	-732.936	0.347	-1943.7
DZD-Brent	-0.076	-175.216	-0.091	-485.298
NGN-Brent	-0.006	-25.653	0.139	-654.972
NOK-Brent	-0.14	-382.998	0.052	-102.782
RUB-Brent	-0.127	-38.904	0.08	-298.88
MXN-Brent	-0.022	-35.883	-0.048	-79.489

Note: The values in bold denote the optimal copula model with the smallest AIC value.

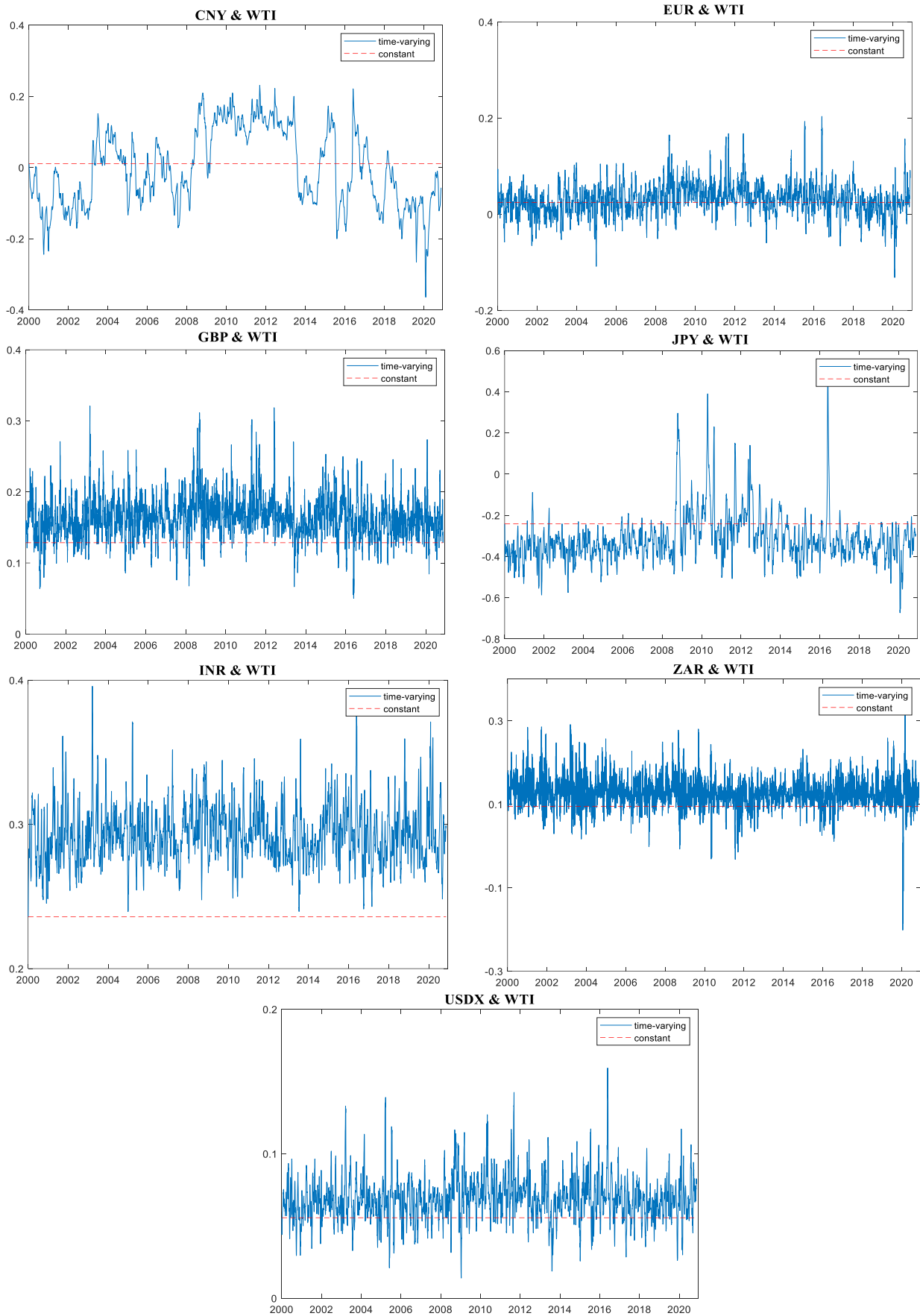


Figure 4 Dynamic dependences between oil returns and exchange rates in oil importers

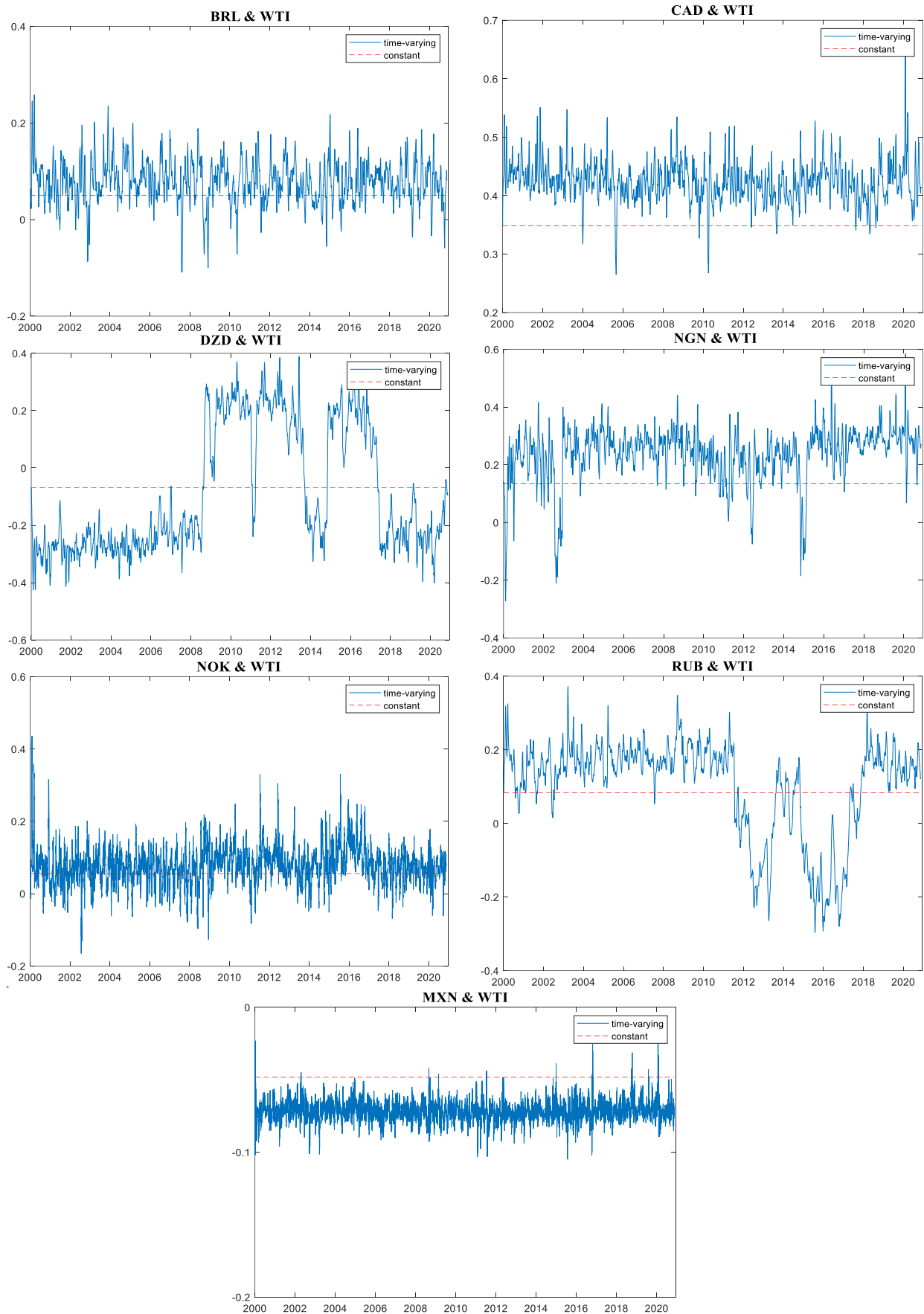


Figure 5 Dynamic dependences between oil returns and exchange rates in oil exporters

3.6 Analysis of risk spillover

We calculate the $\% \Delta \text{CoVaR}$ of all exchange rates based on the optimal time-varying factor copulas at the 95% confidence level ($\alpha = \beta = 0.05$) to analyze the risk dependence of exchange rates when the oil price fluctuates extremely. Table 6 shows the comparison of the average in $\% \Delta \text{CoVaR}$ between the exchange rate markets and crude oil markets, conditional on the common factors. On the whole, the exchange rate market has a low marginal risk premium to the crude oil market, while the oil market has a high risk premium to the exchange market, indicating that the oil market has significant fluctuation. The markets have been at a low level for most of the time, but there have been extreme fluctuations during the economic crashes (2007 to 2008, and 2015 to 2016).

Firstly, this result indicates that the higher risks and risk spillovers from oil market to the exchange rate,

though crude oil market has undergone the sharp drops and low price levels during the period from 2013 to 2017. The crude oil returns have a great impact on the risk spillover of the JPY, the INR, the CAD and the NGN. Accordingly, it is clear that they have a higher Kendall dependence and a higher risk spillover conditional on the common factors. The risk premium of WTI to CAD and NGN reached 407.752% and 963.133% respectively. It indicates that the governments should pay more attention to the risk spillover effects of the crude oil market on corresponding exchange rates and. Secondly, from the exchange rate market to the oil market, and there is almost no risk spillover effect between these two markets in the long run. The Canadian exchange rate market has a relatively large risk spillover to the crude oil market, so it is a key risk monitor.

Table 6 $\% \Delta \text{CoVaR}$ between exchange rate market and crude oil market ($\alpha=5\%$)

		Relative magnitude of risk spillover from exchange rate markets to crude oil markets		Relative magnitude of risk spillover from crude oil markets to exchange rate markets	
		WTI	Brent	WTI	Brent
Oil-importing countries	CNY	0.103%	0.206%	-41.107%	14.314%
	EUR	0.976%	0.487%	25.981%	9.783%
	GBP	5.123%	4.969%	146.462%	108.772%
	JPY	-7.246%	-8.513%	-331.318%	-
					290.366%
	INR	5.965%	6.485%	376.709%	308.864%
Oil-exporting countries	ZAR	5.208%	7.235%	87.599%	89.676%
	USD	2.121%	2.143%	63.091%	47.112%
	BRL	2.795%	3.193%	62.474%	52.790%
	CAD	10.111%	11.233%	407.752%	344.033%
	DZD	-1.363%	-2.299%	-132.248%	-
					122.832%
	NGN	3.026%	2.986%	963.133%	815.145%
	NOK	2.432%	2.602%	67.167%	55.305%
	RUB	2.182%	2.567%	132.785%	116.097%
	MXN	-1.822%	-1.845%	-82.683%	-62.630%

Note: The values in bold denote the market with high levels of risk spillover.

4 Conclusion

We apply the factor copula modeling methods in order to study the dynamic dependence between the foreign exchange and oil markets as well as risk

spillover more accurately. Through the empirical analysis, the following conclusions are obtained in this paper.

First, from the statistical indicators and the

dynamic characteristics among the return series, the two-factor copula model is superior to the three-factor copula and the Copula-GARCH model. We capture the common factors by factor analysis, and the selected common factors could well describe macro-economy changes.

Second, the common factors fluctuated greatly from 2008 to 2010 and in 2020, and the dependence of oil-exchange rate pairs also fluctuated greatly during this period. It can be seen from the empirical results that the correlation between the two markets under the common factors both show a significant decrease in contrast to the Copula-GARCH model.

Third, based on the factor copula model, the overall dependence of oil-exchange rate is larger for the oil exporters than it for the oil importers. In addition, there is a positive correlation between crude oil returns and oil-importing countries' exchange rate, and a negative correlation with oil-exporting countries.

Fourth, the risk spillover between crude oil market and exchange rate market is complex and dynamic, with higher Kendall dependence and risk spillover between the two markets under the influence of common factors. On the whole, the risk spillover from oil market to exchange rate market is higher than that from exchange rate to oil market, indicating that the volatility of oil market is more significant.

Thus, this paper argues that market investors and financial regulators need to accurately identify cross-risk spillover between crude oil and exchange rate markets by focusing on the dynamic characteristics of the common factors. Policymakers and exchange rate regulators should closely monitor the movement of crude oil prices and judge the volatility of exchange rate to oil prices to guard against risk spillovers. Meanwhile, they could set the target zones for exchange rates to avoid market sentiment changes

caused by small fluctuations of exchange rate.

This paper identifies the common factors affecting the foreign exchange and crude oil markets in order to more accurately portray the dynamic dependence. Therefore, the relevant researchers can also explore the tail extreme dynamic interdependence model under this framework and apply the factor copula model to analyze dependence structure and risk spillover among other financial markets.

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煤炭去产能过程中“央地”政策协同困境及影响因素：基于两阶段演化博弈方法

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摘要：碳达峰碳中和加快世界能源低碳化发展步伐，包括煤炭在内的化石能源消费将收到严格控制，我国煤炭工业发展必将受到重大影响，有效化解煤炭产能过剩问题已成为中国能源系统转型以及经济可持续发展的关键。为此，本研究立足于中国煤炭行业管理体制，采用演化博弈论方法构建包含政策制定和政策执行两阶段的央地政府的煤炭产能过剩治理模型，来探讨去产能过程中央地政策协同困境及影响因素。模型分析表明：首先，政策制定阶段，中央政府策略演化仅与其此阶段净收益相关，地方政策策略演化仅与其此阶段净收益相关；其次，政策执行阶段，中央政府策略演化和地方政府策略演化相互影响；最后，政策制定阶段中央政府策略选择对两阶段中央政府和地方政府演化策略产生影响。

关键词：去产能；政策协同；两阶段演化博弈

"Central-local" policy coordination dilemma and influencing factors in process of coal overcapacity: Based on a two-stage evolutionary game method

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Abstract: Carbon peaking and carbon neutralization will accelerate the development of low-carbon energy in the world. The consumption of fossil energy including coal will be strictly controlled. The development of my country's coal industry will be greatly affected. Effectively resolving the problem of coal overcapacity has become China's energy source. System transformation and the key to sustainable economic development. Therefore, based on the management system of China's coal industry, this study adopts the method of evolutionary game theory to construct a coal overcapacity governance model of the central and local governments that includes two stages of policy formulation and policy implementation, to explore the dilemma and impact of central and local policy coordination in the process of overcapacity reduction. factor. The model analysis shows that: first, in the policy formulation stage, the evolution of the central government strategy is only related to its net income at this stage, and the evolution of local policy strategies is only related to its net income at this stage; secondly, in the policy implementation stage, the evolution of the central government strategy and the evolution of local government strategies interact with each other. Finally, the strategy choice of the central government in the policy-making stage has an impact on the evolution strategy of the central government and the local government in the two stages.

Key words: Overcapacity Reduction; Policy Coordination; Two-stage evolutionary game

What really influences the development of renewable energy? A systematic review and meta-analysis

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Abstract: Promoting renewable energy is one key strategy to increase energy security and mitigate global warming. What really influences the development of renewable energy has aroused public attention worldwide. Numerous studies have identified and evaluated the critical influence factors (CIFs) for renewable energy development (RED); however, there is no consensus among the previous studies on these CIFs and their importance level. Given that, this study, for the first time, conducts a systematic review and meta-analysis of these CIFs. With evidence from 33119 observations in 67 studies between 2010 and 2022, the systematic review identifies 44 CIFs. To further provide a synthesis of previous studies, a meta-analysis approach is used. Results demonstrate that: (i) 27 CIFs with statistical significance and their importance level are identified; (ii) the top three driving factors are industrial infrastructure investment, R&D and financial development, and the top three inhibiting factors are fossil-based energy consumption structure, policy uncertainty and population life; (iii) the publication year, country's economy and the RED links play a moderating role of the CIFs' influence mechanism. This study not only contributes to the existing RED knowledge body but also provides references to policy makers and practitioners in formulating policies and good practices to promote RED.

Key words: Renewable energy development; Influence factors; Systematic literature review; Meta-analysis;

中国电力资源空间错配：测度方法、时空格局及环境后果

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摘要：尽管资源错配与生产率的关系是近年来的研究热点，但鲜有文献考察资源空间错配及其对区域环境质量的影响。基于中国电力市场地理分割和价格分割的特征事实，本文构建了一种既能反映电力资源空间错配程度又能反映错配方向的测算模型，并测算了中国电力资源空间错配的程度、方向和趋势，分析了电力资源错配的时空格局演化特征。在此基础上，探讨了电力资源空间错配对区域碳排放的影响效应与传导机制，并利用 1988-2017 年中国 29 个省区的面板数据进行实证检验。结果表明：中国电力资源的空间错配水平整体较高，且呈现出省区配置过度与配置不足并存、东西部地区错配程度不断上升而中部地区逐渐下降等时空分异特征；电力资源空间错配对区域碳排放具有显著的负面影响；进一步，电力资源空间错配主要通过影响区域产业结构进而影响区域碳排放。研究结论对中国实现高质量发展目标具有重要的启示作用。

关键词：电力资源；空间错配；时空分异；碳排放

Spatial misallocation of power resources in China: Measurement methods, spatiotemporal patterns, and environmental consequences

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Abstract The relationship between resource misallocation and productivity has become a hot topic in recent years, but few studies examined the impact of spatial misallocation of electric power resources (SMEPRs) on carbon emissions. Here, we constructed a calculation model of SMEPRs that can measure both the misallocation degree and direction and uncovered the spatiotemporal evolvement mechanism of SMEPRs. On this basis, we explored the impact of SMEPRs on regional carbon emissions using panel data from 29 provinces in China from 1988-2017. The results demonstrate that the high level of SMEPRs in China shows complex spatiotemporal characteristics and significantly affects the regional carbon emissions. Specifically speaking: first, SMEPRs presents the characteristics of the coexistence of excessive and insufficient allocation among provinces and regions, the increasing extent of misallocation in the eastern and western regions, and the gradual decline in the central region; second, SMEPRs has a strong negative effect on the regional carbon emissions by affecting regional industrial structures, which indicates that SMEPRs is an important factor restricting the high-quality development of regional economies. The research observations offer fresh insights to upgrading the high-quality and green development of China's power sector and promoting regional economic transformation and ecological sustainability.

Keywords Electric power resources; Spatial misallocation; spatiotemporal differentiation; Carbon emissions

城市网约车电动化驱动机制建模仿真研究

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摘要：实现公共交通领域电动化是实现碳达峰的重要途径，网约车兼具出租车与私家车特点，实现网约车电动化可以为实现私家车电动化提供参考。为分析城市网约车电动化进程以及驱动机制分析，建立基于Agent的城市网约车电动化驱动机制仿真模型，从网约车主购车角度出发，综合分析车主购车的自身使用效用与运营使用效用，设置基准情境、兼职情境、宣传情境、财税政策情境与非财税政策情境共五种情境进行敏感性分析，结果显示在2035年左右网约车实现全电动化；购置补贴退坡政策对于网约车电动化影响不明显；限制性政策措施会缩短网约车电动化进程；充电基础设施建设补贴是降低用户“里程焦虑”以及增强用户对于新能源汽车采用意愿的有效途径。基于上述结论提出城市采取购置补贴退坡以及充电基础设施建设补贴政策有助于加快网约车电动化进程，限制性政策措施是决定网约车电动规划进程的重要因素。

关键词：网约车电动化，多 Agent 建模，购买决策，里程焦虑，敏感性分析

Research on Modeling and Simulation of driving mechanism of electric car hailing in urban network

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Abstract: Realizing the electrification of public transport is an important way to achieve carbon peak. Online car Hailing has the characteristics of both taxis and private cars. Realizing the electrification of online car Hailing can provide a reference for realizing the electrification of private cars. In order to analyze the process and driving mechanism of urban online car Hailing electrification, a simulation model of urban online car Hailing electrification driving mechanism based on agent is established. From the perspective of online car Hailing owners, the self-use utility and operation use utility of car owners are comprehensively analyzed, and the benchmark situation, part-time situation, publicity situation. The sensitivity analysis of fiscal and tax policy scenarios and non-fiscal and tax policy scenarios shows that online car Hailing will be fully motorized around 2035; The purchase subsidy retrogression policy has no obvious impact on the electrification of online car Hailing; Restrictive policies and measures will shorten the electrification process of online car Hailing; Charging infrastructure construction subsidy is an effective way to reduce users' "mileage anxiety" and enhance users' willingness to adopt new energy vehicles. Based on the above conclusions, it is proposed that the decline of purchase subsidies and the subsidy policy for charging infrastructure construction in cities will help to speed up the process of online car Hailing electrification, and restrictive policies and measures are important factors determining the process of online car Hailing electrification planning.

Key Words: Electrification of online car Hailing, Multi-agent modeling, Purchase decision, Mileage anxiety, sensitivity analysis

能源需求预测研究知识图谱——基于 VOSviewer 的计量分析

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摘要：能源需求预测在促进能源转型、经济高质量发展以及保障国家安全中起着基础性作用。近年来，随着全球气候治理的推进，能源需求预测研究文献越来越受到关注。为增强对能源需求预测领域的关键研究、新兴趋势和新发展的见解和洞察，本文基于 2000-2020 年 Web of Science 收录的 28500 份研究文献，采用描述性统计分析、共被引分析、合作网络分析和关键词共现分析，全面概述了能源需求预测研究领域最关键的国家的、机构、期刊、作者、文献、合作网络关系和研究趋势，系统地构建了该领域的知识谱图。在此基础上，进一步构建了石油、电力等 10 类能源需求预测研究的知识图谱，分析了各知识图谱间的关联关系，揭示了各类能源需求预测的研究之间的协同性和异质性。

关键词：能源需求预测；文献计量分析；知识谱图；VOSviewer

Knowledge Mapping for Energy Demand Forecasting Studies—— Bibliometric Analysis Based on VOSviewer

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Abstract: Energy demand forecasting plays a fundamental role in promoting energy transition, high-quality economic development, and ensuring national security. In recent years, with the advancement of global climate governance, the research literature on energy demand forecasting has attracted more and more attention. In order to enhance the insights and insights into the key research, emerging trends and new developments in the field of energy demand forecasting, based on the 28,500 research literatures included in the Web of Science from 2000 to 2020, this paper uses descriptive statistical analysis, co-citation analysis, cooperative network analysis and keyword co-occurrence analysis to comprehensively summarize the most critical countries, institutions, journals, authors, literature, cooperative network relations and research trends in the field of energy demand forecasting research, and systematically constructs the knowledge spectrum in this field. On this basis, the knowledge graph of 10 types of energy demand forecasting research such as petroleum and electricity is further constructed, the correlation relationship between each knowledge graph is analyzed, and the synergy and heterogeneity between the research on various energy demand forecasts are revealed.

Keywords: energy demand forecasting; bibliometric analysis; knowledge mapping; VOSviewer

基于灰色模型的可再生能源发电趋势研究

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摘要：随着工业化进程进一步加深，我国对能源的需求也随之上升，然而传统能源的过度使用带来的是能源短缺和全球变暖等问题。因此，新能源的大规模开发和使用是必然趋势，也将是我国实现碳中和的主力军。在对可再生能源进行开发的过程中，为避免大面积“弃风弃光”现象，使可再生能源更好地消纳，深入研究可再生能源现状及其未来发电趋势十分关键。本文首先对我国能源现状进行分析，后通过 GM(1,1) 模型对我国可再生能源装机容量及其发电量进行预测讨论。根据预测得出，我国的可再生能源在未来几年内发展趋势良好，发展空间大。最后综合电力预测数据和结论提出策略建议，希望可以为可再生能源的发展提供一些帮助和参考。

关键词：可再生能源，发展趋势，前景分析，灰色模型

Renewable Energy Generation Trends Based on Grey Models

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Abstract: With further industrialisation, China's demand for energy has risen, however, the overuse of traditional energy sources has brought about problems such as energy shortages and global warming. Therefore, the development and use of new energy sources on a large scale is an inevitable trend, and will be the main force in achieving carbon neutrality in China. In the process of exploring renewable energy, it is crucial to study the current situation of renewable energy and its future power generation trend in order to avoid the phenomenon of "abandoned wind and light" and to make renewable energy better consumed. This paper first analyses the current energy situation in China and then discusses the forecast of China's installed renewable energy capacity and its power generation through the GM(1,1) model. According to the forecast, it is concluded that China's renewable energy will have a good development trend in the next few years and there is much space for development. Finally, the electricity forecast data and conclusions are integrated to put forward strategic suggestions, which I hope can OFFER some help and reference for the development of renewable energy.

Key Words: renewable energy, development trend, prospect analysis, grey model

基于 DPSIR-TOPSIS 模型的矿业型“无废城市”建设评价 ——以徐州市为例

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摘要：基于 DPSIR-TOPSIS 模型和障碍度模型构建了矿业城市建设“无废城市”的评价体系和障碍因素，并分析了徐州市“无废城市”建设状况、障碍因素。结果表明，至 2020 年，徐州市“无废城市”建设基本成型，废物基本妥善处置，城市废物排放增加趋缓；“无废城市”建设的五个主要障碍指标包括地表水达到或优于Ⅲ类比例、工业固体废物产生强度、建筑业生产总值、人均 GDP、城市化水平，子系统障碍度的具体排序为：压力>驱动力>影响>状态>响应。结合研究结论提出徐州市进一步建设“无废城市”的策略建议，以期为提升矿业城市的“无废城市”建设水平提供思路。

关键词：矿业城市；“无废城市”建设；DPSIR-TOPSIS 模型；徐州市

Evaluation of “zero-waste city” construction in mining city based on DPSIR-TOPSIS model: A case study of xuzhou city

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Abstract: Based on DPSIR-TOPSIS model and obstacle degree model, this paper constructs the evaluation system and obstacle factors for the construction of “zero-waste city” in mining cities, and analyzes the construction status and obstacle factors of “zero-waste city” in Xuzhou. The results show that by 2020, the construction of “zero-waste city” in Xuzhou will be basically formed, the waste will be basically properly disposed of, and the increase of urban waste discharge will slow down; The five main obstacle indicators for the construction of “zero-waste city” include the proportion of surface water reaching or better than Class III, the generation intensity of industrial solid waste, the GDP of construction industry, per capita GDP and urbanization level. The specific order of subsystem obstacle degree is: pressure > driving force > impact > state > response. Combined with the research conclusions, this paper puts forward strategic suggestions for further building a “zero-waste city” in Xuzhou, in order to provide ideas for improving the construction level of “zero-waste city” in mining cities.

Key Words: Mining city; Zero-waste city construction; DPSIR-TOPSIS model; Xuzhou city

中国氢能产业政策效力演化与绩效研究

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摘要：发展氢能源等绿色能源技术，对中国未来能否实现双碳目标和高质量的可持续发展具有重要影响。近年，中央和地方政府加快颁布了相关政策以保障氢能产业的高速发展，对氢能政策进行量化研究可以为分析政策演化规律和评估政策绩效提供理论支撑。以 2000 年至 2020 年间中国各级政府颁布的 325 条氢能发展政策作为研究对象，从政策力度、政策目标和政策措施三个维度，对政策进行量化赋分，用定量描述的形式表现政策效力水平的演化规律，并运用岭回归模型分析政策在氢能产品进出口产生的绩效。研究发现：中国氢能政策演化主要集中于政策目标和政策措施两个方面，并且存在明显的阶段性特征；双碳目标的提出促使人才引进和项目拨款逐渐成为氢能发展主要的政策措施；政策绩效分析结果显示，中国氢能政策对不同时段内氢能产品进出口数据存在较明显的正向影响。更进一步，研究结果为中国未来氢能产业发展方向和碳减排工作提供了理论参考。

关键词：氢能产业；政策效力；演化规律；绩效评估

Research on the Policy Effectiveness and Performance of China Hydrogen Energy Industry

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Abstract: The development of green energy technologies such as hydrogen energy will decide the future achievement of China dual-carbon targets and high-quality sustainable development. The 325 hydrogen energy development policies promulgated by Chinese governments at various levels from 2000 to 2020 are the research objects in this article. These policies are rated on three dimensions: policy strength, policy goals, and policy measurements, which embody the evolutionary rules of policy efficacy in the form of a quantitative description. We also use the ridge regression method to look at the performance of hydrogen energy policies. The results show that the effectiveness of policy objectives and policy measures in China hydrogen energy policies is rapidly increasing, with clear stage characteristics; with China increasing emphasis on the development of hydrogen energy, the introduction of talents and project funding has become the main industry development basis; and performance analysis results show that China hydrogen energy policy has a relatively obvious positive impact on the import and export data of hydrogen energy. Furthermore, the findings give a theoretical foundation for China hydrogen energy industry's future expansion and efforts to reduce carbon emissions.

Key words: Hydrogen energy industry; Policy effectiveness; Evolutionary rules; Performance evaluation

博彩文化、制度环境与并购商誉

章砚

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摘要：本文以 2008-2019 年 A 股上市公司为研究对象，从非正式制度视角考察了博彩文化对微观企业并购的影响。研究发现，地区博彩文化越浓厚，管理层越容易过度自信，企业越倾向于高溢价并购，导致高并购商誉的产生；正式制度环境的改善能够显著弱化博彩文化对并购商誉的负面影响。异质性分析发现，当高管团队中海外背景高管、金融背景高管或研发背景高管所占比例较大时，高管团队特征会对博彩文化与并购商誉之间的关系产生推波助澜的作用。此外，由地区博彩文化推高的并购商誉会提高后续商誉减值规模、增加股价崩盘风险和降低企业全要素生产率，不利于企业的长远发展。本文从微观企业层面拓展了“文化与公司财务”研究，提供了正式制度可以在一定程度上弱化非正式制度的不利影响、高管团队特征会强化非正式制度对企业行为的影响的经验证据，为监管部门如何有效防范系统性风险提供决策参考。

关键词：博彩文化，并购商誉，制度环境，高管过度自信

Gambling Culture, Institutional Environment and M&A Goodwill

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Abstract: Employing a data set of A-share listed companies from 2008 to 2019, this study investigates the impact of gambling culture on the merge and acquisition (M&A) goodwill. Empirical evidences show that the stronger the gambling culture, the more overconfidence the management team are possessing, as proxied by a higher M&A premium. We further find that regional formal institutional environment can significantly weaken the negative impacts of gambling culture on M&A goodwill. Heterogeneity analysis found that with more executives with overseas background, financial background, or R&D background, the effect from regional gambling culture to M&A goodwill is stronger. In addition, the M&A goodwill promoted by regional gambling culture is followed with an increased scale of goodwill impairment in the future, which is also correlated with an increased risk of stock price crash which in turn will reduce enterprise value. This research expands the theoretical cognition of regional cultural and economic consequences from the micro-enterprise level and provided important policy implications at last.

Key Words: gambling culture, M&A goodwill, institutional environment, overconfidence

一、引言

党的十九大报告指出,中国经济已由高速增长阶段转向高质量发展阶段,正处于转变发展方式、优化经济结构、转换增长动力的攻坚期。并购重组作为资本市场实现资源配置的重要方式,是企业实现外延式增长的主要手段^[1],日益成为资本市场服务国家发展战略的重要工具^[2]。近年来,我国A股市场并购交易不断增加,产生的商誉也随之累积。CSMAR数据库显示,拥有商誉的上市公司已由

2007年的450家上升至2020年的2186家,A股上市公司商誉总额也从2007年360.00亿元攀升至2020年1.18万亿元。然而,这种由于非理性预期导致的高额商誉及其减值风险犹如“达摩克利斯之剑”,会成为企业经营的沉重负担^[3]、引发投资者过度反应^[2]、导致股价崩盘风险^[4],成为威胁资本市场稳定的不容忽视的风险因素,这与资本市场持之以恒“防范化解金融风险”的目标背道而驰。博彩文化体现了企业所在地在信息不完全时承担风险的基本态度和心理状态。

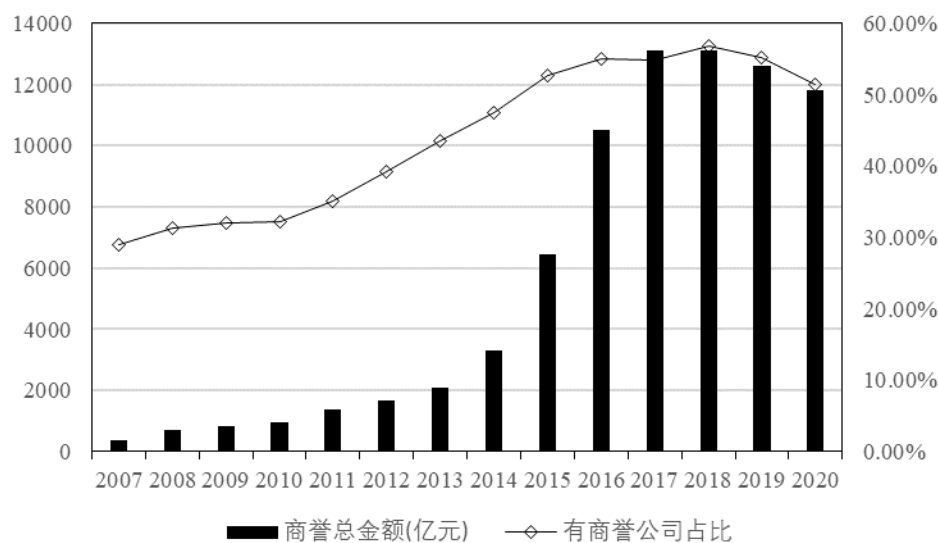


图1 2007-2020年A股商誉变动趋势

通常而言,博彩消费越高,投机氛围越浓厚,以非正式制度为代表的博彩文化折射出地区博彩文化对经济主体行为的重要影响^[5-6]。彩票行业自诞生以来建立了以销量为核心的绩效评价指标体系,追求销量最大化一直是彩票机构的行为目标^[7]。因此,彩票发行数量在一定程度上可以反映出地方博彩文化。总体来看,东部沿海及中部地区人均彩票发行量较低,而北部及西部地区人均彩票发行数量相对较高,这表明我国不同地区的人均彩票发行数量存在较大差异。我国地域广袤,迥异的地区博彩文化是否会对企业并购行为产生异质性影响,其中的作用机制又是什么,现有文献并未给出答案。

基于此,本文以2008-2019年A股非金融类上市公司为研究对象,探究博彩文化对企业并购商誉的影响。本文的增量贡献主要体现在以下三个方面:第一,从博彩文化这一非正式制度视角拓展了企业

并购商誉影响因素的研究边界。关于并购商誉影响因素的研究,现有文献大多集中于企业内部控制^[8]、审计师行为^[9]、管理层异质性^[1,4,10]等方面,鲜有文献从非正式制度视角探讨博彩文化对微观企业并购的影响。本文将企业并购商誉的影响因素拓展到地区博彩文化视角,丰富了“文化与公司财务”研究,深化了非正式制度影响经济主体行为决策的理论认知。第二,提供了正式制度可以在一定程度上弱化非正式制度不利影响的经验证据。本文通过实证分析发现,区域制度环境的改善可以有效缓解地区博彩文化对并购商誉的刺激作用,这说明培育良好的正式制度环境对于优化企业资源配置和风险管理水平具有重要意义,也从侧面证实了正式制度可以在一定程度上矫正非正式制度缺陷的论断^[11,12,13]。第三,揭示了人力资本在非正式制度影响企业行为中的重要作用。本文进一步探讨了高管团

队特征在地区风险偏好影响企业并购行为中所发挥的作用，发现当企业高管团队中海外背景高管、金融背景高管或研发背景高管所占比例较大时，高管团队特征会强化地区博彩文化对并购商誉的影

响。这揭示了人力资本在非正式制度环境中的重要作用，加深了对非正式制度影响微观企业行为的作用情境的理解。

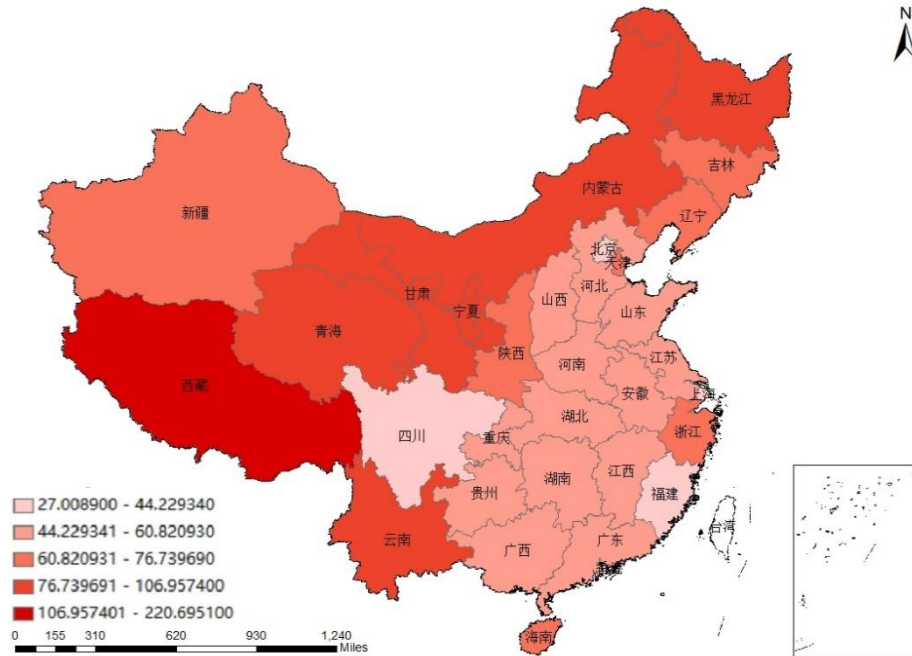


图2 我国人均彩票发行量区域分布

(图片来源: 本文绘制)

二、文献综述、理论分析与研究假设

1、文献综述

现有文献主要从内部因素与外部环境两个方面研究并购商誉的影响因素。从内部因素来看，管理层异质性、内部控制与会计方法选择均对并购商誉产生显著影响。首先，企业并购溢价决策由于管理者过度自信而产生了非理性动机，由此产生了高额的并购溢价^[10]，最终增大了商誉规模^[1]；同时，闫华红和王亚茹（2020）^[14]研究发现管理层权力与并购商誉存在显著的正相关关系，即管理层权力越大，并购商誉越大。其次，企业高质量的内部控制能够约束管理者的行为，促使管理者谨慎选择并购目标，审慎估计并购价值，减少高额商誉的产生^[8]。最后，通过对并购企业会计处理方法选择的研究，谢纪刚和张秋生（2013）^[15]发现以发行股份为对价的交易制度将会使得企业并购商誉被明显高估。从外部环境方面来看，一方面，并购商誉受到“同伴效应”的影响，并因其所处外部环境不确定性的程

度不同存在差异^[16]；如经济政策不确定性的增加会抑制企业的并购决策，且对不同行业的企业并购决策的影响有所差异^[17]。另一方面，产业政策的支持会显著提高并购商誉，如政府补贴越多，并购商誉金额越高^[18]，同时产权性质、市场化程度对两者的关系具有调节作用^[4]。

关于博彩文化，它本质上隶属于地域文化，现有文献普遍认为它会对企业的行为产生重要影响。“一方水土养一方人”，地域文化不显于自然山水，亦不见诸于典章律法，却能够对经济主体行为产生春风化雨且源远流长的影响^[19,20]。文化作为一种重要的非正式制度深刻地塑造着经济主体的认知和行为^[21]，研究表明，宗教、语言、社会信任等区域文化因素都会对企业的投融资决策产生重要影响。不同地域文化导致经济主体的价值取向和价值获取方式不同，进而影响其信息披露、交付方式和管理行为，并开始发挥其约束作用，影响公司治理与决策^[22]。受到地域文化影响的利益相关者会自觉或者非自觉地将地域文化通过各种渠道传递给公司，

并最终使其成为公司文化的一部分^[23]。

2、理论分析与研究假设

Hambrick 和 Mason 提出的高阶理论认为“作为认知和价值观的基础，高管团队的个人背景等异质性是影响企业战略决策、组织行为和企业绩效的重要因素”。处于不同地域文化下的管理层在价值观念和行爲偏好上会表现出明显差异，并映射在微观企业的经营管理活动中^[24]。已有文献关注到风险偏好作为影响高管决策的重要心理因素，同时也将对高管投资效率、并购交易决策和盈余管理等行为产生明显作用^[25]。

并购作为一种面临较高风险性和不确定性的重大投资活动，其决策会受到经济主体的风险偏好和风险承担意愿的影响。地方博彩文化作为一种重要的非正式制度深刻地塑造着经济主体的认知和行爲^[24]，它有助于企业内部形成崇尚冒险的文化氛围，进而影响企业行爲决策。首先，博彩文化浓厚地区的管理层将在并购交易过程中表现得更为激进，积极主动地挑选高成长性的企业发起并购，以提升企业财务业绩，从而使并购商誉增加^[14]；其次，身处崇尚冒险文化氛围的管理者容易高估自身能力以及所掌握信息的准确性，从而低估项目投资风险，使企业采取过度兼并收购或过度投资的行为^[26]；最后，地区博彩文化还会通过影响管理层风险偏好程度来降低其对外部环境的敏感性，如缓解由于外部经济政策不确定性因素导致的企业投资下降以及对超额商誉的抑制作用^[27]。上述分析表明，管理者风险偏好程度越高，管理层将越激进，越有可能在并购交易过程中支付高溢价，形成“商誉泡沫”^[9,26]。据此，本文提出第一个假说：

假说 H1：地区博彩文化越浓厚，企业的并购决策越激进，并购商誉越高。

新制度经济学家 North 在 1990 年首先注意到制度对市场主体的影响，将制度定义为社会博弈的规则，并将其划分为正式制度（例如法律）、非正式制度（例如风俗习惯）和制度的执行。Acemoglu 等（2004）认为正式制度塑造了经济主体的激励结构，可以指引市场参与主体的决策行为。在我国，

制度环境不仅在时间序列上动态演变，还在不同地区和企业中表现出横截面上的差异。作为重要的外部制度环境，市场化进程会显著影响上市公司的日常行爲，对企业的并购投资行爲产生一定的激励与约束效应。市场化程度较高的地区往往伴随着较高的经济发展水平、较好的营商环境与较为成熟的市场发展水平^[28]。一方面，对企业而言，市场化程度提升意味着政府干预减少与企业融资行爲市场化，这将进一步提升银行放贷决策及企业融资决策的市场化程度，使得经济政策不确定性对超额商誉的抑制作用更为显著^[27]；另一方面，在市场化进程高的地区，中介机构发育程度更好，法律制度环境也更完善，管理层的自由裁量权大大降低^[29]，因此能够保护中小投资者的利益，提升公司的信息披露和治理水平，进而抑制企业超额并购的动机。综合上述研究不难发现，市场化水平越高，越能抑制企业超额并购的动机。基于此，本文提出第二个假说：

假说 H2：市场化水平可以有效缓解博彩文化对企业并购商誉的刺激，即良好的地区正式制度环境可以在一定程度上抑制地区博彩文化的负面影响。

三、研究设计

1、样本选取与数据来源

本文以 2008-2019 年沪深两市 A 股的所有非金融类上市公司为初始研究样本。之所以选择 2008 年为研究起点，是因为财政部网站从 2008 年开始披露衡量博彩文化的彩票销售数据。同时对样本进行如下筛选：（1）剔除 ST、*ST 类公司；（2）剔除资产负债率小于 0 的公司；（3）剔除财务数据缺失的样本。最终，得到包含 2769 家公司的非平衡面板数据。本文的彩票销售数据来源于财政部官网，上市公司财务数据来自于国泰安数据库。为避免异常值影响，对所有连续型变量进行上下 1% 的 Winsorize 处理。

2、变量定义

（1）并购商誉（GW）。与李丹蒙等（2018）^[1]、杨威等（2018）^[2]等（2020）^[14]相一致，采用经

总资产调整后的商誉值作为并购商誉的度量。具体地，将年末商誉净额除以年末总资产，商誉净额等于商誉账面金额减去相应的减值准备。

(2) 地区风险偏好 (*Lottery*)。本文从地区彩票销售角度来刻画地区博彩文化。这是因为彩票销售与当地风险态度息息相关，彩票消费与当地投机偏好关联性较强。谢露等 (2021)^[21] 基于人均彩票销售额占地区国民生产总值的比重来刻画地区博彩文化，本文认为彩票消费并非高档消费，普通民众如果风险偏好高，即使收入较低也会购买大量彩票来博取微小概率的巨额收益。因此，借鉴陈欣等

(2021)^[6] 的做法，采用地区福利彩票和体育彩票的销售额合计与地区常住人口的比例乘以 100 来衡量。该数值越大，表明当地的博彩文化越浓厚，风险厌恶程度越低。

(3) 控制变量。借鉴李丹蒙等 (2018)^[1]、杨威等 (2018)^[2] 的研究，本文控制了如下变量：公司规模 (*Size*)、财务杠杆 (*Lev*)、盈利能力 (*Roa*)、公司年龄 (*Age*)、账面市值比 (*Bm*)、股权集中度 (*Top1*)、企业成长性 (*Grow*)、地区经济发展水平 (*GDP*)。

具体变量定义如表 1 所示。

表 1 变量定义

变量名称	变量符号	变量说明
并购商誉	<i>GW</i>	企业当年账面商誉净额/年末总资产
地区风险偏好	<i>Lottery</i>	福利彩票和体育彩票累计销售额/常住人口数/100
公司规模	<i>Size</i>	年末总资产的自然对数
财务杠杆	<i>Lev</i>	总负债/总资产
盈利能力	<i>Roa</i>	净利润 / 总资产平均余额
公司年龄	<i>Age</i>	公司上市年限取自然对数
账面市值比	<i>Bm</i>	股东权益/公司市值
股权集中度	<i>Top1</i>	公司第一大股东持股比例
企业成长性	<i>Grow</i>	(本年营业收入-上年营业额收入) / 上年营业收入
地区经济发展水平	<i>GDP</i>	企业所在地区的人均国内生产总值
时间	<i>Year</i>	年度虚拟变量
行业	<i>Industry</i>	行业虚拟变量

3、模型设定

为验证假说 H1，我们构建了如下回归模型：

$$GW_{i,t} = \alpha_0 + \alpha_1 Lottery_{i,t} + \sum Controls_{i,t} + i.Industry + i.Year + \varepsilon_{i,t} \quad (1)$$

其中，下标 *i* 和 *t* 分别代表企业和时间。

$\sum Controls_{i,t}$ 为一系列控制变量，*Industry* 和 *Year* 分别代表行业固定效应和时间固定效应。这里主要关注 α_1 ，它代表了地区博彩文化对企业并购商誉的影响。若 α_1 显著为正，说明地区风险偏好对企业并购商誉产生了促进作用，反之则为抑制作用。

四、实证结果与分析

1、描述性统计

表 2 列示了主要变量的描述性统计。*GW* 的均值和中位数分别为 0.0238 和 0.0001，表明样本中存在较高并购商誉的企业数量众多。同时，*GW* 的最大值为 0.3935，说明个别企业的并购商誉水平极高，接近该企业总资产的 40%。*Lottery* 的均值为 2.6198，表明中国各地区人均福利彩票和体育彩票的销售额为 261.98 元。同时，地区博彩文化的最大值和最小值分别为 0.5115 和 5.9625，不同地区之间的博彩文化存在很大差异。

表 2 主要变量的描述性统计

变量	N	均值	标准差	中位数	最小值	最大值
<i>GW</i>	18723	0.0238	0.0653	0.0001	0.0000	0.3935
<i>Lottery</i>	18723	2.6198	1.2398	2.5963	0.5115	5.9625
<i>Size</i>	18723	22.0209	1.2769	21.8585	19.3740	26.0183
<i>Lev</i>	18723	0.4499	0.2124	0.4489	0.0491	0.9058
<i>Roa</i>	18723	0.0415	0.0576	0.0374	-0.2315	0.2293
<i>Age</i>	18723	2.1343	0.7525	2.3026	0.0000	3.2581
<i>Bm</i>	18723	0.5959	0.2384	0.5964	0.1109	1.1327
<i>Top1</i>	18723	0.3508	0.1509	0.3318	0.0878	0.7517
<i>Grow</i>	18723	0.2162	0.5522	0.1196	-0.6151	3.8685
<i>GDP</i>	18723	10.1251	0.7890	10.1856	7.6116	11.4257

2、回归结果分析

表 3 列示了本文的回归结果。列（1）为未加入控制变量、行业固定效应和年度固定效应时博彩文化对并购商誉的影响，列（2）为未加入控制变量，但考虑了年度和行业固定效应的回归结果，列（3）为同时考虑控制变量和年度、行业固定效应的回归

结果。可以发现，*Lottery* 的回归系数均显著为正，与前文的假说 H1 相一致。这说明在一定程度上，地区博彩文化对企业产生了潜移默化的影响，使当地的企业在并购过程中更加激进，由此推高了并购交易的支付对价从而形成了高额商誉。

表 3 假说 H1 和 H2 的检验

变量	全样本			<i>Market</i> =1	<i>Market</i> =0
	(1) <i>GW</i>	(2) <i>GW</i>	(3) <i>GW</i>	(4) <i>GW</i>	(5) <i>GW</i>
<i>Lottery</i>	0.0122*** (17.42)	0.0023*** (2.76)	0.0015* (1.88)	0.0008 (0.56)	0.0032** (2.08)
<i>Size</i>			0.0038*** (5.03)	0.0049*** (4.42)	0.0025*** (2.73)
<i>Lev</i>			-0.0319*** (-7.06)	-0.0343*** (-5.13)	-0.0301*** (-5.35)
<i>Roa</i>			-0.0291** (-2.53)	-0.0384** (-2.09)	-0.0164 (-1.18)
<i>Age</i>			-0.0054*** (-5.22)	-0.0040*** (-2.78)	-0.0069*** (-4.93)
<i>Bm</i>			-0.0103*** (-2.74)	-0.0126** (-2.15)	-0.0061 (-1.35)
<i>Top1</i>			-0.0445*** (-9.69)	-0.0439*** (-6.73)	-0.0450*** (-8.19)
<i>Grow</i>			0.0170*** (12.98)	0.0183*** (8.72)	0.0158*** (9.47)
<i>GDP</i>			0.0008 (0.83)	0.0018 (1.00)	0.0004 (0.38)
常数项	-0.0081*** (-5.45)	-0.0080*** (-3.06)	-0.0472*** (-3.02)	-0.0762*** (-2.70)	-0.0196 (-1.11)
<i>Industry/Year</i>	No	Yes	Yes	Yes	Yes
<i>N</i>	18723	18723	18723	9050	9673
<i>adj. R²</i>	0.053	0.223	0.261	0.250	0.275

注：①*、**、***分别表示在 10%、5%和 1%水平上显著；②小括号内为 t 值，基于公司层面的聚类稳健标准误，下同。

为验证假说 H2，我们按市场化进程指数大小对样本进行分组并分别回归。当企业所在的市场化进程指数高于年度中位数时 *Market* 赋值为 1，否则取 0。由列（4）和列（5）可知，在市场化程度较高组中（*Market*=1），*Lottery* 的回归系数不显著，而当市场化程度较低时，*Lottery* 的回归系数为 0.0032

且在 5%的水平上显著。这表明企业所在地的制度环境越完善，企业受博彩文化的影响越小。即在一定程度上，正式制度可以显著弱化非正式制度对企业并购行为的负面影响，假说 H2 得证。

3、内生性处理

地区博彩文化会给企业并购商誉带来不利影

响,但这一结果可能受到反向因果的干扰,本文选取企业注册地的寺庙和道观数量(*Temtao*)为工具变量来缓解可能的内生性问题²¹。我国宗教地域分布广泛,并以佛教和道教为主,是地区文化的鲜明代表。佛教和道教均明确反对赌博等输赢有利益关系的经济活动,如佛教指出了赌博的九大恶果,道教创始人老子一生崇尚俭朴的生活,反对赌博和奢侈浪费。因此,选取寺庙和道观数量作为地区博彩文化的工具变量满足相关性要求。同时,企业注册地寺庙和道观的数量一般不会影响上市公司的并购行为,满足外生性要求。如表4所示,在第一阶段,*Temtao*与地区博彩文化显著负相关,与理论预期相符;在第二阶段,*Lottery*的系数为0.0207且在1%的水平上显著为正,表明前文的研究结论具有稳健性。

4、稳健性检验

本文进行了如下七种稳健性检验:(1)观察更长期的影响,分别滞后一期、两期和三期;(2)替换因变量,对企业并购商誉分别进行地区层面和行业层面的调整;(3)替换自变量,分别构建以福利彩票和体育彩票为代表的地区博彩文化指标;(4)按博彩文化的年度中位数分为博彩文化高和低两组分别回归;(5)增加内部治理水平和地区其他特征为控制变量;(6)剔除金融危机影响;(7)排除董事长个人风险偏好等竞争性解释。前文研究结论仍然保持不变²²。

五、进一步分析

1、作用机制检验

采用薪酬最高的前三名高管薪酬之和占所有高管薪酬之和的比例(贾洪文等,2019)^[30]来度量管理层过度自信(*Con*),并构建如下回归模型:

$$Con_{i,t} = \beta_0 + \beta_1 Lottery_{i,t} + \sum Controls_{i,t} + i.Industry + i.Year + \varepsilon_{i,t} \quad (2)$$

$$GW_{i,t} = \gamma_0 + \gamma_1 Lottery_{i,t} + \gamma_2 Con_{i,t} + \sum Controls_{i,t} + i.Industry + i.Year + \varepsilon_{i,t} \quad (3)$$

首先,自变量*Lottery*对中介变量*Con*进行回归,若 β_1 显著为正,说明地区博彩文化增大了管理层的过度自信;其次,将自变量和中介变量同时加入回归模型,对模型(3)进行回归,若 γ_2 显著说明自变量通过中介变量对因变量产生了影响;最后,判断自变量*Lottery*的系数显著性,若 γ_1 显著说明中介变量是部分中介,反之为完全中介。我们同时采用逐步回归法和Bootstrap法进行检验。如表5列

(1)所示,*Lottery*与在1%的水平上显著正相关,地区博彩文化显著提高了管理层的过度自信;然后将*Lottery*与*Con*同时带入回归模型(1)中,两者的系数均显著为正,并通过了Sobel Z,表明管理层过度自信是博彩文化影响并购商誉的部分中介。表6中间接效应的95%置信区间为[0.000053, 0.000151],不含0,同样验证了中介路径的存在性。综上,地区博彩文化通过增加管理层过度自信,形成了高额的并购商誉。

表4 工具变量法(2SLS)

变量	第一阶段 (1) <i>Lottery</i>	第二阶段 (2) <i>GW</i>
<i>Lottery</i>		0.0207*** (2.82)
<i>Temtao</i>	-0.0035*** (-9.11)	
<i>Controls</i>	Yes	Yes
<i>Industry/Year</i>	Yes	Yes
<i>N</i>	18723	18723
adj. <i>R</i> ²	0.497	0.194

²¹ 该数据来源于国泰安数据库文化研究中的宗教子模块。

²² 篇幅所限,稳健性检验表格未在文中列示,备索。

Cragg-Donald Wald F 统计量	82.918
Stock-Yogo weak ID test	8.960
Critical Values:10% MaximalIV	

表 5 作用机制检验：逐步回归法

变量	(1) <i>Con</i>	(2) <i>GW</i>
<i>Lottery</i>	0.0092*** (3.06)	0.0014* (1.75)
<i>Con</i>		0.0097*** (2.75)
<i>Controls</i>	Yes	Yes
常数项	1.4804*** (19.56)	-0.0612*** (-3.70)
<i>Industry/Year</i>	Yes	Yes
<i>N</i>	18681	18681
<i>adj. R²</i>	0.113	0.262
<i>Sobel Z</i>	0.000***	4.139
<i>Goodman-1</i>	0.000***	4.109
<i>Goodman-2</i>	0.000***	4.169

表 6 作用机制检验：Bootstrap 法 (N=5000)

中介路径	间接效应		直接效应	
	Effect	95%置信区间	Effect	95%置信区间
<i>Lottery</i> → <i>Con</i> → <i>GW</i>	0.000102	[0.000053, 0.000151]	0.007447	[0.006610, 0.008284]

2、异质性分析

高管团队特质是否对博彩文化与并购商誉之间的关系产生影响？本文进一步从管理层海外背景、金融背景和研发背景三方面进行考察。海外背景 (*Overseas*) 是指高管团队成员中有海外任职和海外求学经历背景高管所占的比例；金融背景 (*Economics*) 等于高管团队成员中有曾任职于商业银行、保险公司、证券公司、基金管理公司等金融

机构背景高管所占的比例；研发背景 (*Research*) 是指高管团队成员中任职于研发部门高管所占的比例。

由表 7 可知，管理层海外背景、金融背景和研发背景与地区博彩文化的交乘项系数均至少在 10% 的水平上显著为正，即当高管团队中有海外背景、金融背景或研发背景的高管所占比例较大时，高管团队特质对博彩文化与并购商誉之间的关系起到推波助澜的作用。

表 7 地区博彩文化、高管团队特质与并购商誉

变量	(1) <i>GW</i>	(2) <i>GW</i>	(3) <i>GW</i>
<i>Lottery</i>	0.0003 (0.36)	0.0012 (1.43)	-0.0004 (-0.43)
<i>Overseas</i>	-0.0516*** (-2.88)		
<i>Overseas</i> × <i>Lottery</i>	0.0245*** (3.62)		
<i>Economics</i>		-0.0195* (-1.91)	
<i>Economics</i> × <i>Lottery</i>		0.0076* (1.65)	
<i>Research</i>			-0.0501*** (-3.42)
<i>Rd</i> × <i>Lottery</i>			0.0195*** (3.00)
常数项	-0.0416*** (-2.65)	-0.0457*** (-2.93)	-0.0444*** (-2.83)
<i>Controls/Industry/Year</i>	Yes	Yes	Yes
<i>N</i>	18718	18723	18717
<i>adj. R²</i>	0.264	0.261	0.262

3、经济后果检验

博彩文化推高了企业的并购商誉，这些被高估的商誉会给企业带来什么样的影响呢？本文分别从后续商誉减值、股价崩盘风险和企业全要素生产率三个角度进行探讨。

本文采用两种方法度量商誉减值：①商誉减值的规模（*Impairment*），等于本期商誉减值金额除以总资产；②是否发生商誉减值（*Loss*），若当年发生了商誉减值，赋值 *Loss* 为 1，否则取 0。观察表 8 的列（1）和列（2）可以发现，不论是减值的规模还是是否发生减值，*GW* 的回归系数均在 1% 的水平上显著为正。即并购商誉越多，后续的商誉减值越多。

对股价崩盘风险分别从负收益偏态系数

（*NCSKEW*）和收益上下波动比例（*DUVOL*）两方面衡量（杨威等，2018）^[2]。*NCSKEW* 和 *DUVOL* 的取值越大，公司的股价崩盘风险越高。如表 8 的列（3）和列（4）所示，*GW* 的系数分别为 0.3940 和 0.4484，并在 1% 的水平上显著为正，说明并购商誉越大，股价崩盘风险越高。

构建柯布道格拉斯生产函数计算企业全要素生产率，并同时采用 *LP* 法和 *OP* 法进行测算。如表 8 的列（5）和列（6）所示，*GW* 的系数分别为 -0.4866 和 -0.4869，且均在 1% 的水平上显著，说明并购商誉降低了企业的全要素生产率。上述三个维度的检验结果表明，由博彩文化推高的并购商誉，最终对企业长远发展带来不利影响。

表 8 并购商誉的经济后果检验

变量	(1) <i>Impairment</i>	(2) <i>Loss</i>	(3) <i>NCSKEW</i>	(4) <i>DUVOL</i>	(5) <i>TPF_lp</i>	(6) <i>TPF_op</i>
<i>GW</i>	0.0144*** (5.74)	2.1389*** (9.34)	0.3940*** (3.91)	0.4484*** (4.73)	-0.4866*** (-4.67)	-0.4869*** (-4.68)
<i>Controls</i>	Yes	Yes	Yes	Yes	Yes	Yes
常数项	-0.0046*** (-2.64)	-5.3663*** (-8.91)	1.0094*** (7.99)	1.4664*** (12.42)	-3.9861*** (-16.61)	-3.9875*** (-16.61)
<i>Industry/Year</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	18723	18723	17910	17910	18702	18702
<i>adj. R²/Pseudo_R²</i>	0.058	0.1287	0.224	0.296	0.747	0.747

六、研究结论与启示

本文以 2008-2019 年沪深 A 股非金融类上市公司为样本，从博彩文化这一非正式制度视角探讨区域文化对企业并购行为的影响。研究表明，上市公司所在地的博彩文化与企业并购商誉显著正相关，主要原因是地区博彩文化会对企业管理层产生潜移默化的影响，容易引发管理层过度自信，从而做出激进的并购决策。但同时，地区博彩文化这一非正式制度对企业行为的影响会因正式制度的不同而表现出差异性，当制度环境较为完善时地区博彩文化的不利影响将被弱化，这一发现暗含了正式制度可以在一定程度上矫正非正式制度缺陷的经验判断。博彩文化与并购商誉之间的关系同样受高管团队特征的影响，在高管团队成员中当海外背景高管、金融背景高管和研发背景高管所占的比例

越高时，博彩文化将进一步提升并购商誉规模。此外，被推高的并购商誉后续会引发大规模商誉减值、增加股价崩盘风险和降低企业全要素生产率，最终给企业的长远发展带来不利影响。

本文的研究结论具有一定的启示意义：

首先，政府应厚植良好的制度环境土壤。当外部制度环境较为完善时，地区博彩文化对企业并购决策的不利影响将被弱化甚至消除，这体现出正式制度即使深陷不利的非正式制度的“围剿”时，也能在规范经济主体行为和防范系统性金融风险方面彰显出强大的力量。因此，政府应将完善制度环境放在首位，发挥制度环境优势破除非正式制度对经济主体不利影响的藩篱。

其次，监管部门应加强对并购活动的过程审查和信息披露。地区博彩文化会加剧管理层的过度自

信,而管理层过度自信是产生高额商誉的首因^[1]。因此,证券监管部门要加强对企业并购事件的过程审查,尤其对于商业性质不合理或者交易规模异常的并购项目更要严格审查、严加把控,规范并购交易的信息披露制度,抑制和杜绝商誉泡沫的产生,以防范系统性金融风险的发生。

最后,企业在并购过程中需审慎估值谨防高溢价并购。高额并购商誉的经济后果检验表明,由地区博彩文化推动的并购商誉最终会计提大额减值、引发股价崩盘和降低企业全要素生产率,泡沫终将被破灭^[2,8,9]。因此,企业管理层应合理评估被并购方的真实价值并做出理性决策,真正通过并购实现自身的高质量发展。

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上市公司质量、投资者情绪与股价崩盘风险

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摘要：随着金融市场的发展，市场风险也愈发凸显，为了预防各类风险，政府积极推动提高上市公司质量，国资委将统筹开展提高央企控股公司质量行动。提高上市公司质量尤为重要，那么上市公司质量应该从哪几方面评价？上市公司质量可以抑制股价崩盘吗？投资者情绪发挥了什么作用？文章从价值创造、治理优化、社会责任、研发创新及绿色发展五个维度构建了上市公司质量综合评价体系，利用沪深 A 股上市公司 2011-2020 年的数据，探究上市公司质量、投资者情绪与股价崩盘风险的关系，研究表明上市公司质量的提高对降低股价崩盘风险具有积极作用，随着上市公司质量的提高投资者情绪也会显著提高，投资者情绪在上市公司质量与股价崩盘风险的关系中存在间接效应，具体表现为遮掩效应，即投资者情绪的存在会抵销一部分上市公司质量对股价崩盘的影响。文章的研究结论为有关部门推动提高上市公司质量提供了有利的理论依据。

关键词：上市公司质量，股价崩盘，投资者情绪，CRITIC 赋权法

Quality of Quoted Company, Investor Sentiment and Stock Price Crash Risk

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Abstract: With the development of the financial market, market risks are increasingly prominent. In order to prevent all kinds of risks, the government actively promotes the improvement of the quality of listed companies, and the State-owned Assets Supervision and Administration Commission (SASAC) will coordinate the improvement of the quality of central enterprises holding companies. It is particularly important to improve the quality of listed companies, so what aspects should the quality of listed companies be evaluated from? Can listed company quality restrain stock price collapse? What role did investor sentiment play? This paper constructs a comprehensive quality evaluation system for listed companies from the five dimensions of value creation, governance optimization, social responsibility, R&D innovation and green development. Using the data of a-share listed companies in Shanghai and Shenzhen from 2011 to 2020, this paper explores the relationship between the quality of listed companies, investor sentiment and stock price crash risk. The research shows that the improvement of the quality of listed companies plays a positive role in reducing the risk of stock price crash. With the improvement of the quality of listed companies, investor sentiment will also significantly improve. There is an indirect effect of investor sentiment on the relationship between the quality of listed companies and the risk of stock price crash, which is embodied in the hiding effect. That is, the existence of investor sentiment will offset the impact of quality of some listed companies on stock price collapse. The conclusion of this paper provides a favorable theoretical basis for relevant departments to promote the quality improvement of listed companies.

Keywords: quality of quoted company, stock price crash, investor sentiment, CRITIC method

一、引言

我国股票市场自建立以来,股价暴涨暴跌现象频发,迄今共经历了六次大规模股价崩盘。2020年爆发的世界范围的大规模新冠疫情进一步加剧了股票市场的波动,美股暴跌在短短两周内就触发了四次熔断机制。股价的异常波动不仅会对上市公司和投资者产生不利影响,而且会降低整个证券市场的效率,危害经济发展,已经引发理论届、实务届和监管层的广泛关注。

对于股价崩盘的形成, Caplin 和 Leahy (1994)^[1]提出了信息不完全假说,认为股票交易信息影响股价,证券市场中的投资者所掌握的信息是不对称的,知情交易者拥有更多非公开信息,而非知情交易者仅仅掌握股票的部分信息,因此股票价值难以被完全真实地反映出来; Hong 和 Stein (2003)^[2]在行为金融理论的基础上提出投资者异质信念假说,认为不同的投资者对待同一信息可能存在积极、消极等不同态度进而影响其交易行为,由于卖空机制的限制导致负面信息不能完全反映在股价上; Jim 和 Myers (2006)^[3]基于代理理论提出了信息隐藏假说,认为股价崩盘源于公司管理层的“捂盘”行为,具体来说,现代企业的所有权与管理权分离产生了一系列代理问题,公司管理层在利益驱使下可能会隐藏或推迟上市公司负面消息发布。

关于股价崩盘风险的影响因素,目前已有文献研究发现信息披露(蒋红芸和王雄元, 2018^[4]; 曹廷求和张光利, 2020^[5])、内部控制(黄政和吴国萍, 2017^[6])、社会责任(宋献中等, 2017^[7])、企业创新(孙艳梅等, 2019^[8]; 侯婧, 2019^[9])等与股价崩盘风险相关。沈冰和陈锡娟(2019)^[10]基于投资者情绪的角度研究发现投资者情绪加剧了股权质押行为引发的股价崩盘风险,随后郝芳静等(2020)^[11]基于噪声交易研究发现,市场层面的投资者情绪加大了股价崩盘风险。也有学者从宏观角度研究股价崩盘风险,研究发现市场化进程推进、制度环境改善、产品市场竞争等有助于缓解股价崩盘风险(施先旺等, 2014^[12]; 罗进辉和杜兴强, 2014^[13]; 苗丹, 2017^[14])。可以发现,股价崩盘受到多个方

面的综合影响。

目前,已有大量文献探究股价崩盘的影响因素,但现有研究文献都是探索单一因素对股价崩盘风险的影响,缺乏微观综合因素对股价崩盘风险影响的研究,且较少有文献将公司内部影响因素与外部投资者情绪结合起来研究股价崩盘风险。依据 2020 年 10 月国务院发布的《关于进一步提高上市公司质量的意见》的文件精神,本文利用沪深 A 股上市公司 2011-2020 年的数据,探究上市公司质量、投资者情绪及股价崩盘风险的关系。

本文的贡献包括:首先,构建了上市公司质量综合评价体系,从价值创造、治理优化、社会责任、研发创新以及绿色发展五个维度评价上市公司质量,突破了传统财务评价的局限,拓宽了上市公司的综合评价体系;其次,综合上市公司整体质量探究对股价崩盘的影响,并进一步探究投资者情绪在其间扮演的“角色”,丰富了股价崩盘的研究文献,同时为推动提高上市公司质量提供了理论支持。

二、理论分析与研究假设

1、上市公司质量与股价崩盘风险

上市公司质量反映了公司在微观层面的综合表现,迄今为止学术界对上市公司质量没有统一的界定。张跃文和王力(2018)^[15]基于价值的角度分别从价值创造、价值管理以及价值分配三个方面对上市公司质量进行评价。国务院(2020)^[16]针对进一步提高上市公司质量的建议中指出应当优化公司治理结构、提高信息披露质量、规范公司运作、健全激励约束机制、提高风险防控能力。除此之外,提高公司的创新质量对于提高上市公司质量也很重要(宋志平, 2020^[17])。习近平总书记(2019)^[18]提出“追求绿色发展繁荣”,在生态环境持续恶化的今天,“绿水青山就是金山银山”,生态文明建设和经济发展相辅相成,因此绿色发展也是衡量上市公司质量的重要维度。

在新时代高质量发展的背景下,结合当前的政策指引以及上市公司目前存在的现实问题,本文认为应该从价值创造水平、治理优化水平、社会责任水平、研发创新水平以及绿色发展水平五个维度对

上市公司质量进行综合评价。价值创造水平是衡量上市公司质量的基础性指标,反映了上市公司的财务状况以及价值创造情况;治理优化水平反映了治理结构、信息披露、内部控制及风险管理情况;社会责任水平反映上市公司对利益相关者的履责情况,包括对股东、员工以及公众的社会责任;研发创新水平反映了公司的核心竞争力;绿色发展水平反映了上市公司可持续发展能力,是对“绿水青山就是金山银山”新发展理念的积极响应。具体分析如下:

(1) 价值创造与股价崩盘风险

投资者往往偏向财务状况良好的上市公司(苍玉权和严华麟, 2005^[19]), 而投资偏好影响上市公司的股价, 对于财务状况欠佳的上市公司, 其管理者可能会为了维持股价进行盈余管理(张月玲和李少君, 2020^[20]), 从这个层面讲, 高质量的上市公司, 其财务状况稳定, 相应地管理层盈余管理的动机较小, 从而有利于缓解股价崩盘风险。

(2) 治理优化与股价崩盘风险

蒋红芸和王雄元(2018)^[4]研究发现内控信息的披露有助于降低未来股价崩盘风险, 此外, 公司的盈余管理加剧了股价崩盘风险(杨超等, 2014^[21]), 而有效的内部控制通过制约管理层“捂盘”等机会主义行为提高了信息披露质量, 缓解信息不对称问题, 降低了股价崩盘风险(黄政和吴国萍, 2017^[6])。此外, 合理的治理结构与有效的风险管理可以抑制代理人的机会主义行为(王跃堂, 2008^[22]; Barton, 2001^[23])。所以, 公司的治理优化水平越高, 管理层的“捂盘”动机和“捂盘”机会越小, 信息不对称程度越低, 股价崩盘风险越小。

(3) 研发创新与股价崩盘风险

一方面, 基于信号传递理论, 企业的研发创新可以发挥“信号弹”的作用, 间接向外界传递公司良好的发展前景以及未来升值的信号, 提高了投资者的信心(唐玮和崔也光, 2017^[24]), 有助于稳定股价; 另一方面, 基于激励约束理论, 上市公司加大创新投入用于内部提升, 为应对投资风险会减少盈余管理, 有助于抑制股价崩盘风险(孙艳梅等,

2019^[8])。

(4) 社会责任与股价崩盘风险

已有研究发现上市公司在履行社会责任方面的良好表现可以通过信息效应和声誉保险效应降低股价崩盘风险(宋献中等, 2017^[7])。

(5) 绿色发展与股价崩盘风险

根据企业声誉理论, 绿色发展的形象有助于增加客户粘性, 获得投资者的青睐, 成为公司的声誉资本(相福刚和迟甜甜, 2020^[25])。在生态环境持续恶化、自然资源不断减少的现实背景下, 支持绿色发展的上市公司往往有着前瞻性的发展战略, 相较之下更容易获得投资者尊重, 从而为公司带来良好的声誉, 声誉资本的积累可以有效发挥保险效应, 缓解利空消息对股价造成的不利影响(宋献中等, 2017^[7]), 有助于抑制股价崩盘风险。

综上所述, 公司价值创造、治理优化、社会责任、研发创新以及绿色发展方面表现越好, 上市公司质量越高, 股价崩盘风险越低。因此, 提出如下假设:

H1: 上市公司质量与股价崩盘风险负相关。

2、上市公司质量与投资者情绪

上市公司质量越高, 社会声望越高, 根据企业声誉理论, 声誉是企业的一项重要无形资产, 有助于企业获得商品溢价(沈洪涛等, 2011^[26]), 同时, 声誉是信号传递机制中的信息载体, 良好的声誉向外界传递利好的信号, 有助于提高投资者的信心(王晓祺和胡国强, 2020^[27]), 因此, 上市公司质量影响投资者情绪, 上市公司质量越高, 投资者情绪越高涨, 投资者越有信心。因此, 提出假设:

H2: 上市公司质量与投资者情绪正相关。

3、投资者情绪的间接效应

根据投资者情绪理论, 在非完全市场中, 噪音交易使得投资者的主观偏好影响证券价格, 有研究表明投资者情绪加剧了股价崩盘风险(郝芳静等, 2020^[11])。我国证券市场存在大量的非理性投资者, 大多数投资者往往依据上市公司过去的行为和表现进行证券交易, 投资者的个人情绪很大程度上决定其交易行为, 进而影响股价。上市公司整体表现

较好即上市公司质量越高则更容易获得投资者青睐,使得投资者情绪持续高涨,而这种用情绪“堆砌”的股价并不稳定,很可能会因为市场的利空消息而化为泡沫,进而增加了股价崩盘风险。因此,本文认为投资者情绪可能会抵销一部分上市公司质量对股价崩盘风险的影响,基于此,提出如下假设:

H3: 投资者情绪在上市公司质量与股价崩盘风险间存在遮掩效应。

三、研究设计

1、样本选择和数据来源

本文以 2011-2020 年 A 股上市公司为样本。数据来自 CSMAR 数据库。通过剔除金融业、ST 类、

PT 类上市公司、年度个股周收益率数据不足 30 周的样本、数据缺失和数据异常的样本、当年上市的公司样本,以及对部分变量进行双向缩尾等处理得到最终样本。本文通过 Excel2010、Stata16、SPSSAU 等软件进行相关的数据处理。

2、变量的选择和度量

(1) 上市公司质量

本文通过自行构建的综合评价体系得到上市公司质量 Q。

本文在选取具体指标时,基于代表性、全面性和可获得性三个原则,构建了如表 1 所示的上市公司质量综合评价体系。

表 1 上市公司质量评价指标

评价维度	一级指标	二级指标	指标说明
价值创造水平	财务状况	营业利润率、应收账款周转率、现金比率、利润增长率	分别表示公司盈利能力、营运能力、偿债能力以及成长能力。
	价值创造	EVA 增长率、每股 EVA	—
治理优化水平	治理结构	二职合一、独董比例	若总经理与董事长不是同一人,二职合一赋值为 1,否则为 0。
	信息披露	财务重述、财报披露时滞	—
	内部控制	内部控制审计意见、内部控制有效性	标准无保留意见=1、无保留意见加事项段=0、否定意见和无法表示意见=-1。
	风险管理	总杠杆、金融资产占比	—
社会责任水平	股东责任	股利分配率、股东及债权人权益保护	同时披露股东和债权人权益保护赋值为 2,披露其一赋值为 1,否则为 0。
	员工责任	人均职工薪酬、人均培训费	—
	公众责任	税收贡献、社会公益	税收贡献为所得税占总资产比例;社会公益为哑变量。
研发创新水平	研发投入	研发费用占比、研发人员占比	—
	研发产出	资本化研发费用比例、专利数量	—
绿色发展水平	环保理念	环保重视程度	根据环保管理制度、环保教育与培训、环境事件应急机制完善情况分别赋值为 0、1、2、3。
	环保行动	环保荣誉或奖励	获得环保荣誉或奖励赋值为 1,否则为 0。

对上述相关评价数据分别进行正向化、负向化处理,综合考虑数据波动情况和各指标间的相关性,

本文通过 CRITIC 权重法对各指标赋权以减少信息的重叠,得出更客观可靠的评价结果(吴希, 2016^[28]),加权后得出的综合评分 Q 代表上市公司质量水平, Q 值越大说明上市公司质量越高。

(2) 股价崩盘风险

借鉴 Chen et al. (2001)^[29]的方法,用负收益偏态系数(NCSKEW)和收益上下波动比率(DUVOL)衡量股价崩盘风险。

首先,计算个股周收益率:

$$R_{i,t} = \beta_0 + \beta_1 R_{m,t-2} + \beta_2 R_{m,t-1} + \beta_3 R_{m,t} + \beta_4 R_{m,t+1} + \beta_5 R_{m,t+2} + \varepsilon_{i,t}$$

其中, $R_{i,t}$ 为 t 周考虑现金红利再投资的个股收益率, $R_{m,t}$ 为 t 周市场收益率。利用残差 $\varepsilon_{i,t}$ 计算个股特有收益率: $W_{i,t} = \ln(1 + \varepsilon_{i,t})$

最后,根据得到的 $W_{i,t}$ 计算 NCSKEW 和 DUVOL:

$$NCSKEW_{i,t} = -[n(n-1)^{3/2} \sum W_{i,t}^3] / [(n-1)(n-2)(\sum W_{i,t}^2)^{3/2}]$$

$$DUVOL_{i,t} = \log\{[(n_u - 1) \sum_{Down} W_{i,t}^2] / [(n_d - 1) \sum_{Up} W_{i,t}^2]\}$$

$NCSKEW_{i,t}$ 和 $DUVOL_{i,t}$ 越大,股价崩盘风险越大。 n 为个股交易周数, n_u 和 n_d 为周收益率高于和低于其年均收益率的周数。

(3) 投资者情绪

根据翟淑萍等(2014)^[30]的研究, Tobin'Q 包含了资本市场股票的未来机会和投资者情绪引起的股价变动,因此通过分解 Tobin'Q 的方法可以衡量公司层面的投资者情绪 IS,在控制行业变量 Industry 和年度变量 Year 后,将公司 Tobin'Q 与净资产收益率 Roe、资产负债率 Lev、营业收入增长率 Grow、公司规模 Size 进行回归:

$$Tobin'Q_{i,t} = a_0 + a_1 Roe_{i,t} + a_2 Lev_{i,t} + a_3 Grow_{i,t} + a_4 Size_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t}$$

将残差 ε 标准化后得到投资者情绪 IS。

(4) 控制变量

为了保证研究结果的可靠性,借鉴已有研

究(许年行等, 2013^[31]),控制公司规模 Size、月均超额换手率 Dturn、收益波动 Sigma,股票回报率 Ret,行业变量 Industry 和年度变量 Year。

3、实证模型

首先,用模型(1)检验上市公司质量和股价崩盘风险的关系:

$$CR_{i,t} = \alpha_0 + \alpha_1 Q_{i,t} + \alpha_2 Ret_{i,t} + \alpha_3 Sigma_{i,t} + \alpha_4 Dturn_{i,t} + \alpha_5 Size_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \quad (1)$$

其中, CR 为股价崩盘风险的替代变量 NCSKEW、DUVOL, $Q_{i,t}$ 是通过本文构建的上市公司质量评价体系,由表 1 所示的相关变量通过 CRITIC 权重法赋权得出的综合评分,代表上市公司质量。

其次,用模型(2)检验投资者情绪和上市公司质量的关系:

$$IS_{i,t} = \beta_0 + \beta_1 Q_{i,t} + \beta_2 Ret_{i,t} + \beta_3 Sigma_{i,t} + \beta_4 Dturn_{i,t} + \beta_5 Size_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \quad (2)$$

最后,用模型(3)检验投资者情绪在上市公司质量与股价崩盘风险关系中的作用,采用逐步回归法检验中介效应,构建如下模型:

$$CR_{i,t} = \gamma_0 + \gamma_1 Q_{i,t} + \gamma_2 IS_{i,t} + \gamma_3 Ret_{i,t} + \gamma_4 Sigma_{i,t} + \gamma_5 Dturn_{i,t} + \gamma_6 Size_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \quad (3)$$

根据温忠麟和叶宝娟(2014)^[32]的中介效应检验方法,若系数 β_1 和 γ_2 均显著,且乘积 $\beta_1 * \gamma_2$ 与 α_1 符号相反,说明投资者情绪存在遮掩作用,否则为中介作用。

四、实证结果与分析

1、描述性统计分析

根据表 2 结果可知: Q 均值为 0.508,最大为 0.854,最小为 0.101。NCSKEW 和 DUVOL 的均值分别为 -0.326 和 -0.217,标准差分别为 0.721 和 0.479。Senti 最大达到 37.909,最小为 -3.303。

表 2 描述性统计

变量	N	均值	最小值	25% 分位数	中值	75% 分位数	最大值	标准差
Q	7547	0.508	0.101	0.407	0.526	0.595	0.854	0.122
NCSKEW	7547	-0.326	-5.170	-0.699	-0.278	0.102	3.676	0.721
DUVOL	7547	-0.217	-2.018	-0.529	-0.211	0.096	2.224	0.479
IS	7547	0.000	-3.303	-0.397	-0.111	0.223	37.909	1.000
Ret	7547	0.005	-0.045	-0.001	0.004	0.010	0.062	0.010
Sigma	7547	0.063	0.014	0.044	0.055	0.074	0.229	0.028
Dturn	7547	-3.374	-589.3	-14.01	0.604	14.81	319.4	44.73
Size	7547	22.65	18.19	21.62	22.42	23.52	28.51	1.437

表 3 报告了上市公司质量与股价崩盘风险的回归结果, 该模型控制了行业变量 *Industry* 和年度变量 *Year*, 列(1)、(2)中 *Q* 的回归系数 α_1 显著为负, 即上市公司质量越高, 股价崩盘风险越低, 验证了

H1。回归结果中控制变量 *Ret*、*Sigma*、*Size* 的系数均为负且显著性水平较高, 表明股票回报率、收益波动、上市公司资产规模等有助于抑制股价崩盘风险。

表 3 上市公司质量与股价崩盘风险

变量	(1) NCSKEW	(2) DUVOL	(3) CRASH	(4) NCSKEW _{t+1}	(5) DUVOL _{t+1}	(6) NCSKEW _{t+2}	(7) DUVOL _{t+2}
Q	-0.317*** (0.069)	-0.195*** (0.046)	-0.079*** (0.030)	-0.198*** (0.074)	-0.073 (0.048)	-0.200** (0.080)	-0.089* (0.052)
Ret	-5.040*** (1.487)	-6.085*** (0.993)	-5.458*** (0.620)	14.582*** (1.465)	9.721*** (0.949)	3.861** (1.529)	1.634 (0.996)
Sigma	-8.649*** (0.640)	-4.411*** (0.389)	0.251 (0.242)	-1.884*** (0.589)	-1.261*** (0.379)	-1.414** (0.624)	-0.784* (0.410)
Dturn	-0.000 (0.000)	-0.000** (0.000)	0.000* (0.000)	-0.001*** (0.000)	-0.001*** (0.000)	-0.000* (0.000)	-0.000* (0.000)
Size	-0.075*** (0.007)	-0.057*** (0.005)	-0.008*** (0.003)	-0.047*** (0.008)	-0.043*** (0.005)	-0.049*** (0.008)	-0.046*** (0.005)
Constant	1.987*** (0.183)	1.396*** (0.119)	0.313*** (0.076)	0.816*** (0.188)	0.769*** (0.122)	1.022*** (0.201)	0.919*** (0.130)
Industry	控制	控制	控制	控制	控制	控制	控制
Year	控制	控制	控制	控制	控制	控制	控制
N	7,547	7,547	7,547	7,547	7,547	6,632	6,632
R ²	0.103	0.105	0.024	0.069	0.078	0.049	0.061

表 4 列(1)为上市公司质量对投资者情绪的回归结果, 回归系数 β_1 为 0.325, 且在 1%水平上显

著, 说明上市公司质量显著提高了投资者的信心, 上市公司质量越高, 投资者情绪越高涨, H2 成立。

表 4 列 (2)、(3) 报告了投资者情绪的中介作用, 模型中加入中介变量投资者情绪后, 股价崩盘风险与投资者情绪的回归系数 γ_2 (0.020 或 0.016) 在不低于 5% 的水平上显著为正, 即投资者情绪加剧了股价崩盘风险, 与已有研究 (郝芳静等, 2020^[11]) 结论一致, 综合表 4 列 (1) 的回归结果表明投资者情绪在上市公司质量与股价崩盘风险的间接效

应显著, 且上市公司质量的间接效应 $\beta_1 * \gamma_2$ (0.325*0.020 或 0.325*0.016) 的符号与直接效应 α_1 (-0.317 或 -0.195) 的符号相反, 说明投资者情绪在上市公司质量与股价崩盘风险间发挥了部分遮掩效应, 投资者情绪抵销了上市公司质量对股价崩盘风险的部分影响, H3 得到验证。

表 4 上市公司质量、投资者情绪与股价崩盘风险

变量	(1) Senti	(2) NCSKEW	(3) DUVOL
Q	0.325*** (0.080)	-0.324*** (0.069)	-0.200*** (0.046)
IS		0.020** (0.008)	0.016*** (0.005)
Ret	32.123*** (2.871)	-5.685*** (1.526)	-6.613*** (1.016)
Sigma	-0.186 (0.822)	-8.646*** (0.640)	-4.408*** (0.389)
Dturn	0.001* (0.000)	-0.000 (0.000)	-0.000** (0.000)
Size	0.010 (0.021)	-0.076*** (0.007)	-0.057*** (0.005)
Constant	0.325*** (0.080)	-0.324*** (0.069)	-0.200*** (0.046)
Industry	控制	控制	控制
Year	控制	控制	控制
N	7,547	7,547	7,547
R ²	0.053	0.104	0.106

3、稳健性检验

(1) 替换被解释变量

用哑变量 CRASH 作为将被解释变量进行回归, 表 3 列 (3) 的结果再一次验证了 H1。

(2) 内生性检验

为了检验股价崩盘和上市公司质量的内生性问题, 参考已有研究 (许年行等, 2013^[31]), 将股价崩盘风险分别滞后一期 ($NCSKEW_{t+1}$ 和 $DUVOL_{t+1}$)、两期 ($NCSKEW_{t+2}$ 和 $DUVOL_{t+2}$) 重新回归, 回归结

果见表 3 列 (4) - (7), 除了滞后一年的 DUVOL 回归不显著, 其他回归结果均表明上市公司质量与股价崩盘风险显著负相关。

模型无法排除因股价崩盘引起的上市公司质量的逆向影响, 为了进一步缓解存在的内生性问题, 参考王海芳和张笑愚 (2021)^[32] 的研究, 将滞后一期的上市公司质量 LQ 作为工具变量, 并采用 2LSL 进行回归, 结果如表 5 所示, 列 (1) 第一阶段 F 值为 108.52, 即不存在弱工具变量问题, 列 (2) - (3)

为 2LSL 第二阶段的回归结果, 结果表明上市公司质量与股价崩盘风险显著负相关, 增强了结论的可靠性。

表 5 工具变量检验

	(1)	(2)	(3)
变量	一阶段 Q	二阶段 NCSKEW	二阶段 DUVOL
LQ	0.481*** (30.68)		
Q		-0.672*** (-3.27)	-0.294** (-2.14)
Controls	控制	控制	控制
Constant	-0.117** (-3.04)	1.920*** (7.34)	1.376*** (7.88)
F (一阶段)	108.52		
N	3838	3,838	3,838
R^2	0.333	0.111	0.117

(3) 变换上市公司质量评价指标赋权方法 重新赋权, 回归结果如表 6, 虽然回归系数有所变化, 但上市公司质量与股价崩盘风险仍然显著负相关。为了验证上市公司质量综合评分的可靠性, 分别采用熵值法和独立性权重对上市公司质量指标

表 6 改变上市公司质量综合评价方法

	熵值法		独立性权重	
变量	NCSKEW	DUVOL	NCSKEW	DUVOL
Q	-0.279*** (0.097)	-0.133** (0.064)	-0.615** (0.256)	-0.365** (0.170)
Ret	-5.014*** (1.489)	-6.074*** (0.995)	-4.964*** (1.489)	-6.040*** (0.995)
Sigma	-8.555*** (0.639)	-4.344*** (0.389)	-8.565*** (0.641)	-4.358*** (0.389)
Dturn	-0.000 (0.000)	-0.000** (0.000)	-0.000 (0.000)	-0.000** (0.000)
Size	-0.077*** (0.007)	-0.059*** (0.005)	-0.080*** (0.007)	-0.060*** (0.005)
Constant	1.912*** (0.185)	1.363*** (0.120)	2.072*** (0.185)	1.447*** (0.120)
Industry	控制	控制	控制	控制
Year	控制	控制	控制	控制
N	7,547	7,547	7,547	7,547
R^2	0.102	0.103	0.101	0.104

(4) 增加控制变量

增加市场化发展程度、控股股权性质等控制变量, 结论与前文一致。

五、研究结论与建议

本文利用 2011-2020 年沪深 A 股上市公司的数据, 从价值创造、治理优化、社会责任、研发创新及绿色发展五个维度构建了上市公司质量的评价体系, 通过 CRITIC 赋权法得到上市公司质量综合评分, 检验了上市公司质量与股价崩盘风险的关系并探究投资者情绪的间接效应。实证研究发现: 上市公司在价值创造、治理优化、社会责任、研发创新及绿色发展五个方面综合表现越好, 股价崩盘风险越小, 投资者情绪也会随着上市公司质量的提高而提高, 且个股投资者情绪会抵销上市公司质量对股价崩盘风险的影响, 换言之, 个股投资者情绪存在遮掩效应。

本文采用工具变量法、滞后被解释变量缓解内生性问题, 同时通过替换被解释变量、改变上市公司质量赋权方法、加入其他控制变量增加研究结论的稳健性。针对本文的结论, 提出建议:

1、提高上市公司质量。上市公司应当全方位发展, 不仅要提高价值创造水平, 还要重视提升公司声誉, 良好的公司形象与声誉可以有效增强投资者信心, 稳定股价缓解股价崩盘风险。上市公司可以通过社会责任的履行、研发创新以及绿色发展等方式积累公司声誉资本, 提高上市公司质量。

2、理性投资。政府应积极引导投资者从多方面综合评价上市公司质量, 理性选择投资对象, 避免投资者情绪“堆砌”的股价泡沫。尤其我国个体投资者比重大, 专业知识和时间精力有限, 很难保持完全理性, 应预防非理性投资对证券市场造成的不利影响。

3、优化公司上市门槛。监管部门应完善公司上市的门槛制度, 优化公司上市标准, 支持优质公司上市, 积极引导上市公司通过正确的方式和途径提高其自身质量, 增加违规经营的成本, 提高上市公司质量, 同时优化市场环境, 降低股价崩盘风险。

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非正式环境规制激发了实质性绿色创新吗？ ——来自环境信息公开的准自然实验

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摘要：实质性绿色创新是实现环境保护与经济增长双赢目标的关键所在，正式环境规制的失灵使得学界越来越关注非正式环境规制的创新激励作用。因此，本文以“公众环境研究中心”对部分城市进行环境信息公开这一准自然实验为例，使用 2003-2018 年 286 个城市的面板数据并采用渐进 DID 方法，系统考察了环境信息公开对城市实质性绿色创新水平的影响效应、异质性特征及作用机制。研究发现：环境信息公开显著提高了城市实质性创新水平，该结论在经过平行趋势、安慰剂及工具变量等一系列稳健性检验后依然成立。进一步的异质性分析表明，环境信息公开的实质性绿色创新效应在城市层面和时间层面存在显著差异，环保重点城市、实质性创新水平越高城市内的创新效应更强，政策第二阶段的创新效应比第一阶段更强。机制分析表明，环境信息公开主要通过外商直接投资和人力资本积累等有效渠道促进城市实质性创新水平的提升。本文结论为协同推进环境保护与经济发展提供了有效参考，论证了非正式环境规制在绿色创新中的重要性。

关键词：非正式环境规制；实质性绿色创新；环境信息公开；双重差分

Does Informal Environmental Regulation Stimulate Substantial Green Innovation?--A Quasi-Natural Experiment from Environmental Information Disclosure

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Abstract: Substantial green innovation is the key to achieving the win-win goal of environmental protection and economic growth. The failure of formal environmental regulations has led to an increasing interest in the innovation incentives of informal environmental regulations. Therefore, using a panel data of 286 cities from 2003 to 2018, this paper use the DID model to systematically investigates the effect of environmental information disclosure on substantive green innovation. It is found that environmental information disclosure significantly promotes substantive innovation, and it still holds after a series of robustness tests including parallel trend, placebo and instrumental variables. Heterogeneity analysis shows that the effects of environmental information disclosure differ significantly at the city level and at the time level. Mechanism analysis shows that environmental information disclosure promotes substantive innovation through foreign direct investment and human capital accumulation. This paper provide an effective reference for the synergistic promotion of environmental protection and economic development, and argue for the importance of informal environmental regulation in green innovation.

Key Words: Informal environmental regulation; Substantive green innovation; Environmental information disclosure; Difference-in-differences

引言

经济新常态下,党和政府提出创新驱动发展战略。绿色创新是打破经济与环境“非此即彼”局面的着力点。然而,绿色创新的双重外部性导致企业不愿意主动进行绿色技术创新^{[1]、[2]}。环境规制作为一种较为成熟且应用广泛的管制手段,其目的便是通过将环境成本内化于企业生产决策的方式,倒逼企业采取绿色技术,最终降低污染排放^{[3]、[4]}。

环境规制分为政府主导下的正式环境规制以及社会公众和环保非政府组织参与下的非正式环境规制^[5]。然而,正式环境规制导向下的绿色创新可能并不是追求质量的实质性创新,而是一种求量不求质的策略性创新行为。这是因为正式环境规制的非完全执行现象较为普遍^[6]。一方面,受到成本、精力等约束,环境管制者和污染者之间的信息不对称现象较为突出^[7]。因此,企业可能通过短时间内重复无意义的绿色创新成果释放虚假的创新信号,以规避政府的环境监管^{[8]、[9]}。另一方面,以GDP为主要指标的官员晋升机制为企业采取策略性创新提供制度土壤^[10]。地方官员出于自身政治利益的考虑,可能对企业的创新行为“睁一只眼闭一只眼”,只要企业的创新产出达标即可^[11]。因此,企业为了迎合官员的政治需求和降低自身的减排压力,过度追求创新的速度和数量,而不愿意进行周期长、难度高,风险大的高质量创新^[12]。信息不对称和政企合谋下的正式环境规制难以得到有效执行,导致企业策略性创新行为频发,创新质量停滞不前。

黎文靖和郑曼妮^[13]指出,策略性创新是对政府政策和监管的迎合,其目的并不是为了提升企业竞争力而是为了获取某种利益,只有实质性创新才能真正地推动技术进步和获取竞争优势。鉴于正式环境规制在实践中的问题,非正式环境规制逐渐受到学界关注^[14]。其中,环保非政府组织作为非正式环境规制中的代表性力量,在我国现行的环境治理体系中发挥着重要作用。由公众环境研究中心发布的污染源监管信息透明指数不仅提高公众环境参与度,也有助于提升政府环境监管效率和倒逼企业环境守法,是政府失灵和市场失灵下的有力补充和有

效替代^[15]。鉴于此,本文尝试回答以下问题:环境信息公开是否可以实现实质性创新水平的提升?如果可以,又是通过何种渠道发挥作用?厘清上述问题对发挥非正式环境规制对实质性创新的倒逼作用,利用创新驱动因素实现环境与经济的融合发展,有着重要的理论意义和实践价值。

本文可能的边际贡献体现在:第一,扩展了波特假说理论的研究范畴。现有文献对于非正式环境规制的研究较少,且关于非正式环境规制的研究主要集中在其对于污染排放的影响^{[16]、[17]}。随着我国生活水平的提升和创新驱动战略的提出,非正式环境规制的绿色创新效应不容忽视。第二,利用环境信息公开这一准自然实验,避免了因非正式环境规制度量不准确所带来的内生性问题。以往文献^{[18]、[19]}大多采用诸如环境信访数和来信数、环境方面的人大建议数和政协提案数等指标间接表征非正式环境规制,然而这些指标均不能很好地反映非正式环境规制的真实水平。第三,加深了对创新行为和创新动机的理解。创新行为可分为以推动技术进步和保持竞争优势为目的的实质性创新,以及以获取其他利益为目的的策略性创新^[20]。经济下行形势下,原有的强势环保举措在执行中可能遇到更多的阻碍,市场则长期存在劣币驱逐良币的情况。本文基于非正式环境规制视角,探究实质性创新行为的倒逼机制,有助于理解绿色创新过程中“政府-企业-社会”多主体互动机制。

政策背景与研究假设

政策背景

公众环境研究中心(IPE)是一家致力于推动公众环境参与和完善环境治理机制的环保民间组织,其联合美国自然资源保护协会共同开发了污染源监管信息公开指数(PITI)。IPE自2008年发布首期PITI报告以来持续至今。2008-2012年,PITI报告共对113座城市进行环境信息公开,2013年起在原来113个城市基础上新增7个城市,总计120座城市。自报告发布以来,公众所能获取的环境信息类型和数量均有较大程度的提升,环境知情权也得到较大程度的保障。PITI报告已成为公众甄别和处理

环境风险的一个有效工具,是环保非政府组织积极参与城市环境建设,推动环境信息公开的体现。

研究假设

环境信息公开对城市实质性创新水平的影响

环境信息公开对城市实质性创新水平的影响具体体现在以下两点。一方面,环境信息公开有效抑制政企合谋。地方政府存在为快速达到创新标准而扶持有大量成果产出但质量欠缺的企业^[21]。企业也存在为“寻扶持”而进行地方政府所希望的短时间内有创新产出的策略性创新行为^[22]。环境信息公开对政府和企业环境行为的曝光增大了企业寻租成本^[23],企业不得不为了自身长期发展而进行高质量的实质性创新。另一方面,环境信息公开缓解了信息不对称现象^{[24]、[25]}。PITI 报告是公众了解政府和企业环境行为的一个重要渠道^[26]。在公众和环保社会组织的监督下,企业的环境违法成本大大提高。鉴于求量不求质的策略性创新无法真正地实现差异化产品,企业只能进行实质性绿色创新以增强产品的市场竞争力。此外,政府受到资源、人手和成本等的限制无法监管到中小型企业的环境违法行为,得益于环境信息公开,企业无法通过简单创新来“糊弄”环境执法人员,只能进行实质性创新降低自身污染排放。

假说 1: 环境信息公开能够促进实质性创新水平的提升。

环境信息公开影响城市实质性创新水平的作用渠道

一是外商直接投资渠道。FDI 的技术溢出效应是东道主国家技术创新的重要来源^[27]。研究表明,FDI 通过示范模仿效应、前后产业关联效应、竞争效应以及人员流动和培训效应产生技术溢出,从而推动当地技术创新能力有效提升^[28]。环境信息公开这一环保非政府组织自发形成的非正式环境规制制度,通过对环境污染信息的披露无形中强化了 FDI 的技术溢出效应。环境信息公开不仅能够提高外来资本的“绿色化程度”,也增强了本土企业的外资吸收能力。在非正式环境规制的约束下,本土企业更愿意也更加积极地借鉴和模仿行业内顶尖外

资企业的成功经验,提高自身产品和服务的科技含量。这是因为,与正式环境规制这种“硬约束”相比,环境信息公开相对柔性,短期内并不会显著增加企业的生产成本致使企业创新激励不足。此外,公众越来越关注环境质量,企业出于树立自身社会形象和赢得市场份额的需要,往往会加大研发投入,提高产品附加值^{[29]、[30]}。

假说 2: 环境信息公开通过外商直接投资渠道提升实质性绿色创新水平。

二是人力资本积累渠道。知识经济时代,技术进步离不开高层次创新型和高技术技能型人才的推动作用^[31]。科研人员所拥有的强大的知识获取、吸收、消化和转化能力能够精准快速地将新知识、新技术应用于新产品的生产和销售中。因此,人力资本积累尤其是高端技术人才存量的增加是城市技术进步的支撑与动力。长期以来,公众的环境知情权的缺失致使社会信任度不足,由环境问题引致的社会矛盾较为尖锐和突出^[32]。环境信息公开保障了公众环境知情权,有助于缓解政企合谋等腐败现象^[33],进而增强社会公众对政府官员的信任度。此外,环境信息公开城市的环境不确定风险较小^[34],即使出现了环境风险,借助于环境信息这一充足证据,公众维权和上访的成本更低,成功率更高。因此,公众更愿意居住在环境信息公开城市进而为城市的建设添砖加瓦。

假说 3: 环境信息公开通过人力资本积累渠道提升实质性绿色创新水平。

简而言之,环境信息公开缓解了正式环境规制下可能存在的政企合谋和信息不对称等不良现象,总体上起到了激发城市实质性绿色创新的作用。结合已有文献,本文认为环境信息公开可能通过外商直接投资和人力资本两大渠道提升实质性绿色创新水平。理论机制见图 1。

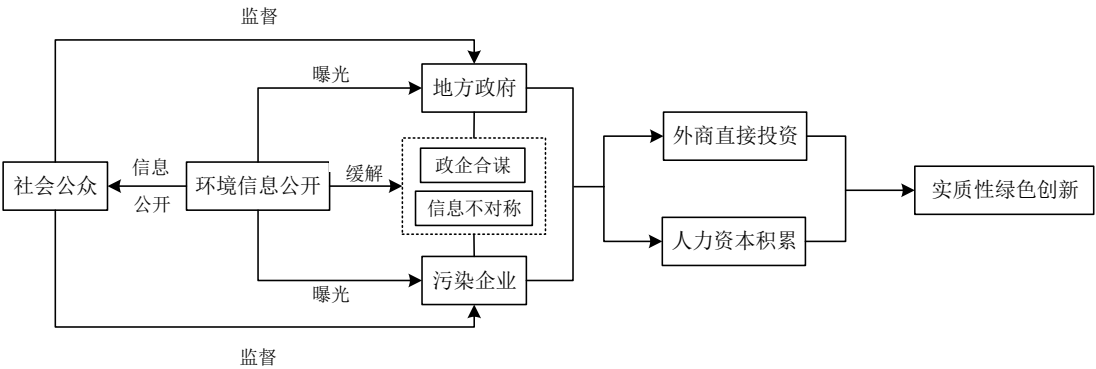


图 1 环境信息公开激发实质性绿色创新的理论机制

模型设定、变量与数据说明

模型

由于环境信息公开城市是分两批次设立的，故设定如下渐进双重差分模型：

$$lngreen_{it} = \alpha_0 + \alpha_1PITI_{it} + \gamma_jX_{itj} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

其中， $lngreen_{it}$ 表示城市*i*在年份*t*的实质性绿色创新水平； $PITI_{it}$ 是虚拟变量，若城市*i*在年份*t*属于环境信息公开城市，则取 1，否则取 0； X_{itj} 为控制变量矩阵； μ_i 为城市固定效应； λ_t 为时间固定效应； ε_{it} 为聚类到城市层面的随机误差项。回归系数 α_1 反映政策的净效应。

变量

实质性绿色创新。黎文靖等人^[13]将发明专利申请行为认定为实质性创新行为。参考黎文靖等人^[13]的研究，本文选用绿色发明专利申请量占地区当年绿色专利申请量百分比的对数衡量城市实质性绿色创新水平。出于稳健性考虑，后续研究中采用绿

色发明专利申请量(*patent*)和人均绿色发明专利申请量(*perpatent*)作为城市实质性绿色创新水平的替换指标。

控制变量包括：①产业结构(*lnstruct*)。以城市第三产业增加值占地区生产总值比重的对数衡量。②污染水平(*lnpollu*)。以当地工业废水排放量的对数衡量。③经济发展水平(*lngdpper*)。以人均 GDP 的对数衡量，按 2000 年不变价折算。④财政盈余(*deficit*)。以地方财政收入与支出之差除以地方财政支出衡量。数据来源于《中国城市统计年鉴》。

为避免样本城市前后不一致性对估计结果的偏误，将《2003 年中国城市统计年鉴》所列出的 286 个城市作为本文的研究对象。最终样本为 2003-2018 年 286 个城市组成的面板数据，包括 120 个环境信息公开城市(实验组)和 166 个非环境信息公开城市(对照组)。主要变量的描述性统计见表 1。

表 1 主要变量描述性统计

变量	变量含义	样本数	均值	标准差	最小值	最大值
lngreen	实质性绿色创新	4274	2.42	0.48	-0.21	3.54
PITI	环境信息公开	4566	0.28	0.45	0	1
lngdpper	经济发展水平	4561	9.90	0.76	4.35	12.80
lnstruct	产业结构	4552	3.61	0.26	2.15	8.42
lnpollu	污染水平	4498	8.31	1.12	1.95	11.45
deficit	财政盈余	4561	-0.52	0.23	-0.97	0.54

实证结果与分析

基准回归

表 2 报告了环境信息公开对城市实质性绿色创新水平影响的结果。列(1)和列(2)的全样本回归结果

显示，无论是否加入控制变量，PITI 的系数至少在 5%的水平上显著为正，表明环境信息公开显著促进城市实质性绿色创新水平的提升。列(3)-(6)表明环境信息公开政策的实质性绿色创新水平提升效应

在排除直辖市和副部级城市之后依然具有稳健性。

表 2 基准回归结果

	全部城市		排除直辖市		普通地级市	
	(1)	(2)	(3)	(4)	(5)	(6)
PITI	0.1067*** (0.0399)	0.0915** (0.0400)	0.1036** (0.0403)	0.0896** (0.0403)	0.0911** (0.0420)	0.0798* (0.0418)
lnstru ct		0.1004 (0.1331)		0.1005 (0.1339)		0.0965 (0.1348)
lnpoll u		-0.0076 (0.0232)		-0.0079 (0.0234)		-0.0090 (0.0244)
lngdp per		-0.0787 (0.0731)		-0.0756 (0.0739)		-0.0704 (0.0782)
deficit		0.1144 (0.1140)		0.1076 (0.1146)		0.0939 (0.1250)
Const ant	2.3851*** (0.0120)	2.9312*** (1.0788)	2.3854*** (0.0118)	2.8985*** (1.0851)	2.3849*** (0.0114)	2.8614** (1.1233)
City-fi xed	YES	YES	YES	YES	YES	YES
Year-f ixed	YES	YES	YES	YES	YES	YES
N	4274	4202	4210	4142	3970	3906
R ²	0.251	0.251	0.249	0.249	0.242	0.242

注：小括号内数值为聚类（cluster）到省份层面的稳健标准误；*、**、***分别表示 10%、5%、1% 的显著水平。下同。

稳健性检验

平行趋势检验

双重差分方法有效的一个重要前提是平行趋势假设。模型构建如下：

$$lngreen_{it} = \alpha_0 + \sum_{k=-10, k \neq -1}^{10} \beta_k D_{it}^k + \gamma_j X_{itj} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

虚拟变量 D_{it}^k 定义为：设城市 i 首次环境信息公开的年份为 s_i ，令 $k=s_i-t$ ，若城市 i 在年份 t 属于环境信息公开城市，则 $D_{it}^k = 1$ ，否则 $D_{it}^k = 0$ 。其余变量描述与模型(1)一致。将环境信息公开政策设立的前一年($k=-1$)作为基准年份。 β_k 表示环境信息公开与未公开城市的实质性绿色创新水平差异。图 2 表明，在环境信息公开之前的各年， β_k 的置信区间均包括 0，表明政策实施前两组的实质性绿色创新水平并不存在显著差异。环境信息公开当年的系数不显著，在后一年才开始显著为正，表明环境信息公开的政策效应具有滞后性。政策实施后的 β_k 显著为正且波动幅度较小，说明环境信息公开的提升效应

具有较好的持续性。

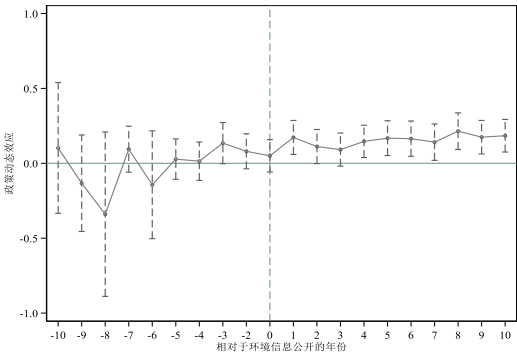


图 2 平行趋势检验

其他稳健性检验

为增强文章结论的可信度，本文进行如下操作：①更换度量指标。分别采用绿色发明专利申请量 (patent) 和人均绿色发明专利申请量(perpatent)表征实质性绿色创新水平 (见表 3 列(1)和列(2))。②控制潜在遗漏变量。在基准回归的基础上，进一步控制了城市信息建设能力、人口聚集程度以及金融发展水平对城市实质性创新水平的影响，分别以互联网

宽带接入用户数的对数、人口密度、年末金融机构人民币各项贷款余额占地区生产总值比重的对数测度(见表 3 列(3))。③在基准回归模型的基础上控制了省份-年份交互固定效应(见表 3 列(4))。在更换指标、控制变量等一系列操作之后,本文结论依然具有稳健性。

表 3 其他稳健性检验结果

	更换度量指标		控制潜在 遗漏变量	交互固 定
	(1)	(2)	(3)	(4)
	patent	perpatent	lngreen	lngreen
PITI	0.4029*** (0.0762)	0.6249*** (0.1055)	0.0862** (0.0406)	0.0922** (0.0405)
Control Variables	YES	YES	YES	YES
City-fixed	YES	YES	YES	YES
Year-fixed	YES	YES	YES	YES
省份-年份固定				YES
Constant	5.3317*** (2.0136)	8.4004*** (2.6261)	2.1613* (1.1573)	3.2212*** (1.1690)
N	4395	4391	4146	4115
R ²	0.547	0.594	0.249	0.282

其他政策冲击

本文控制了样本期内其他可能影响到城市实质性绿色创新水平的政策冲击,具体包括:①二氧化硫排放权交易试点。2007 年财政部会同原国家环境保护部,国家发展改革委批准 11 个省(市)为国家级排污权交易试点。②低碳试点。2010 年 8 月国家发改委发布《关于开展低碳省区和低碳城市试点工作的通知》,明确在“五省八市”开展低碳试点工作。③碳排放权交易试点。2011 年 10 月,国家发展改革委发布《关于开展碳排放权交易试点工作的通知》,确定北京、天津、上海、重庆、湖北、广东及深圳市开展碳排放权交易试点。上述试点政策可能会通过增大试点城市的环境规制压力倒逼城市实质性绿色创新水平的提升。表 4 表明,在剔除一系列可能影响实质性绿色创新水平的政策之后,PITI 的系数依旧显著为正。

表 4 控制其他政策冲击

	SO ₂ 排放权 交易试点	低碳试点	碳交易试点
	(1)	(2)	(3)
	lngreen	lngreen	lngreen
PITI	0.1283** (0.0509)	0.0851* (0.0483)	0.0895** (0.0441)
Control	YES	YES	YES

Variables			
City-fixed	YES	YES	YES
Year-fixed	YES	YES	YES
Constant	0.9556 (0.9712)	2.7897** (1.2789)	2.9851** (1.1931)
N	2569	3149	3655
R ²	0.243	0.230	0.245

安慰剂检验

本文通过随机选择处理组和处理时间构造虚假的 PITI 变量进行安慰剂检验。图 3 依次展示了被解释变量为 lngreen、patent、perpatent 方程的 PITI 的估计系数的核密度图。三类方程的随机抽样 1000 次的回归系数均值都集中在 0 附近,而基准回归的系数分别是 0.0915、0.4029、0.6249,大于绝大多数模拟值,可被视为极端值。同时,参数估计值的 p 值大多大于 0.1,表明虚构的 PITI 的回归系数多数不能通过显著性检验,上述分析说明虚构的环境信息公开政策不存在显著的实质性绿色创新水平提升效应。

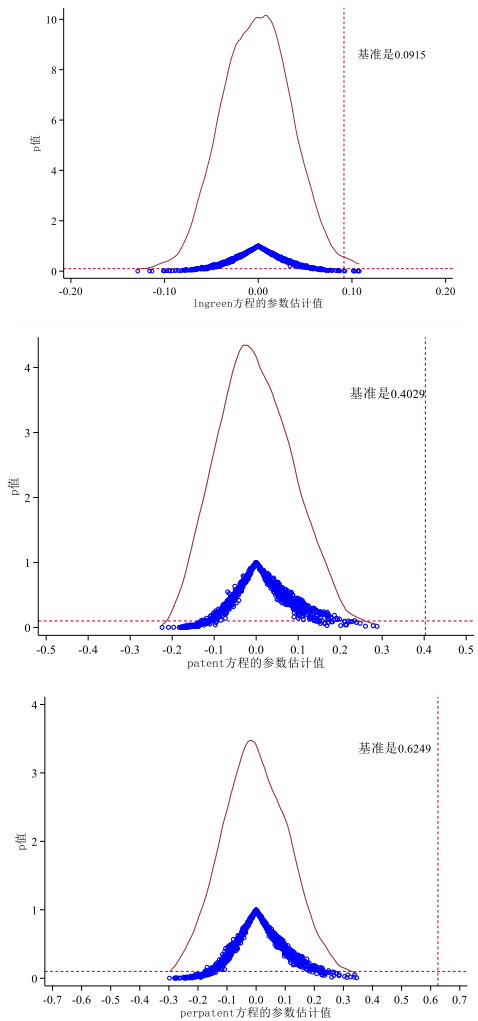


图 3 安慰剂检验结果的 1000 次模拟

工具变量法

虽然环境信息公开这一事件可被近似看做外生政策冲击，但本文仍然担心环境信息公开城市的选择具有潜在的内生性。为此，继续采用工具变量方法，模型如下：

$$PITI_{it} = \alpha_0 + \alpha_1 IV_i \times Post_t + \gamma_j X_{itj} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

$$lngreen_{it} = \alpha_0 + \alpha_1 PITI_{it} + \gamma_j X_{itj} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

模型(3)和(4)分别是第一阶段和第二阶段的回归模型。 $Post_t$ 定义为政策实施当年及以后取 1，否则取 0。 IV_i 是工具变量，参照史贝贝等人[35]的研

表 5 所示。以被解释变量 $lngreen$ 为例对回归结果进行分析。列(1)表明，城市报纸种类数量与 $PITI$ 具有显著的正向关系，且 F 值大于 10，表明不具有弱工具变量的可能性。列(2)中 $PITI$ 的系数在

研究，选择城市的报纸种类数量 23 作为是否是环境信息公开的工具变量。原因在于：城市报纸种类数量与当地的媒体披露水平息息相关，城市的报纸种类数量越多，越能扩充当地民众的环保诉求渠道，该地被选作环境信息公开城市的几率越大，即满足工具变量的相关性假定；而城市报纸种类数量不太可能通过除环境信息公开外的其他渠道影响地区的实质性绿色创新水平，满足工具变量外生性假定。为了增强结果的可信度，本文又额外选用 $patent$ 和 $lnpatent$ 作为被解释变量，回归结果如

1%的水平上显著为正，表明在考虑了模型潜在的内生性问题后，环境信息公开依旧会显著促进城市的实质性创新水平的提升。同理，列(3)和列(4)、列(5)和列(6)的回归结果分析类似，凸显文章结论的稳健。

表 5 工具变量

	lngreen		patent		perpatent	
	(1)	(2)	(3)	(4)	(5)	(6)
	第一阶段	第二阶段	第一阶段	第二阶段	第一阶段	第二阶段
PITI		0.2756*** (0.0752)		3.0112*** (0.9647)		2.4455*** (0.6428)
IV×Post	0.0664*** (0.0169)		0.0697*** (0.0177)		0.0696*** (0.0177)	
F-value	18.04		16.39		16.35	
Control Variables	YES	YES	YES	YES	YES	YES
City-fixed	YES	YES	YES	YES	YES	YES
Year-fixed	YES	YES	YES	YES	YES	YES
Constant	0.9768 (0.8267)	1.4155 (0.8828)	1.0144 (0.8399)	2.1812 (2.2349)	0.9991 (0.8375)	6.7739*** (2.5768)
N	3235	3235	3346	3346	3343	3343
R ²	0.5814	0.0285	0.5595	0.0900	0.5600	0.0673

进一步分析

异质性分析

A.环保城市与非环保城市

考虑到环保重点城市与非环保重点城市之间在经济发展、产业结构、资源禀赋等方面存在诸多差异，本文根据国家环保重点城市名单²⁴将样本分为环保城市与非环保城市，回归结果见表 6 列(1)和列(2)。结果表明，相比于非环保城市，环保城市的环境信息公开的提升效应更大。这可能是因为，作为生态文明建设模范城市，环保城市往往承受着更大的环境规制压力，在环保非政府组织的监督下，更有可能采取实质性创新而不是策略性创新来提

升实质性绿色创新水平以达到地方环保目标。

B.时间异质性

为了比较两个阶段的政策实施效果，本文设定如下计量模型。

$$lngreen_{it} = \alpha_0 + \alpha_1 Treat_i \times year0812 + \alpha_2 Treat_i \times year1318 + \gamma_j X_{itj} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

$year0812$ 定义为 2008-2012 年区间取 1，否则取 0； $year1318$ 则定义为 2013-2018 年区间取 1，否则取 0。 $Treat_i$ 表示是否是环境信息公开城市。交互项的系数 α_1 和 α_2 分别表示两阶段的政策效应。回归结果见表 6 列(3)和列(4)。无论是否加入控制变量， $Treat \times year0812$ 的系数始终小于 $Treat \times year1318$ 的系数。这意味着相比于第一阶段，第二阶段环境信

确定

²³ 数据来源于《中国重要报纸全文数据库》

²⁴ 环保重点城市由《国家环境保护“十一五”规划》

息公开的政策效应更强。这可能是因为，随着时间的推移，环境信息公开力度不断加强，相关的政策保障措施也在不断完善，企业对政策的理解程度和执行能力有所提升，导致政策第二阶段的影响效应更强。

表 6 城市异质性和时间异质性

	城市异质性		时间异质性	
	(1)	(2)	(3)	(4)
	环保城市	非环保城市	模型设定 1	模型设定 2
PITI	0.2436* (0.1051)	0.1667** (0.0602)		
Treat×year0812			0.0776* (0.0431)	0.0719* (0.0429)
Treat×year1318			0.1405** (0.0473)	0.1436** (0.0474)
Control Variables	YES	YES	NO	YES
City-fixed	YES	YES	YES	YES
Year-fixed	YES	YES	YES	YES
Constant	0.2580* (0.1381)	0.0085 (0.1821)	2.3827** (0.0130)	3.3094** (0.6588)
N	1705	2497	4274	4201
R ²	0.059	0.215	0.252	0.251

C. 实质性绿色创新水平的异质性

本部分采用面板分位数模型以检验不同分位点下环境信息公开的实质性绿色创新水平提升效应。模型设定如下：

$lngreen_{it,q} = \alpha_{0,q} + \alpha_{1,q}PITI_{it} + \gamma_{j,q}X_{itj,q} + \mu_{i,q} + \lambda_{t,q} + \varepsilon_{it,q}$ (6)

其中，下标 i、t、q 分别表示城市、年份和分位点，本文选取 5 个具有代表性的分位点（10%、25%、50%、75%、90%），结果见表 7。在 10% 和 25% 的低分位点下，环境信息公开的政策效应虽然为正但不显著，只有在中高分位点下，环境信息公开政策才能显著提高城市的实质性绿色创新水平。随着城市实质性绿色创新水平的提升，环境信息公开的实质性绿色创新水平提升效应更强。可能的原因是，实质性绿色创新水平越高的城市拥有更多的创新资源，城市内部具有浓厚的创新激励氛围，绿色创新潜力较大。在此背景下，由于环境信息公开使得城市的污染源监管信息更加透明，促使城市内部的创新资源得到有效配置，更多地流向绿色技术创新领域进而提升实质性绿色创新水平。

表 7 城市实质性创新水平的异质性检验

	(1)	(2)	(1)	(2)	(3)
	10%	25%	50%	75%	90%
	lngreen	lngreen	lngreen	lngreen	lngreen
PITI	0.0365 (0.0740)	0.0639 (0.0501)	0.0945** (0.0367)	0.1225** (0.0477)	0.1448** (0.0661)
Control Variables	YES	YES	YES	YES	YES
City-fixed	YES	YES	YES	YES	YES
Year-fixed	YES	YES	YES	YES	YES
N	4202	4202	4202	4202	4202

机制分析

为了厘清环境信息公开提升城市实质性绿色创新水平的作用机制，设定如下模型：

$lngreen_{it} = \alpha_0 + \alpha_1PITI_{it} + \alpha_2PITI_{it} \times lnfdi_{it} + \alpha_3lnfdi_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$ (7)

$lngreen_{it} = \alpha_0 + \alpha_1PITI_{it} + \alpha_2PITI_{it} \times lntalent_{it} + \alpha_3lntalent_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$ (8)

前文理论分析可知，外商直接投资和人力资本是环境信息公开的两个作用渠道，本文分别采用当年实际利用外商直接投资额占地区生产总值比重的对数(lnfdi)和科研综合技术服务业从业人员数占第三产业从业人员数比重的对数(lntalent)作为度量指标。表 8 中 PITI×lnfdi 的系数显著为正，表明环境信息公开能通过发挥出外商直接投资的技术外溢效应进而提高当地实质性绿色创新水平。PITI×lntalent 的系数显著为正，表明环境信息公开城市能吸引更多的科研人员，从而提高当地的实质性绿色创新水平。

表 8 作用机制检验

	外商直接投资机制		人力资本机制	
	(1)	(2)	(3)	(4)
	lngreen	lngreen	lngreen	lngreen
PITI×lnfdi	0.0260* (0.0141)	0.0243* (0.0145)		
PITI×lntalent _t			0.1294** (0.0325)	0.1211** (0.0321)
PITI	0.1248** (0.0425)	0.1236** (0.0429)	1.7393** (0.4073)	1.6213** (0.4021)
Control Variables	NO	YES	NO	YES
City-fixed	YES	YES	YES	YES
Year-fixed	YES	YES	YES	YES
Constant	2.3559** (0.0227)	3.2134** (0.6538)	1.9566** (0.4936)	2.4327** (1.1716)
N	4085	4028	4267	4198
R ²	0.256	0.255	0.254	0.253

结论与政策建议

正式环境规制的效力不足致使创新主体动力

不足,策略性创新行为频发。为此,本文采用发明专利数据衡量实质性绿色创新水平,使用渐进双重差分方法识别环境信息公开对实质性创新的激励作用及其内在机制。结果表明:(1)整体来看,非正式环境规制显著提升城市实质性创新水平。(2)基于城市特征视角,环保城市、实质性创新水平越高的城市受到政策的冲击更大;基于时间趋势视角,第二阶段的政策效应高于第一阶段。(3)机制分析表明,环境信息公开通过外商直接投资和人力资本积累渠道发挥作用。

基于上述研究结论,本文提出以下三条建议:

第一,健全环境信息法规体系,提高环境信息公开强度。当前我国应以已出台的环境信息公开法规为基础,通过完善立法和制定政策,不断建立健全环境信息公开的法规体系。此外,还应进一步扩大环境信息公开城市范围,提高环境信息公开的质量、数量和频率。

第二,构建多元环境治理体系,拓宽社会环境监督渠道。如充分利用“互联网+”时代的优势,加强环境信息公开政务平台建设,形成政府和公众的良性互动机制;拓宽消费者协会、工会、网络新闻媒体等社会监督渠道,利用社会舆论压力倒逼企业实质性创新。

第三,建立绿色政绩考核体系,强化中央环保监督执法。地方官员可能为应付中央考核对中小型企业“一刀切”式管理,或是因顾忌大型企业而选择性执行环境规制。建议加大对绿色技术研发和推广等具体环保措施的考核比重,积极开展中央环保督察巡视和专题调研等活动,推动政府环境信息完整真实地公开。

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多个大股东对企业费用粘性的影响研究

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摘要：多个大股东可以缓解控股股东的私利，但大股东之间的协调成本，可能使监督管理者自利行为的力度和效率下降，导致费用粘性增加。基于此，文章以2010–2020年沪深A股企业为样本，检验了多个大股东对企业费用粘性的影响。研究表明，多个大股东的股权结构会增加企业的费用粘性；除控股股东外，其他大股东数量越多、持股比例越多，对费用粘性的增加作用越强。在使用固定效应模型、倾向得分匹配和Heckman两阶段控制内生性，以及变换年份和大股东衡量标准后，得到的结论依旧稳健。进一步研究发现，多个大股东对费用粘性的增加作用是通过代理成本这一中介实现的；多个大股东对费用粘性的增加作用在非国有企业、市场化程度低的企业中更加明显。研究补充了多个大股东对管理者成本管理行为的负面影响，为全面理解多个大股东这一股权结构在公司治理中的作用提供了经验证据。

关键词：多个大股东，费用粘性，代理问题

The Effect of Multiple Large Shareholders On Corporate Cost Stickiness

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Abstract: Multiple large shareholders can alleviate the private interests of the controlling shareholders, but the coordination cost between the large shareholders may reduce the strength and efficiency of supervision of managers' self-interest behavior, resulting in increased cost stickiness. Based on this, the study tests the impact of multiple large shareholders on cost stickiness using the data of A-share companies in Shanghai and Shenzhen stock market in China from 2010 to 2020. The results show that the ownership structure of multiple large shareholders will increase the cost stickiness, and in addition to the controlling shareholder, the more large shareholders and the greater the shareholding ratio, the stronger the increase in the cost stickiness. After using the fixed effect model, propensity score matching and Heckman two-stage control endogeneity, as well as changing the year and the measurement standard of major shareholders, the conclusion is still robust. Further research finds that the increase in cost stickiness of multiple large shareholders is realized through the agency problem, and the increase is more significant in non-state-owned enterprises and low degree of market-oriented enterprises. The research supplements the negative impact of multiple large shareholders on the cost management behavior of managers, and provides empirical evidence for a comprehensive understanding of the role of multiple large shareholders in corporate governance.

Key Words: multiple large shareholders, cost stickiness, agency problem

一、引言

多个大股东既存在抑制控股股东谋取控制权私利的“监督”效应（姜付秀等，2017；马影等，2019；赵彦锋等，2022）^[1-3]，也存在与控股股东共谋侵占企业利益的“合谋”效应（Cheng et al., 2013；吕怀立和李婉丽，2015；牛瑞阳等，2021）^[4-6]。但是，现有研究主要针对多个大股东对控股股东的影响，很少考虑多个大股东对管理者的影响。近期有学者发现，多个大股东之间存在的协调成本，会降低企业对管理者的监督效率，给予管理者自利的机会（Fang et al., 2018；赵国宇，2019）^[7-8]。费用粘性作为成本管理决策的结果，为揭示管理者的成本管理行为提供了线索（Anderson et al., 2003）^[9]，而管理者的机会主义行为会增加费用粘性（Chen et al., 2012）^[10]。那么，多个大股东的股权结构是否会增加管理者的机会主义行为，进而增加企业的费用粘性呢？回答这个问题对全面认识多个大股东的公司治理效应具有重要的意义。

文章收集了2010-2020年我国沪深A股上市公司的数据，研究了多个大股东对费用粘性的影响。结果发现，多个大股东的股权结构增加了企业的费用粘性，这一作用是通过代理成本实现的，且在非国有企业和市场化程度低的企业中更为显著。本文与以往研究的不同点在于：（1）从费用粘性视角，研究了多个大股东对管理者成本管理行为的影响，将多个大股东的治理效应从对控股股东的影响扩展到了对管理者的影响，丰富了多个大股东股权结构的经济后果研究，有助于全面认识多个大股东在公司治理中的作用；（2）验证了代理问题的中介效应，发现多个大股东的股权结构弱化了对管理者的监督效率，提高了第一类代理成本，致使企业的费用粘性增加，进一步拓宽了代理问题对费用粘性动因的解释，有助于认识多个大股东的股权结构影响费用粘性的机制；（3）研究了产权性质和市场化程度对多个大股东影响费用粘性的差异性，拓展了不同制度和不同外部环境下多个大股东的股权结构影响管理者行为的框架，明确了公司治理环境对多个大股东股权结构治理效应的影响，对如何正确发

挥多个大股东的治理作用提供了启发。

二、国内外文献综述

1、费用粘性的成因及影响因素

Anderson et al. (2003)^[9]将费用随业务量变动的不对称现象定义为费用粘性，具体是指业务量上升时费用增加的幅度大于业务量下降时费用减少的幅度。费用粘性的动因主要有调整成本（Pfann 和 Palm, 1993；Banker 和 Chen, 2006）^[11-12]、管理者乐观预期（Anderson et al., 2003；Banker et al., 2011）^{[9][13]}以及代理问题三个观点（Banker et al., 2010）^[14]。代理问题在公司治理中更为普遍，是阐释企业费用粘性的主要动因。其核心观点是，管理者在资源决策过程中有自利动机（孙铮和刘浩，2004）^[15]，为了提高个人的权力和声望，通过并购与过度投资等决策扩大企业规模，完成“帝国构建”获取私利（Chen et al., 2012）^[10]，导致企业资源配置和成本费用偏离最优水平。现有文献验证了代理问题对费用粘性的增加作用，在管理者任期更长（江伟和姚文韬，2015）^[16]，拥有的自由现金流更多（牟伟明，2018）^[17]，以及收到的政府补助更多时（南晓莉和张敏，2018）^[18]，更容易通过资源配置实施机会主义行为。针对代理问题这一动因，国内外学者从提高公司治理水平（Calleja et al., 2006；Chen et al., 2012）^{[19][10]}、加强内部控制（牟韶红，2015）^[20]、加强外部审计（梁上坤等，2015）^[21]、实施薪酬改革（曹晓雪和董文静，2018）^[22]等角度探讨了解决方法。

从与管理者有关的代理问题这一视角出发，部分学者展开了股权结构对企业费用粘性的影响研究，主要集中于第一大股东持股的治理效应，但并未达成一致结论。王明虎和席彦群（2011）^[23]、谢获宝和惠丽丽（2014）^[24]认为股东监督能力和积极性随持股比例增加而上升，第一大股东持股越多，治理环境越好，越能抑制管理者私利和降低费用粘性。而万寿义和田园（2017）^[25]指出，第一大控股股东控制权越高，谋取私利的可能性越大，费用粘性随之增加；且第二至第十大股东对第一大股东制衡越多，费用粘性越低。牟伟明（2018）^[26]也得出

相同结论, 股权制衡度越高, 对企业费用粘性的抑制作用越强, 但二位学者对大股东的界定遵从于持股比例的顺序, 而非有实质权力的 10% 以上持股的股东。

2、多个大股东与公司治理

多个大股东的治理作用分为积极和消极两个方面。积极作用是指多个大股东具有“监督”效应, 能够有效缓解控股股东侵占中小股东利益的行为。已有研究发现, 其他大股东能够通过监督控股股东, 降低企业融资约束(姜付秀等, 2017)^[1]、降低债务融资成本(王运通等, 2017)^[27]、减少公司避税行为(Ouyang et al., 2020)^[28]、提高内部控制质量(马影等, 2019)^[2]和抑制实体企业金融化(赵彦锋等, 2022)^[3]等。消极作用是指多个大股东之间的“合谋”效应, 即其他大股东和控股股东共谋分享控制权私利, 侵占中小股东利益, 具体反映为公司价值降低(Cheng et al., 2013)^[4]、非效率投资(吕怀立等, 2015)^[5]和审计费用提高(牛瑞阳等, 2021)^[6]等。另外, 还有文献从过度监督以及第一类代理问题角度研究了多个大股东的消极作用。朱冰等(2018)^[29]发现, 由于存在多个大股东对控股股东的过度监督, 限制了控股股东的积极性, 对企业的创新行为产生了抑制作用。Fang et al.(2018)^[7]和赵国宇(2019)^[8]发现, 多个大股东的股权结构在缓解控股股东利益侵占的同时, 股东间的协调摩擦降低了对管理者的监督效率。

综上所述, 现有文献发现代理问题是费用粘性产生的动因之一, 股权制衡度越高, 对费用粘性的抑制作用越强。然而, 关于股权制衡度的计量是按股东持股比例的顺序计算的, 而不是具有实质权力的大股东。已有文献关于多个大股东在公司治理中的作用, 还仅限于其他大股东对控股股东的治理效应, 而对管理者行为的影响研究还相对较少, 因此本文从管理者成本管理行为视角, 研究多个大股东对第一类代理问题的影响, 可以更好地理解多个大股东在公司治理中的作用。

三、理论分析与研究假设

管理者应注重提升企业价值, 根据市场前景和

企业发展战略合理扩张或削减资源, 以保证企业处于最优资源配置水平和最佳发展状态(Berle 和 Means, 1932)^[30]。然而, 管理者更倾向追求个人利益(Jensen 和 Meckling, 1976)^[31], 为了提高自身地位和权力, 在日常资源配置时常常忽略企业的实际需求, 由此产生费用粘性。股权结构是公司治理的重要内容, 不同的股权结构安排将会引起股东控制权支配差异和对管理者的监督差异, 进一步影响企业资源配置效率。相较于单一大股东, 多个大股东的股权结构可能从以下两个方面降低企业对管理者的监督, 给予管理者谋取私利的空间, 引起费用粘性上升。

第一, 多个大股东的股权结构使集中的股权和控制权变得相对分散, 导致控股股东对管理者的监督力度下降。当股权集中时, 控股股东的利益与公司利益密切相关, 对管理者进行监督的收益大于成本, 因而监督的动机和能力最强(宋力和韩亮亮, 2005)^[32]。管理者在严格监督下, 会基于股东利益和企业发展情况及时调整经营决策, 将费用控制在合理的范围内。而当企业股权结构由集中持股的单一大股东转变为相对持股不高的多个大股东时, 原控股股东的持股比例下降, 控制权被分散, 此时对管理者的监督收益不一定能够弥补监督成本, 这可使控股股东失去监督的动力, 同时使控股股东影响管理者决策的绝对权力消失。Chakraborty 和 Gantchev(2013)^[33]认为, 相较于单一大股东拥有集中投票权去惩罚表现较差的管理者, 多个大股东投票权的分散增加了投票结果的不确定性, 这印证了多个大股东对管理者监督力度的下降。

第二, 控股股东要负责应对其他大股东的监督与可能存在的利益分歧, 即使最终达成一致目标也需要经历讨价还价的协调过程(Chakraborty 和 Gantchev, 2013)^[33], 甚至出现其他大股东与控股股东争夺控制权的现象, 这不但会引发企业治理混乱, 而且在各个大股东时间和精力有限的情况下会忽视对管理者的监督, 导致监督效率下降。赵景文和于增彪(2005)^[34]认为, 中国独有的血缘和同窗等关系文化塑造了股东之间的“圈子”, 利益冲突比

西方企业会更为激烈,因而更容易引起经营效率低下和代理成本上升等问题。徐莉萍等(2006)^[35]也认为大股东之间的控制权争夺会导致企业价值下降,同时也会给管理者实施自利行为提供机会。“宏智科技股权之争”“鄂武商控制权之争”“东北高速资源争夺”等案例研究(郝云宏和汪茜,2015;朱红军和汪辉,2004;李进等,2016)^[36-38]也从实际经营的角度佐证了股东利益纷争会导致企业管理混乱和监督效率下降的观点。

综上所述,管理者出于个人私利,可以利用大股东权力分散以及大股东之间的制衡和摩擦,过度增加企业资源或避免减少相关费用,并凭借信息优势隐藏其自利行为而无法被大股东有效监督,费用粘性由此增加。

基于此,本文提出如下假设:

H1: 多个大股东的股权结构会增加企业费用粘性。

四、研究设计

1、样本选择及数据来源

本文以2010-2020年沪深A股上市企业为初始样本。样本区间的选取有两个因素:第一,2008年股权分置改革完成后,其他性质的大股东才有可能进入国有企业发挥作用;第二,以2010年为起始年份能够避免2008年金融危机及滞后期的影响。对样本进行以下处理:(1)剔除被特别处理(ST、ST*、PT)的样本;(2)剔除金融业样本;(3)剔除资产负债率大于1的样本;(4)剔除数据缺失的样本;(5)剔除第一大股东小于10%即没有大股东存在的样本(姜付秀等,2018)^[39];(6)将十大股东中属于一致行动人的持股比例合并;(7)为避免极端值影响,对连续变量进行首尾1%的缩尾处理。样本中一致行动人数据来源于RESSET数据库和CHOICE数据库,十大股东数据和其他财务数据来源于国泰安数据库和CCER数据库。

2、模型构建

参考Anderson et al. (2003)^[9]构建模型(1)

以检验多个大股东对费用粘性的影响:

$$\Delta Lnexpense = \alpha_0 + \alpha_1 \times \Delta Lnsale + \alpha_2 \times D \times \Delta Lnsale + \alpha_3 \times D \times \Delta Lnsale \times Multi + \alpha_4 \times \Delta Lnsale \times Multi$$

$$+ \alpha_5 \times D \times \Delta Lnsale \times Ai + \alpha_6 \times \Delta Lnsale \times Ai + \alpha_7 \times D \times \Delta Lnsale \times Ei + \alpha_8 \times \Delta Lnsale \times Ei + \alpha_9 \times D \times \Delta Lnsale \times D_twoyear + \alpha_{10} \times D \times \Delta Lnsale \times Gdp + \alpha_{11} \times \Delta Lnsale \times Gdp + \sum Control + \sum Ind + \sum Year + \varepsilon$$

若收入较上年上涨, $D=0$, α_1 描述了收入上升1%时费用随之上升的幅度;若收入较上年下降, $D=1$, $(\alpha_1 + \alpha_2)$ 描述了收入下降1%时费用随之下降的幅度。若 $\alpha_1 > (\alpha_1 + \alpha_2)$, 即 $\alpha_2 < 0$, 表示收入上升、下降变化比例相同时, 费用上升的幅度大于下降的幅度, 费用粘性存在。若假设成立, 则粘性与多个大股东变量的交乘项应显著为负, 表明增加粘性。模型还控制了行业(*Ind*)和年份(*Year*), 按公司聚类(*Cluster*)进行回归并报告经异方差调整的t值(*Robust t*)。

3. 变量定义

(1) 被解释变量

$\Delta Lnexpense$ 表示费用变动, 以当年费用的自然对数减去上一年费用的自然对数求得, 费用为销售费用和管理费用之和。

(2) 解释变量

$\Delta Lnsale$ 表示营业收入变动, 以当年营业收入的自然对数减去上一年营业收入的自然对数求得。 D 为虚拟变量, 若当年营业收入较上年下降, 取值为1, 否则为0。 $Multi$ 为多个大股东的股权结构。

《公司法》规定, 持股10%以上的股东有请求召开临时股东大会、召开董事会临时会议、董事会监事会不履职时自行召集和主持股东大会, 以及提请公司解散的权力。借鉴姜付秀等(2018)^[39], 将十大股东中属于一致行动人的持股比例合并, 以10%作为大股东的临界点, 构造多个大股东股权结构的三个替代变量: A. 是否存在多个大股东(*Ife*), 若当年该企业除控股股东外, 还至少存在一个大股东, 取值为1, 否则为0; B. 其他大股东个数(*Number*), 指当年该企业除控股股东外, 其他大股东的数量之和, 数量越多, 大股东之间的协调成本越高; C. 其他大股东持股比例之和(*Shr*), 指当年该企业除控股股东外, 其他大股东的持股比例之和, 持股比例

越高,使控股股东受限和妥协周旋的可能性越大。

(3) 控制变量

控制变量的选取主要包括资产密集度 (Ai)、员

工密集度(Ei)、收入是否连续两年下降($D_twoyear$)、

宏观经济增长率(Gdp)等经济变量,以及其他控制

变量,具体如表1所示。

表1 控制变量定义

变量定义	变量符号	变量定义
资产密集度	Ai	年末资产总额除以营业收入
员工密集度	Ei	员工人数除以营业收入(百万)
收入是否连续两年下降	$D_twoyear$	虚拟变量,若当年营业收入连续两年下降,取值为1,否则为0
宏观经济增长率	Gdp	当年GDP较上年增长率
总资产报酬率	Roa	当年净利润除以年末资产总额
企业规模	$Size$	年末总资产的自然对数
资产负债率	Lev	年末负债总额除以资产总额
两职合一	$Dual$	虚拟变量,若董事长和总经理为同一人取值为1,否则为0
董事会规模	$Board$	董事会人数之和
第一大股东持股比例	$First_r$	进行合并一致行动人调整后所得
独董比例	Rid	独立董事人数除以董事会总人数

五、实证分析

1、描述性统计

表2为主要变量的描述性统计。费用变动($\Delta Lnexpense$)与收入变动($\Delta Ln sale$)的均值分别为0.109、0.108,与梁上坤(2015)^[40]的发现相近。是否存在多个大股东(Ife)的均值为25.5%,与姜

付秀(2018)^[39]的研究一致,表示有四分之一的公司存在两个及以上持股超过10%的大股东。其他大股东数量($Number$)和其他大股东持股比例(Shr)的最大值分别为2和36.14%,表示除控股股东外最多有2个大股东,以及其他大股东合计最多持股36.14%。

表2 描述性统计

变量	N	mean	sd	min	p50	max
$\Delta Lnexpense$	16447	0.109	0.212	-0.499	0.0990	0.909
$\Delta Ln sale$	16447	0.108	0.241	-0.656	0.0990	0.992
Ife	16447	0.255	0.436	0	0	1
$Number$	16447	0.287	0.516	0	0	2
Shr	16447	4.823	9.052	0	0	36.14
D	16447	0.267	0.442	0	0	1

2、回归结果

表3报告了模型(1)OLS的基本回归结果。第(1)列为费用粘性是否存在的结果,费用粘性($D \times \Delta Ln sale$)显著为负,表示粘性存在。第(2)(3)(4)列在第(1)列的基础上加入是否存在多个大股东与粘性的交乘项($D \times \Delta Ln sale \times Ife$)、其他

大股东数量与粘性的交乘项($D \times \Delta Ln sale \times Number$)、其他大股东持股比例与粘性的交乘项($D \times \Delta Ln sale \times Shr$),分别在5%、5%、10%的水平上显著为负。第(5)(6)(7)列在第(2)(3)(4)列的基础上继续加入控制变量,分别在5%的水平上显著为负。由第(5)列的结果可见,多个大股东股

权结构能够显著增加粘性；由第（6）（7）列的结果 增加作用越强，支持了本文的假设。可见，其他大股东数量越多、持股越多，对粘性的

表3 多个大股东与费用粘性：基本回归

变量	$\Delta Lnexpense$						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\Delta Lnsale$	0.600*** (41.96)	0.584*** (35.89)	0.597*** (41.85)	0.599*** (42.10)	0.597*** (39.32)	0.612*** (45.69)	0.613*** (46.02)
$D \times \Delta Lnsale$	-0.272*** (-15.22)	-0.253*** (-12.44)	-0.269*** (-15.01)	-0.270*** (-15.11)	-0.263*** (-11.94)	-0.279*** (-14.33)	-0.281*** (-14.44)
$D \times \Delta Lnsale \times Ife$		-0.064** (-2.03)			-0.066** (-2.11)		
$\Delta Lnsale \times Ife$		0.053* (1.89)			0.060** (2.25)		
$D \times \Delta Lnsale \times Number$			-0.057** (-2.24)			-0.058** (-2.24)	
$\Delta Lnsale \times Number$			0.050** (2.18)			0.059*** (2.70)	
$D \times \Delta Lnsale \times Shr$				-0.003* (-1.88)			-0.003** (-1.98)
$\Delta Lnsale \times Shr$				0.002 (1.12)			0.002 (1.49)
Constant	0.025 (1.55)	0.028* (1.73)	0.027* (1.65)	0.026 (1.62)	-0.061** (-2.13)	-0.062** (-2.18)	-0.063** (-2.18)
Year/ Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	16447	16447	16447	16447	16447	16447	16447
Adj. R^2	0.420	0.420	0.420	0.420	0.441	0.441	0.441

3、稳健性检验

（1）内生性检验

多个大股东与企业费用粘性之间可能存在潜在的内生性问题，采用以下方法进行处理。首先，使用固定效应模型（FE）代替OLS以缓解遗漏变量导致的内生性问题。在控制年份和其他不随时间改变的因素进行回归后，结果如表4第（1）（2）（3）列所示，依然增加粘性。其次，用倾向得分匹配（PSM）缓解因公司特征差异带来的干扰。以模型（1）中所有控制变量为协变量，进行有放回的1：2近邻匹配，得到具有相似特征的多个大股东处理组和单一大股东控制组，再重新混合进行回归。结果如表4第（4）（5）（6）列所示，结论不变。最

后，参考梁上坤（2017）^[41]，采用Heckman两阶段解决样本自选择问题。第一阶段为Probit回归，被解释变量为是否存在多个大股东（*Ife*），解释变量为所有控制变量和一个工具变量。选定同年度同行业其他存在多个大股东股权结构的企业占比作为工具变量，原因是单一公司的股权结构和同年度同行业其他企业的股权结构相关，而其他企业的股权结构不会直接影响某一公司的费用粘性。将计算得到的逆米尔斯比（*IMR*）代入模型（1）重新回归，如表4第（7）列所示，*IMR*并不显著，表示自选择问题不存在，且多个大股东与粘性的交乘项（ $D \times \Delta Lnsale \times Ife$ ）在10%的水平上显著为负，增加粘性的作用依旧存在。

表4 多个大股东与费用粘性：内生性检验

变量	固定效应			PSM			Heckman
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$D \times \Delta Lnsale \times Ife$	-0.079** (-2.15)			-0.131*** (-3.47)			-0.064* (-1.79)
$D \times \Delta Lnsale \times Number$		-0.070** (-2.36)			-0.115*** (-3.91)		
$D \times \Delta Lnsale \times Shr$			-0.005*** (-2.73)			-0.006*** (-3.24)	
Constant	-0.865*** (-9.40)	-0.866*** (-9.41)	-0.868*** (-9.42)	-0.012 (-0.32)	-0.013 (-0.34)	-0.014 (-0.36)	
IMR							0.000 (0.12)
Control_var	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year/ Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	16447	16447	16447	9014	9014	9014	16447
Adj.R ²	0.430	0.430	0.430	0.437	0.438	0.437	0.441

(2) 其他稳健性检验

本文还进行了以下稳健性检验：(1) 2020年疫情影响对企业的收入和费用会产生波动，故删去2020年重新进行回归，回归结果如表5第(1)

(2)(3)列所示，研究结论不变；(2)将大股东界定标准换为5%，如表5第(4)(5)(6)列所示，多个大股东与费用粘性的交乘项在1%的水平上显著为负，研究结果更加稳健。

表5 其他稳健性检验

变量	删除 2020			5%		
	(1)	(2)	(3)	(4)	(5)	(6)
$D \times \Delta Lnsale \times Ife$	-0.093*** (-2.71)			-0.133*** (-4.63)		
$D \times \Delta Lnsale \times Number$		-0.079*** (-2.63)			-0.073*** (-4.74)	
$D \times \Delta Lnsale \times Shr$			-0.004*** (-2.67)			-0.005*** (-4.00)
Constant	-0.031 (-1.00)	-0.033 (-1.06)	-0.032 (-1.04)	-0.056* (-1.92)	-0.059** (-2.07)	-0.058** (-2.02)
Control_var	Yes	Yes	Yes	Yes	Yes	Yes
Year/ Industry	Yes	Yes	Yes	Yes	Yes	Yes
N	14340	14340	14340	16447	16447	16447
Adj.R ²	0.411	0.411	0.411	0.442	0.443	0.442

六、进一步分析

1、中介效应

本文认为，多个大股东股权结构对企业费用粘性的影响是由于对管理者监督下降，导致管理者自利增加引起的。已有研究发现，管理者会利用多个大股东“制衡”获取超额薪酬（Fang et al., 2018；

赵国宇，2019）^[7-8]，故选取高管超额薪酬作为中介来衡量代理问题。借鉴刘剑民等（2019）^[42]构建模型（2），测得高管期望薪酬；再计算模型（3）实际薪酬与期望薪酬的差额得到高管超额薪酬。

参考温忠麟（2004）^[43]构建中介模型（4）和模型（5）检验中介关系是否成立。观察模型（4）中

β_1 的系数,以验证多个大股东股权结构对高管超额薪酬的影响;观察模型(5)中的 φ_3 和 φ_5 的系数,以验证多个大股东股权结构、高管超额薪酬对企业费用粘性的影响。相较于模型(1),若 β_1 和 φ_5 显著, φ_3 显著性下降,则存在部分中介效应;若 β_1 和 φ_5 显著, φ_3 不再显著,则为完全中介效应。

$$\ln CEOpay = \alpha_0 + \alpha_1 \ln Size + \alpha_2 Roa + \alpha_3 IA + \alpha_4 Zone + \sum Industry + \sum Year + \varepsilon \quad (2)$$

$$Overpay = \ln(CEOpay) - \ln(Expectedpay) \quad (3)$$

$$Overpay = \beta_0 + \beta_1 Multi + \sum Control + \sum Industry + \sum Year + \varepsilon \quad (4)$$

$$\begin{aligned} \Delta \ln expense = & \varphi_0 + \varphi_1 \times \Delta \ln sale + \varphi_2 \times D \times \Delta \ln sale + \varphi_3 \\ & \times D \times \Delta \ln sale \times Multi + \varphi_4 \times \Delta \ln sale \times Multi + \\ & \varphi_5 \times D \times \Delta \ln sale \times Overpay + \varphi_6 \times \Delta \ln sale \times \\ & Overpay + \varphi_7 \times D \times \Delta \ln sale \times Ai + \varphi_8 \times \Delta \ln sale \\ & \times Ai + \varphi_9 \times D \times \Delta \ln sale \times Ei + \varphi_{10} \times \Delta \ln sale \\ & \times Ei + \varphi_{11} \times D \times \Delta \ln sale \times D_twoyear + \varphi_{12} \times \\ & D \times \Delta \ln sale \times Gdp + \varphi_{13} \times \Delta \ln sale \times Gdp + \\ & \sum Control + \sum Industry + \sum Year + \varepsilon \quad (5) \end{aligned}$$

表6报告了中介效应检验的结果。第(1)(2)(3)列为模型(4)的回归结果,高管超额薪酬($Overpay$)与大股东变量皆在1%的水平上显著为正,表明高管会利用多个大股东股权结构为自己增加报酬。第(4)(5)(6)列为模型(5)的回归结果,高管超额薪酬与粘性的交乘项($D \times \ln sale \times Overpay$)皆在1%的水平上显著为负,表示多个大股东对费用粘性的增加作用是通过与管理者有关的代理问题实现的。多个大股东变量与粘性的交乘项分别在在10%、5%、10%的水平上显

著为负,粘性增加作用依然存在,但与表3的基准回归结果相比,交乘项的系数显著性明显下降,即代理问题只是多个大股东影响费用粘性的部分中介。

2、调节效应

(1) 多个大股东、产权性质与费用粘性

为了进一步分析在不同产权性质中多个大股东对费用粘性的影响,本文将样本按照控股股东的性质分为国有企业和非国有企业两组分别进行回归,结果如表7所示。在非国有企业中,多个大股东变量与粘性的交乘项皆在5%的水平上显著为负,表明多个大股东使费用粘性增加更多;而在国有企业中,这种影响并不明显。与国有企业相比,在非国有企业中,其他大股东的进入对控股股东制约的可能性更大,因此持有不同利益目标大股东之间的摩擦更多,协调成本更高,由此导致对管理者的监督下降,代理问题更加严重,最终使粘性的增加效果更强。

(2) 多个大股东、市场化进程与费用粘性

市场化进程作为外部治理机制,与内部治理机制一起对企业发挥重要作用。采用樊纲编写的《中国分省份市场化指数报告2018》(王小鲁等,2019)^[44]中各地区市场化程度得分指标,将样本分为市场化程度高、低两组进行回归,回归结果如表7所示。在市场化程度低的企业中,多个大股东变量与粘性的交乘项分别在10%、5%、10%的水平上显著为负,多个大股东使费用粘性增加更多;而在市场化程度高的企业中并不显著。这可能是,在市场化程度较低的地区,控股股东谋取私利的成本更低,其他大股东对控股股东的制约更多,进而忽视了对管理者的监督,由此导致费用粘性增加。

表6 多个大股东与费用粘性：中介效应检验

变量	<i>Overpay</i>			<i>ΔLnexpense</i>		
	(1)	(2)	(3)	(4)	(5)	(6)
<i>Ife</i>	0.074*** (3.52)					
<i>Number</i>		0.073*** (4.10)				
<i>Shr</i>			0.004*** (3.83)			
<i>D×ΔLnsale×Ife</i>				-0.059* (-1.88)		
<i>D×ΔLnsale×Number</i>					-0.052** (-2.01)	
<i>D×ΔLnsale×Shr</i>						-0.003* (-1.77)
<i>D×Lnsale×Overpay</i>				-0.078*** (-2.92)	-0.077*** (-2.91)	-0.078*** (-2.95)
<i>Constant</i>	-0.997*** (-3.96)	-0.994*** (-3.94)	-0.977*** (-3.87)	-0.056* (-1.96)	-0.057** (-2.00)	-0.057** (-2.00)
<i>Control_var</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year/ Industry</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	16447	16447	16447	16447	16447	16447
<i>Adj.R²</i>	0.047	0.048	0.048	0.441	0.442	0.441

表7 多个大股东与费用粘性：按产权性质和市场化程度分组

变量	产权性质		市场化程度	
	(1) 非国有	(2) 国有	(1) 高	(2) 低
<i>D×ΔLnsale×Ife</i>	-0.101** (-2.37)	0.016 (0.36)	-0.050 (-1.10)	-0.075* (-1.75)
<i>D×ΔLnsale×Number</i>	-0.077** (-2.25)	0.003 (0.08)	-0.046 (-1.26)	-0.069** (-1.97)
<i>D×ΔLnsale×Shr</i>	-0.005** (-2.22)	0.001 (0.41)	-0.002 (-1.00)	-0.004* (-1.83)
<i>Control_var</i>	Yes	Yes	Yes	Yes
<i>Year/Industry</i>	Yes	Yes	Yes	Yes

七、结论与启示

本文从费用粘性的视角，研究了多个大股东对管理者进行资源配置的影响及作用机制。研究结果表明：多个大股东的股权结构会使企业费用粘性增加，并且这一作用是通过管理者的代理成本增加实现的；在非国有企业和市场化程度更低的企业中，多个大股东对费用粘性的增加效果更强。

本文对全面认识多个大股东这一股权结构的治理效应具有补充借鉴意义。研究普遍认为，多个大股东的股权结构能够监督控股股东，缓解大股东

与小股东之间的代理问题。但本文发现，控制权的分散以及协调成本的增加会给予管理者自利的空间，使股东与管理者之间的代理问题增加，进而导致企业资源配置偏离最优水平。所以在实际经营中如何权衡两类代理问题，设置合理的股权结构，对管理者和控股股东都实现有效监督需要重新审视和考虑。本文对企业经营管理实践的启示主要有以下三点：

第一，树立大股东—企业价值共同体理念。对企业的未来发展共同商榷，在长期战略上达成一致，设计以贯彻长期战略和提高协商效率为目标的投

票制度,在短期决策上减少分歧,缓解因大股东利益纷争引起的协调成本和监督失效问题。

第二,强化内部治理,减少代理问题。既要建立健全企业内部治理机制,加强董事会、监事会对管理者的约束,将资源配置效率纳入日常考核中,避免管理者过度扩张,损害企业利益;也要完善薪酬激励制度,激发管理者认真工作的积极性。

第三,加快市场化进程建设,加强外部治理。建设科学、开放、竞争、透明的市场体系,发挥外部治理环境对企业内部经营的监督作用。

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并购资产相关性与业绩承诺

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摘要：基于手工收集的2009-2019年并购重组业绩承诺数据，从投入产出表的视角分析并购资产相关性与业绩承诺的关系及其影响因素，并探讨两者的影响机制。研究发现：（1）并购资产相关性越高、业绩承诺激进程度越低，这种负相关关系在现金支付方式以及单向业绩承诺下表现更为明显；（2）并购资产相关性越高、业绩承诺实现程度越高，股份支付方式、股份补偿方式以及双向业绩承诺增强了这种正相关关系；（3）盈余管理在并购资产相关性与业绩承诺激进程度之间具有中介作用，并购整合程度在并购资产相关性与业绩承诺实现程度之间具有中介作用；（4）在业绩承诺激进程度较低的情况下，并购资产相关性与业绩承诺实现率之间的正相关关系更明显。

关键词：并购重组，资产相关性，业绩承诺

Acquired Asset Correlation and Performance Commitment

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Abstract: Based on manually collected performance commitment data of M&A and restructuring from 2009 to 2019, this study tests the relationship between acquired asset correlation and performance commitment and its influencing factors from the perspective of input-output, and discusses the impact mechanism of the both. The study found that: (1) The higher the correlation of acquired asset, the lower the aggressiveness of performance commitment, and this negative correlation is more obvious in the cash payment method and the one-way performance commitment method; (2) The higher the correlation of acquired asset, the higher the achievement of performance commitment, the way of share payment, share compensation and two-way performance commitment strengthen this positive correlation; (3) Earnings management plays an intermediary role between the correlation of acquired asset and the degree of aggressiveness of performance commitment, the degree of integration plays a mediating role between the correlation of acquired asset and the degree of achievement of performance commitments; (4) Under the condition that the degree of aggressiveness of performance commitments is low, the positive correlation between the correlation of acquired asset and the realization rate of performance commitments is more obvious.

Key Words: mergers and acquisitions, asset correlation, performance commitment

一、引言

并购重组是企业实现战略目标、优化资源配置的重要途径。自中国经济进入中高速增长阶段，热衷多元化战略的企业家以为公司也能凭借跨界并购实现快速发展。不同于舍本逐末，有的公司坚守主业，通过并购夯实经营基础，最终实现成倍的规模扩张，并在资本市场获得高估值。公司应选择专业化还是多元化并购呢？

作为并购重组的事后补偿，业绩承诺是相关部门为缓解信息不对称，保护上市公司及其中小股东利益的制度创新。近年来相悖于制度初衷的行为频发，并购重组业绩承诺及其影响因素的研究成为学术界的热点，对其研究可分为承诺期前的选择动因、承诺期间的业绩完成、承诺期满的经济后果三个阶段。在第一阶段，业绩承诺的正向动机为增强协同效应、增加交易透明度、提高风险承担水平等；负向动机为市值管理^[1]与利益输送^[2]等。这种暗度陈仓式举止损害了中小股东利益和投资者信心。在第二阶段，学者多研究业绩承诺与股价、商誉、并购绩效、盈余管理以及审计等之间的关系。在第三阶段，文献集中研究业绩变脸、精准达标、补偿不到位和公司绩效等问题。期满后若践约失败，显著的掏空效应会危害公司发展^[3]。业绩承诺到期后，上市公司的绩效会出现明显恶化^[4]。业绩承诺金额和实现是交易双方不断权衡的结果，但现有文献较少关注交易双方的关系对业绩承诺的影响。那么，并购资产相关性与业绩承诺有什么关系呢？两者的影响机理是什么样的呢？

鉴于此，本文从并购资产相关性出发，研究其对业绩承诺的影响。一方面引入支付方式、补偿方式和补偿方向为调节变量，分析其调节作用；另一方面引入盈余管理和并购整合程度为中介变量，梳理并购资产相关性对业绩承诺的传导机制。本文贡献在于：①基于投入产出数据计算出连续变量，量

化并购方资产与标的资产的相关程度，不同于已有文献主要采用虚拟变量衡量并购资产与标的资产是否相关的方法。②证明了并购资产相关性对于业绩承诺具有重要影响，从支付方式、补偿方式以及补偿方向的角度，为并购资产相关性对于业绩承诺的作用提供了证据，扩展了业绩承诺影响因素与经济后果的研究。③打开了并购资产相关性影响业绩承诺的“黑箱”，发现并购资产相关性通过盈余管理影响业绩承诺激进程度，且通过并购整合程度影响业绩承诺实现程度。此发现有助于更好地认识高业绩承诺的成因以及为业绩承诺达标提供参考。

二、理论分析与研究假设

1、并购资产相关性与业绩承诺激进程度

(1) 并购资产相关性与业绩承诺激进程度的关系及其影响因素

企业相关性的概念始于 20 世纪 70 年代战略管理的公司多元化研究，并在 80 年代被引入公司并购的研究中，公司面临选择专业化经营还是多元化运作来提升企业价值的难题。曾春华等^[5]认为多元化可提高企业价值，在这个时期公司多采取多元化经营。然而俞雪莲等^[6]认为过度追求多元化对企业价值不利。交易双方相关性影响着企业价值的实现，那是否会影响业绩承诺的制定呢？信息不对称理论认为，并购双方掌握的信息详细程度不一致，通常买方处于信息弱势一方，卖方可利用信息优势投机取巧。由于信息不对称会产生逆向选择，上市公司可能会选择盈利能力不佳的标的资产而不自知^[7]。管理层强烈的机会主义动机扭曲了定价，目标方释放出激进的业绩承诺。如果交易双方存在相关性，收购方对目标方的经营范围和运营模式有一个较为清晰的轮廓，缓解了信息不对称，从而更合理地估计目标方未来收益，避免了高业绩承诺的制定。因此本文提出假设：

假设 1：并购资产相关性与业绩承诺激进程度

负相关。

收购方在选择并购支付方式时会综合考虑自身财务状况以及目标方经营情况,因而选择不同的支付方式,向资本市场传递出对此次交易的风险,隐含着对本次交易的信心^[8]。现金支付更能体现上市公司对交易的信心和能力,反映目标方真实价值^[9]。反观在股份支付方式下,目标方会要求更高的溢价水平,这使得并购资产估值往往虚高^[10]。目标方需要给出较高的业绩承诺来匹配高估值的对价,从而形成了“高估值、高溢价、高业绩”的利益链条。因此与股份支付所要求的高溢价不同,现金支付抑制了高溢价,进一步减弱了并购资产相关性与业绩承诺激进程度之间的负相关关系。因此本文提出假设:

假设 2: 相对于股份支付,并购资产相关性与业绩承诺激进程度的负相关关系在现金支付方式下表现更为明显。

业绩承诺条款中通常规定了目标公司承诺的业绩未达标时的补偿方式,可分为现金补偿、股份补偿和混合补偿。从收购方角度看,高闯等^[11]认为股份补偿有利于收购方财务状况和经营业绩的改善,同时制约大股东对并购重组的高估值和高盈利预测。从目标方角度看,窦炜等^[12]认为高业绩承诺一旦无法完成,目标方签订的股份补偿条款会使其面临更大的惩罚力度。目标方原股东承担的补偿义务远远高于实际业绩与承诺业绩差额的现金补偿,轻则损失收益,重则丧失股东地位。为了规避风险,有了降低高业绩承诺的动机。因此本文提出假设:

假设 3: 相对于现金补偿,并购资产相关性与业绩承诺激进程度的负相关关系在股份补偿方式下表现更为明显。

业绩承诺条款通常会规定业绩承诺补偿方向,分为单向业绩承诺和双向业绩承诺。单向业绩承诺下,目标公司未能完成承诺业绩,需要向收购方进

行补偿。双向业绩承诺是在单向业绩承诺的基础上添加了激励条款,即收购方会给予超额完成业绩的目标方一定的奖励。双向业绩承诺缓解了交易双方的代理问题,减少了收购方对目标方未来收益的担忧,从而更乐意基于更高的交易对价。翟进步等^[13]认为在并购重组事项中签订双向业绩承诺时,资产评估增值率会更高,而高溢价必然会通过高业绩承诺来反映^[14],相反单向业绩承诺下业绩承诺激进程度更低。因此本文提出假设:

假设 4: 相对于双向业绩承诺,并购资产相关性与业绩承诺激进程度的负相关关系在单向业绩承诺下表现更为明显。

(2) 并购资产相关性对业绩承诺激进程度的影响机制分析

从本质上来说,盈余管理是指在会计准则的法允范围内通过改变会计方法、调整应计项目等行为使会计利润达到期望水平。信息不对称理论可解释目标方的盈余管理行为。并购资产相关性越低,交易双方信息不对称程度越低,目标方盈余管理的空间就越大。相反,并购资产相关性越高,盈余管理得到了抑制。

并购资产低相关性是前提,盈余管理只是手段,高溢价与高业绩承诺才是真正的目的。研究表明收购方基于目标方未来较高的业绩水平,会给予更高的溢价^[15]。所以有信息优势的目标方倾向于隐藏优秀的业绩,制定较高的业绩承诺以获得投资者的青睐和满意的对价^[16]。因此并购资产相关性越高,盈余管理行为越少,业绩承诺激进程度越低。基于以上分析,本文提出假设:

假设 5: 盈余管理在并购资产相关性与业绩承诺激进程度之间起中介作用。

2、并购资产相关性与业绩承诺实现程度

(1) 并购资产相关性与业绩承诺实现程度的关系及其影响因素

交易费用理论和协同效应理论认为,优势互补的企业有利于并购。交易费用理论认为,横向并购扩大了企业规模 and 市场份额,降低了生产成本,维持了核心竞争力;纵向并购打通了上下游的关节,促进了公司的一体化。交易费用的节约使企业获得竞争优势,横向并购与纵向并购具有良好的效益反馈^[17]。协同效应理论认为在同行业的并购中,收购方更熟悉目标方,这降低了并购风险与整合成本,并购绩效更好。根据并购资产相关性假说,相关并购优于非相关并购^[18],相关并购带来了协同效应。目标方在收购方高效管理和经营水平下,最终有利于实现业绩承诺。因此本文提出假设:

假设 6: 并购资产相关性与业绩承诺实现程度正相关。

多元化并购具有信息不对称程度高、整合难度大等特点,交易溢价和并购风险相对较高^[19]。从信息不对称的角度看,在并购交易中,目标方会利用信息优势做出损害收购方利益的行为。业绩承诺的一些制度设计可缓解信息不对称^[20]。在现金支付下,收购完成后上市公司与目标方原股东不存在直接关系;但是在股份支付下,原股东持有上市公司股权,能继续参与目标方的经营决策。因此,股份支付下信息不对称程度较低,这有利于完成承诺业绩。从股权激励的角度看,股份支付作为收购方股东的自我保护手段,改善了上市公司的股权结构和治理结构^[21]。目标方原股东与收购方风险共担、利益共享,业绩承诺方有动力积极完成业绩承诺。因此本文提出假设:

假设 7: 相对于现金支付,并购资产相关性与业绩承诺实现程度的正相关关系在股份支付方式下表现更为明显。

风险承担能够很好地解释交易双方对补偿方式的选择。于收购方而言,考虑到并购资产相关性的理性管理者会选择风险较小的股份补偿^[22]。而对

于目标方而言,股份补偿使其面临较高的业绩补偿压力,风险较大。目标方会努力改善管理水平与经营状况,尽可能降低违约几率,有利于业绩承诺的实现。所以股份补偿下并购资产相关性与业绩承诺实现程度的正向关系更明显。因此本文提出假设:

假设 8: 相对于现金补偿,并购资产相关性与业绩承诺实现程度的正相关关系在股份补偿方式下表现更为明显。

激励理论认为特定的方法与管理体系统能够调动人的积极性,目的在于激发其正确行为。单向业绩承诺对目标方仅起到了约束的作用,目标方完成业绩只是为了免于补偿^[23]。薪酬契约式的双向业绩承诺对目标方有着更大的吸引力,激励着目标方完成甚至超额完成业绩承诺。为了获得上市公司给予的超额奖励,目标方有动力积极改善管理水平、努力提升资产业绩,业绩承诺完成情况也更加乐观。

假设 9: 相对于单向业绩承诺,并购资产相关性与业绩承诺实现程度正相关关系在双向业绩承诺下表现更为明显。

(2) 并购资产相关性对业绩承诺实现程度的影响机制分析

资源基础理论认为,企业可通过并购获取互补资源从而提升市场竞争力。并购整合是一个复杂的资源整合过程,分为组织管理、工艺产品、市场营销等多个维度^[24]。跨界并购后上市公司进入新的领域,需要更多的资金以支持资源的整合。所以与多元化并购相比,专业化并购并购整合风险更小,交易双方产业关联度越大,并购协同效应更大^[25]。因此,并购资产相关性越高,并购整合程度越高。

肖海莲等^[26]认为与专业化、相关多元化相比,多元化战略的企业绩效最低,无关并购不利于企业发展。如果并购资产相关性较高,收购方能迅速采取强有力的整合措施,积极配置资源,提高企业绩效。并购资产相关性越高,整合能力越强,并购价

值创造能力越强,越有利于业绩承诺的实现。基于以上分析,本文提出假设:

概念模型如图 1 所示。

假设 10: 并购整合程度在并购资产相关性与业绩承诺实现程度之间起中介作用。

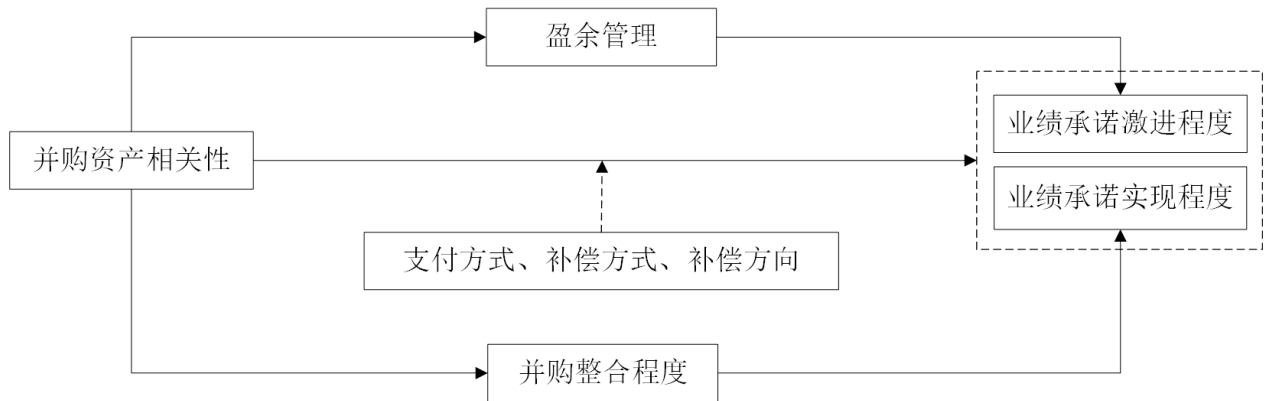


图 1 概念模型

三、研究设计

1、样本与数据来源

本文以 Wind 中国并购库中 2009-2019 年 A 股上市公司的并购事项为初始样本进行如下处理: (1) 剔除金融行业样本; (2) 剔除交易失败的样本; (3) 剔除正实施的样本; (4) 剔除 ST 公司; (5) 剔除对价小于 100 万元的样本; (6) 剔除收购比例小于 30% 的样本。经过以上处理后, 获得 422 家上市公司的 622 条交易事项, 1938 个年度样本。其中, 收购方财务数据来源于 CSMAR 数据库; 业绩承诺、交易特征与目标方财务数据手工搜集得到; 目标方行业基于其经营范围根据《国民经济行业分类》确定; 投入产出表的数据来源于安蕾编制的中国动态投入产出表^[27]和国家统计局编制的全国投入产出表。本文在实证过程中对连续变量在 1%和 99%分位上进行缩尾。

2、变量测度

(1) 被解释变量为业绩承诺激进程度和业绩承诺实现程度。其中, 业绩承诺实现程度使用业绩承诺实现率和业绩承诺是否实现衡量。

(2) 解释变量为并购资产相关性。本文基于中国投入产出表的数据与并购双方的行业计算并购资产的相关性。投入产出表矩阵中的数值 a_{ij} 代表部门 j 总产出需要部门 i 投入的价值, a_{ji} 代表部门 i 总产出需要部门 j 投入的价值。 a_{ij} 与部门 j 总产出的比值为 V_{ij} , V_{ij} 与 V_{ji} 的最大值定义为并购资产相关系数, 以衡量交易双方相关关系^[25]。

(3) 调节变量为支付方式、补偿方式和补偿方向。

(4) 中介变量为盈余管理和并购整合程度。以修正的 Jones 模型衡量盈余管理^[15]。从整合动力、整合难度、整合效果三个方面来衡量整合程度。具体而言, 持股比例达到 100%时整合动力取值为 1; 并购类型为横向、纵向并购时整合难度取值为 1; ROA 变动不小于 0 时整合效果取值为 1; 整合程度为三者之和。

(5) 控制变量为交易规模、关联并购、公司规模、公司杠杆、公司业绩、两职合一、审计质量、制度环境以及年度固定效应。

具体变量定义见表 1。

表 1: 变量定义

Variable	Definition
PA	业绩承诺激进程度, 业绩承诺年平均额/承诺期开始前两年目标方年平均业绩
PR1	业绩承诺实现率, 目标方当年实际业绩与承诺业绩比值
PR2	业绩承诺是否实现, 目标方当年实际业绩超过承诺业绩取值为 1, 否则为 0
Correlation	并购资产相关性, 基于投入产出表衡量
Pay	支付方式, 采用现金支付取值为 0, 否则为 1
CM	补偿方式, 采用现金补偿取值为 0, 否则为 1
CD	补偿方向, 包含超额业绩奖励条款取值为 1, 否则为 0
EM	盈余管理, 并购前一年的可操纵性应计利润
ID	整合程度, 从并购后持股比例、并购类型与 ROA 变动三个方面来衡量
Resize	交易规模, 交易金额的自然对数与收购方 t-1 年度资产总额自然对数比值
Related	是否关联并购, 交易双方为同一控制人取值为 1, 否则为 0
Size	公司规模, 并购方总资产的自然对数
Lev	公司杠杆, 并购方期末总负债/期末总资产
Roa	公司业绩, 并购方当年净利润/平均总资产
Duality	两职合一, 并购方董事长与总经理兼任取值为 1, 否则为 0
Big10	审计质量, 并购方审计师来自国内十大取值为 1, 否则为 0
Envir	制度环境, 市场化指数
Year	年度固定效应

3、模型设计

构建模型 (1) 检验假设 1:

$$PA = \beta_1 Correlation + \beta_2 Controls + \sum Year + \varepsilon \quad (1)$$

样本按支付方式、补偿方式和补偿方向分组
执行模型 (1), 检验假设 2-4。

构建模型 (2)、(3) 检验假设 5:

$$EM = \beta_1 Correlation + \beta_2 Controls + \sum Year + \varepsilon \quad (2)$$

$$PA = \beta_1 Correlation + \beta_2 EM + \beta_3 Controls + \sum Year + \varepsilon \quad (3)$$

构建模型 (4) 检验假设 6:

$$PR = \beta_1 Correlation + \beta_2 Controls + \sum Year + \varepsilon \quad (4)$$

其中, 被解释变量 PR 分别使用业绩承诺实现率 (PR1) 与业绩承诺是否实现 (PR2) 来衡量。

样本按支付方式、补偿方式和补偿方向分组

执行模型 (4), 检验假设 7-9。

构建模型 (5)、(6) 检验假设 10:

$$ID = \beta_1 Correlation + \beta_2 Controls + \sum Year + \varepsilon \quad (5)$$

$$PR = \beta_1 Correlation + \beta_2 ID + \beta_3 Controls + \sum Year + \varepsilon \quad (6)$$

四、实证检验及结果分析

1、描述性统计结果

表 2 列示了主要变量的描述性统计结果, PA 均值是 3.977, 说明样本中业绩承诺激进程度平均为 3.977。PR1 均值为 1.067, 说明业绩承诺的平均实现水平为 106.7%, PR2 均值为 0.776, 说明样本中签订有业绩承诺的交易事项有 77.6%实现了年度业绩承诺。在样本中, 82%的交易事项使用股份支付, 78.6%使用股份补偿, 34.8%含有超额奖励条款。其

他控制变量均在合理范围之内。

表 2：描述性统计

Variable	N	Mean	sd	p50	Min	Max
PA	1938	3.977	3.596	2.547	0.826	14.713
PR1	1938	1.067	0.275	1.034	0.218	2.352
PR2	1938	0.776	0.417	1	0	1
Correlation	1938	0.092	0.116	0.043	0.002	0.520
Pay	1938	0.820	0.384	1	0	1
CM	1938	0.786	0.410	1	0	1
CD	1938	0.348	0.477	0	0	1
Resize	1938	0.939	0.062	0.940	0.784	1.086
Related	1938	0.435	0.496	0	0	1
Size	1938	22.180	0.810	22.160	20.391	24.105
Lev	1938	0.371	0.165	0.356	0.070	0.750
Roa	1938	0.042	0.048	0.044	-0.245	0.167
Duality	1938	0.333	0.472	0	0	1
Big10	1938	0.539	0.499	1	0	1
Envir	1938	7.495	1.293	7.560	4.150	10.000

2、相关性分析

由相关性分析可知：①Correlation 与业绩承诺激进程度的相关系数为-0.098，在 1%水平上显著，说明并购资产相关性与业绩承诺激进程度显著负相关，初步证实假设 1。②Correlation 与业绩承诺实现率、业绩承诺是否实现的相关系数分别为 0.071 和 0.067，均在 1%水平上显著，表示并购资产相关性与业绩承诺实现程度显著正相关，初步证实假设 7。限于篇幅未报告相关系数表。

3、回归结果与分析

（1）并购资产相关性与业绩承诺激进程度的关系及其影响因素

表 3 列示了并购资产相关性与业绩承诺激进程度的关系及其影响因素的回归结果，列 1 列示了并购资产相关性与业绩承诺激进程度之间的关系。Correlation 的系数为-2.982，且在 1%的水平上显著，说明并购资产相关性越高，业绩承诺激进程度越低，

假设 1 成立。

支付方式的调节因素见列 2 和列 3。股份支付组中 Correlation 的系数为-2.210，现金支付组中 Correlation 的系数为-8.006，均在 1%水平上显著，表明并购资产相关性与业绩承诺激进程度的负相关关系在现金支付方式下表现更明显。假设 2 成立。

补偿方式的调节因素见列 4 和列 5。股份补偿组中 Correlation 的系数为-2.693，现金支付组中 Correlation 的系数为-4.510，均在 1%的水平上显著，表明无论收购方采用何种补偿方式，并购资产相关性都能够显著降低业绩承诺激进程度。且相较于股份补偿，并购资产相关性与业绩承诺激进程度的负相关关系在现金补偿下表现更为明显，假设 3 不成立。可能是因为作为并购事后补偿机制，补偿方式对事前制定好的业绩承诺影响无足轻重。

补偿方向的调节因素见列 6 和列 7。双向业绩承诺组中 Correlation 的系数为-2.726，单向业绩承诺组中 Correlation 的系数为-2.987，均在 1%的水平

上显著，表明并购资产相关性与业绩承诺激进程度 4 成立。
的负相关关系在单向业绩承诺下表现更明显，假设

表 3：并购资产相关性与业绩承诺激进程度的关系及其影响因素

Variable	全样本	按支付方式分组		按补偿方式分组		按补偿方向分组	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	PA	Pay=1	Pay=0	CM=1	CM=0	CD=1	CD=0
Correlation	-2.982*** (-4.298)	-2.210*** (-2.985)	-8.006*** (-4.164)	-2.693*** (-3.524)	-4.510*** (-2.664)	-2.726** (-2.098)	-2.987*** (-3.709)
Control	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES
Adj.R ²	0.042	0.048	0.046	0.059	0.003	0.047	0.052
N	1938	1589	349	1523	415	675	1263

注：括号里为 t 值，*、**、***分别表示为在 10%、5%、1%的水平下显著，下同

(2) 并购资产相关性对业绩承诺激进程度的影响机制分析

表 4 检验了盈余管理在并购资产相关性与业绩承诺激进程度之间的中介效应。由列 2 可知，correlation 与 EM 在 1%的水平上显著负相关，即并

并购资产相关性越高，盈余管理越少。进一步地，根据列 3 可知，Correlation 和 EM 均与业绩承诺激进程度在 1%的水平上显著相关。由列 1-3 可知，盈余管理在并购资产相关性与业绩承诺激进程度之间具有中介作用，假设 5 得到证实。

表 4：并购资产相关性对业绩承诺激进程度关系的影响机制

Variable	(1)	(2)	(3)
	PA	EM	PA
Correlation	-2.982*** (-4.298)	-1.435*** (-3.944)	-2.608*** (-3.640)
EM			0.939*** (18.435)
Controls	YES	YES	YES
Year	YES	YES	YES
Adj.R ²	0.042	0.051	0.232
N	1938	1497	1497

(3) 并购资产相关性与业绩承诺实现程度的关系及其影响因素

表 5 列示了并购资产相关性与业绩承诺实现程度的关系及其影响因素的回归结果，PancelA 和 PancelB 分别检验了并购资产相关性与业绩承诺实现率、业绩承诺是否实现的关系及其影响因素。

PancelA 和 PancelB 的列 1 分别列示了并购资产相关性与业绩承诺实现率、业绩承诺是否实现之间的关系。Correlation 的系数分别为 0.159 和 0.229，且均在 1%的水平上显著，说明并购资产相关性越高，业绩承诺实现程度越高，假设 6 得到验证。

支付方式的调节因素见列 2 和列 3。以 PancelA 为例，股份支付组中 Correlation 的系数为 0.167，在 1%水平上显著；现金支付组中 Correlation 不显著。这说明并购资产相关性与业绩承诺实现程度的正相关关系在股份支付方式下表现更明显。，PancelB 同理，假设 7 得到验证。

补偿方式的调节因素见列 4 和列 5。以 PancelA 为例，股份补偿组中 Correlation 的系数为 0.178，在 1%水平上显著；现金补偿组中 Correlation 不显著。这说明并购资产相关性与业绩承诺实现程度的正相关关系在股份补偿方式下表现更明显，PancelB

同理，假设 8 得到验证。

补偿方向的调节因素见列 6 和列 7。以 PancelA 为例，双向业绩承诺组中 Correlation 的系数为 0.266，在 1%水平上显著；单向业绩承诺组中 Correlation 的

系数为 0.110，在 10%水平上显著。这说明并购资产相关性与业绩承诺实现程度正相关关系在双向业绩承诺下表现更明显，PancelB 同理，假设 9 得到验证。

表 5：并购资产相关性与业绩承诺实现程度的关系及其影响因素

PancelA							
Variable	全样本	按支付方式分组		按补偿方式分组		按补偿方向分组	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	PR1	Pay=1	Pay=0	CM=1	CM=0	CD=1	CD=0
Correlation	0.159*** (3.026)	0.167*** (3.104)	0.064 (0.381)	0.178*** (3.401)	0.046 (0.281)	0.266*** (2.981)	0.110* (1.666)
Controls	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES
Adj.R ²	0.064	0.06	0.077	0.06	0.079	0.079	0.056
N	1938	1589	349	1523	415	675	1263
PancelB							
Variable	全样本	按支付方式分组		按补偿方式分组		按补偿方向分组	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	PR2	Pay=1	Pay=0	CM=1	CM=0	CD=1	CD=0
Correlation	0.229*** (2.940)	0.301*** (3.637)	-0.198 (-0.882)	0.277*** (3.285)	0.108 (0.533)	0.415*** (3.010)	0.140 (1.455)
Controls	YES	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES	YES
Adj.R ²	0.101	0.105	0.082	0.108	0.086	0.135	0.083
N	1938	1589	349	1523	415	675	1263

(4) 并购资产相关性对业绩承诺实现程度的影响机制分析

表 6 检验了并购整合程度在并购资产相关性与业绩承诺实现程度之间的中介效应。由列 2 和列 5 可知，Correlation 与 ID 在 1%的水平上显著负相关，即并购资产相关性越高，并购整合效果越理想。进

一步地，根据列 3 和列 6 可知，Correlation 和 ID 均与业绩承诺实现率在 1%的水平上显著正相关。由列 1-3 和列 4-6 可知，并购整合程度在并购资产相关性与业绩承诺实现程度之间具有中介作用。假设 10 得到证实。

表 6：并购资产相关性对业绩承诺实现程度关系的影响机制

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	PR1	ID	PR1	PR2	ID	PR2
Correlation	0.159*** (3.026)	0.551*** (3.526)	0.141*** (2.691)	0.229*** (2.940)	0.551*** (3.526)	0.204*** (2.618)
ID			0.032*** (4.222)			0.046*** (4.040)
Controls	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Adj.R ²	0.064	0.088	0.072	0.101	0.088	0.108
N	1938	1938	1938	1938	1938	1938

五、稳健性检验

为了检验实证的可靠性，本文进行了稳健性检验：更换解释变量和被解释变量的衡量方式；更换回归模型：Bootstrap 抽样法；Heckman 两阶段回归。以上回归结果与前文结论基本保持一致，限于篇幅不一赘述。

六、进一步分析：业绩承诺激进程度对并购资产相关性与业绩承诺实现程度关系的影响

前文研究表明目标方为获取高溢价，会制定高业绩承诺，此情况在并购资产低相关性的并购中更常见。高业绩引来投资者青睐的同时会增加承诺期不能实现的风险。若履约失败，标的资产会成为上市公司的不良资产，这损害了中小股东的利益。那么业绩承诺制定的高低究竟如何影响业绩承诺的实现呢？

表 7：进一步分析：业绩承诺激进程度对并购资产相关性与业绩承诺实现率关系的影响

Variable	(1)	(2)
	PR	PR
Correlation	0.147** (2.490)	0.193 (1.670)
Controls	YES	YES
Year	YES	YES
Adj.R ²	0.044	0.094
N	1365	573

本文借鉴王竞达的划分，使用业绩承诺激进程度的平均数将全样本划分为高业绩组与低业绩组，进行分组回归，结果如表 7 所示。在高业绩组，相关性与实现率之间的关系在 5%的水平上显著正相关。这说明在业绩承诺激进程度较低的情况下，并购资产相关性与业绩承诺实现率之间的正相关关系越明显。在高业绩组，相关性与业绩承诺实现率没有关系。

七、结论与建议

1、研究结论

本文以 2009-2019 年 A 股上市公司为样本，通

过构建回归模型与中介模型，分析了并购资产相关性与业绩承诺之间的关系及支付方式、补偿方式和补偿方向的调节作用，以及盈余管理和整合程度的中介作用，进一步研究了业绩承诺激进程度对并购资产相关性与业绩承诺实现率关系的影响。研究发现：①由于信息不对称，并购资产相关性越高，业绩承诺激进程度越低。现金支付和单向业绩承诺增强了此负相关关系。②由于交易费用成本与协同效应，并购资产相关性越高，业绩承诺实现程度越高。股份支付、股份补偿和双向业绩承诺正向调节此正相关关系。③并购资产相关性通过盈余管理影响业绩承诺激进程度，通过并购整合程度影响业绩承诺实现程度。④业绩承诺低激进程度促进了并购资产相关性与业绩承诺实现率的正相关关系。

2、对策建议

本文提出如下建议：①上市公司在选择目标方时可以考虑双方相关性，基于战略目标优先考虑相关性较高的公司。②部门应健全业绩承诺条款，如约定股份支付比例、建议使用双向业绩承诺等。为提高业绩承诺完成质量，可考虑股份支付、股份补偿、双向业绩承诺等契约安排。③在收购低相关性资产时，应警惕目标方是否利用信息不对称进行盈余管理。在整合阶段要重视目标方子公司身份和业务类型以提高整合速度。④证监会应关注业绩承诺高于以往业绩或预测利润的程度；上市公司应制定合理的业绩承诺。

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ESG 表现与股权资本成本

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摘要：本文基于 A 股全部上市公司 2010-2019 年数据，构建 ESG 评价体系，利用熵权法计算得到企业的 ESG 得分，通过多元回归分析以及中介效应检验，研究 ESG 表现对股权资本成本的影响及路径。研究发现：首先，ESG 与股权资本成本存在显著负相关关系；其次，ESG 表现好的企业其经营风险和财务风险较低，从而降低股权资本成本，财务风险和经营风险起到了部分中介作用。

关键词：ESG，股权资本成本，熵权法

ESG performance and cost of equity capital

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Abstract: Based on the data of all A-share listed companies from 2010 to 2019, this paper constructs an ESG evaluation system, uses the entropy weight method to calculate the ESG score of the company and studies the impact and path of ESG performance on the cost of equity capital through multiple regression analysis and mediation effect test. The study found that: firstly, ESG has a significant negative correlation with the cost of equity capital; secondly, companies with good ESG performance have lower operational and financial risks, thereby reducing the cost of equity capital, and financial risk and operational risk play a partial intermediary role.

Key Words: ESG, cost of equity capital, entropy weight method

一、引言

自工业革命以来，全球碳排放量剧增，导致全球变暖，极端天气频发等一系列问题，可持续发展理念越来越成为人们的共识。2020 年，我国在联合国大会上做出承诺，力争于 2030 年前达到碳顶峰，2060 年前实现碳中和。在碳中和的背景下，企业的 ESG 表现越来越为投资者所关注。ESG 概念由联合国全球契约组织于 2004 年提出，是环境，社会责任，公司治理的英文缩写，反映了企业的可持续发展能力，同时也是一种由管理单一商业生态向管理多元社会生态转变的理念。ESG 表现好的企业可以通过享受政策红利，和对消费趋势变化的准确预测，从而降低成本，提升企业价值。此外，良好的 ESG 表现还可以起到降低企业风险和法律保障等作用。

随着 ESG 理念的普及，传统的财务报告已不能满足投资者的需求，2021 年，证监会将 ESG 信息纳入《上市公司投资者关系管理指引（征求意见稿）》

的沟通内容。目前在我国，ESG 投资理念尚处于发展阶段，很多上市公司对于 ESG 信息的披露并不充分，同时，ESG 评价指标有待进一步完善。尽管如此，越来越多的机构和投资者关注 ESG 题材，并把 ESG 作为投资考核的标准，通过评估企业的 ESG 表现，投资者倾向于将资金投向可持续发展能力更强的业务或企业。那么，在碳中和的背景下，企业能否通过良好的 ESG 表现，从而降低企业的股权资本成本呢？

二、文献回顾

国外有学者研究了 ESG 表现与资本成本的关系。（Atan, 2018）^[1] 研究结果显示，环境、社会或公司治理的综合得分会对企业的加权资本成本（WACC）产生显著影响。而（Ng, 2015）^[2] 研究发现 ESG 可以显著降低股权资本成本。（Chava, 2014）^[3] 发现对于环境状况较差的公司而言，股权资本成本和债务资本成本更高；（Breuer, 2018）^[4]

认为,社会责任表现与股权资本成本之间的关系取决于企业所在国家或地区的投资者保护法,在对投资者保护较强的国家或地区,社会责任的较高表现降低股权了资本成本。

目前国内机构评级受限于研究数据的数量及质量,往往无法得出客观全面的结果,鲜少有文献研究 ESG 表现与股权资本成本的关系。(赵雪延, 2021)^[5]利用商道融绿提供的沪深 300 和中证 500 成分股企业 ESG 评级数据,分别研究了 ESG 与股权资本成本及债务资本成本的关系。但因其研究样本数量较少,且是资本市场上表现较好的企业,对整个市场的解释力度还不够。(邱牧远, 2019)^[6]并未采用 ESG 评级,而是分别构建了环境,社会责任,公司治理的代理变量,研究上述三个方面对股权和债务资本成本的影响。也有学者尝试自己构建 ESG 评价体系,但仅是针对某一行业,(袁家海, 2019)^[7]选取了电力行业,针对该行业的特点构建了 ESG 评价体系,但并未研究 ESG 表现与资本成本的关系。综上,并未有学者通过构建 ESG 评价体系,研究 ESG 对股权资本成本的影响。

本文选取了 A 股市场的所有上市公司,利用熵权法构建 ESG 评价体系,进一步分析了企业 ESG 表现影响股权资本成本的路径。本文的贡献主要体现在:一是构建了 A 股市场的 ESG 评价体系,使研究不再局限于某一行业或某一板块;二是探索了 ESG 表现对股权资本成本的影响路径,丰富了之前的研究;三是为 ESG 投资者提供重要证据,推动投资者及企业管理者更加重视企业的可持续发展。

三、理论分析与研究假设

利益相关者理论认为股东并不是公司唯一的所有者,企业应该追求利益相关者的整体利益。同时企业应当坚持可持续发展理念,承担社会责任,满足各利益相关者的需求,实现利益相关者的福利最大化。根据利益相关者理论,ESG 表现良好的企业,通过塑造创新、绿色、负责的企业形象,以此吸引更多更优质的利益相关者,如投资者、员工、客户等,并与之建立稳定的合作关系,从而为企业带来更多资源和经济利益。随着人们对环境问题的

日益关注,投资者更倾向于将资金投向可持续发展能力更强的业务或企业。(Heinkel, 2001)^[8]认为负面筛选使得污染公司被更少的投资者所持有,进而导致股票价格下跌和资本成本上升。(Kölbel & Busch 2017)^[9]认为,资本提供者会相应地调整他们对风险和回报的预期,并且通常愿意接受较低的回报和贷款利率,以便向 ESG 表现优异的公司提供资金。(Cheng, 2014)^[10]研究表明:ESG 会影响投资者对公司未来现金流量的不确定性和风险的评估。ESG 表现好的企业,意味着企业与各利益相关者有着良好的互动关系,从而能够吸引更多资金。如果投资者重视企业的 ESG 表现,将 ESG 纳入自己的投资决策,可能会间接降低股本资本的成本。

因此,本文提出假设:

H1: ESG 表现越好的企业股权资本成本越低。

根据风险评估理论,企业的风险水平越高,企业的股权资本成本也就越高。而 ESG 表现良好的企业可以降低自身风险,因为公司在进行参与环保、履行社会义务时,可以帮助企业在市场中建立良好声誉,减少企业负面事件的发生,从而降低企业经营风险和财务风险。企业还可以通过完善的 ESG 风险管控,增强企业在多元环境和社会性需求中的抗风险能力。优秀的 ESG 表现使企业得到投资者以及社会公众广泛的信任与支持,可以及时防范和化解风险。因此,本文提出假设:

H2: 企业 ESG 表现越好,经营风险越低,股权资本成本越低。经营风险在 ESG 与股权资本成本的关系中起中介作用。

H3: 企业 ESG 表现越好,财务风险越低,股权资本成本越低。财务风险在 ESG 与股权资本成本的关系中起中介作用。

四、研究设计

1、ESG 评价体系设计

(1) 指标选取依据

国外的 ESG 评价体系相对成熟,但是国外机构所选取的指标很多并不符合我国国情。国内也有类似机构出具 ESG 评级数据,如商道融绿等,但其提供的评级数据只能覆盖 A 股部分上市公司。现阶段

我国企业对于 ESG 信息的披露水平不够,而评级机构设置的指标却有上百个,在数据获取方面存在很大难度,最后只能评价出部分企业的 ESG 表现。因此,本文借鉴国内外 ESG 评价体系,从上百个指标中提炼出二十多个核心指标,设计出更为简洁,更具有普适性且符合我国国情的 ESG 评价体系,从而满足学术研究的需求。指标选取的依据主要有可持续发展理论、利益相关者理论、企业社会责任理论以及企业伦理观念等。

A. 环境指标

环境指标的选取主要依据可持续发展理论,现有 ESG 评价体系大多关注企业的行为对空气、土壤、水源,气候及生态系统的影响,以及企业是否建立相应的环境管理机制。此外,MSCI 和汤森路透等国外机构还关注企业是否利用与环境相关的发展机会,在减轻环境压力的同时,为企业创造更多价值。

结合我国国情,本文从环境压力和环境管理两个方面来衡量企业对于环境的影响。由于无法得到大部分企业的污染物排放数据,本文选取了是否属于重点排污单位以及排污种类数两个指标进行替代,以此衡量企业对环境造成的负面影响。同时本文选取是否参与环保教育与培训,是否在年报中披露环保理念,是否建立环境事件应急机制以及环保投资占营业收入的比例来衡量企业在环境管理方面所作的积极努力。

B. 社会责任指标

利益相关者理论和企业社会责任理论认为,企业应积极承担社会责任,实现包括股东、员工、社区、政府在内的利益相关者福利最大化。因此现有 ESG 评价体系中所选取的社会责任指标大多是围绕利益相关者展开。考虑到数据的可得性,本文从员工,上下游关系,政府,社会公众四个方面来衡量企业承担社会责任的状况。员工方面,本文选取职工培训费以及平均薪资衡量企业在人力资本方面的投入,以薪酬差距来衡量员工的满意度。在上下游关系中,本文选取应付账款周转率和应收账款周转率,以此反映企业与上下游企业的信用关系。政府方面,本文采用人均税收这一指标来衡量企业的

税收贡献。社会公众方面,借鉴现有的国内外 ESG 体系,选取新增就业岗位来衡量企业对社会的就业贡献,选取慈善捐赠占营业收入比重和扶贫资金,来衡量企业和社会公益事业上的投入力度。

C. 公司治理指标

企业伦理观念强调企业经营过程中遵守商业道德,不能产生危害社会的行为。MSCI 关注企业的商业伦理,商道融绿将企业负面事件纳入评价体系,其本质也是评价企业是否遵循商业伦理。现有 ESG 评价体系也关注公司的治理结构,如董事会,高管薪酬以及股权结构等。最终本文从治理结构,公司治理异常,公司治理负面事件三个方面衡量企业的公司治理水平。

在治理结构上,本文选取独立董事占比这一指标来反映董事会的独立性,考虑到高管薪酬的数据并不全面,本文采用高管持股比例进行替代,在股权结构上,本文采用了第一大股东持股比例、机构投资者持股比例两个指标。在公司治理异常上,本文选取第一大股东是否变更、控制权是否变更两个指标。在公司治理负面事件上,本文选取是否被交易所公开批评或谴责,是否被出具非标准审计意见,公司是否参与诉讼仲裁,上市公司是否被通报违规四个指标。

(2) 指标评价方法

本文采用熵权法,对指标进行正向化或逆向化处理,正向化指标得分越高,ESG 表现越好,逆向化指标得分越高,ESG 表现越差。本文采用 SPSSAU 对取得的数据进行处理,分别计算出环境得分,社会责任得分以及公司治理得分,最后加总得到 ESG 得分。基于熵权法的原理,熵值越小,所赋权重也就越大。如果变量为虚拟变量,其取值只有 0 和 1,相较于连续变量,信息熵值过小,得到的权重分配过高,对最终结果会产生很大影响。因此本文将同属于一级指标下的多个虚拟变量,按照指标性质,加总成为多分类变量,以此来缓解上述问题。在实际数据处理中,缺失值均替换为 0。具体指标见表 1。

表 1 ESG 具体指标表

一级指标	二级指标	三级指标	指标性质
环境	环境压力	是否属于重点污染监控单位	逆向化指标
		排污种类数	逆向化指标
	环境管理	是否建立环境事件应急机制	正向化指标
		否参与环保教育与培训	正向化指标
		是否在年报中披露环保理念	正向化指标
		环保投资占营业收入比重	正向化指标
		职工培训费	正向化指标
	员工	平均薪资	正向化指标
		员工满意度	逆向化指标
		应付账款周转率	正向化指标
社会责任	上下游关系	应收账款周转率	正向化指标
		应付账款周转率	正向化指标
	政府	人均税收	正向化指标
		新增就业岗位	正向化指标
		慈善捐赠额占营业收入比重	正向化指标
	社会公众	投入扶贫资金	正向化指标
		独立董事占比	正向化指标
		第一大股东持股比例	逆向化指标
		高管人员持股比例	正向化指标
		机构投资者持股比例	正向化指标
公司治理	治理结构	第一大股东是否变更	逆向化指标
		公司当年控制权是否变更	逆向化指标
		公司是否参与诉讼仲裁	逆向化指标
	公司治理异常	上市公司是否被通报违规	逆向化指标
		是否被交易所公开批评或谴责	逆向化指标
		是否被出具非标准审计意见	逆向化指标
	公司治理负面事件		

2、变量定义与数据来源

本文选取 2010-2019 年所有 A 股上市公司作为样本，不包括金融业和 ST 企业。分析师预测每股收益数据来自 wind 数据库，股票日价格数据来自锐思数据库，其余数据来自国泰安数据库。为了避

免极值影响，在进行回归之前，连续变量都在 1% 的水平上进行缩尾处理，具体变量见表 2。

本文采用的多元回归模型如下所示：

$$rPEG_{i,t} = \beta_0 + \beta_1 ESG_{i,t} + SCONTROLS + SIND + m$$

$$rOJN_{i,t} = g_0 + g_1 ESG_{i,t} + SCONTROLS + SIND + d$$

表 2 变量定义表

变量性质	变量符号	变量名称	变量定义
被解释变量	rPEG	股权资本成本	根据 PEG 模型计算
	rOJN	股权资本成本	根据 OJN 模型计算
解释变量	ESG	企业 ESG 表现	通过构建 ESG 评价体系计算得出
中介变量	IV	经营风险	过去 3 年主营业务收入的标准离差率
	SV	经营风险	(t-2, t+2) 五年内的年个股回报率标准差
	AL	财务风险	资产负债率
	F	财务风险	根据 F 分数模型计算得出
控制变量	SIZE	公司规模	当年度企业流通市值的对数
	TR	年换手率	来自国泰安数据库
	BM	账面市值比	每股账面价值/公司股票价格
	BETA	系统风险	来自国泰安数据库
	GR	公司成长性	当年度主营业务收入的增长率
	SOE	产权性质	国有企业取值为 1，非国有企业取值为 0
	IND	行业虚拟变量	控制行业效应

五、实证结果

1、描述性统计及相关性分析

如表 3 所示，企业 ESG 得分均值为 0.48，最小值为 0.202，3/4 分位数为 0.598，说明大多数企业的 ESG 得分在 0.2-0.6 这一区间。rOJN 的均值为 0.13，rPEG 均值为 0.11，两种模型计算出的股权资本成本相差不大。资产负债率的最小值为 0.070，3/4 分位数为 0.614，说明大多数企业的负债率在 65%

以下。公司成长性的中位数为 0.153，说明半数企业的主营业务收入增长率在 15%以上。

经过检验，变量间不存在多重共线性，其次，股权成本与 ESG 呈负相关，但是关系并不显著，后续将引入多元回归模型进一步分析。如表 4 所示，公司规模与 ESG 及股权资本成本均显著相关，这一点在内生性讨论中将进一步分析。

表 3 描述性统计

变量	样本量	均值	标准差	最小值	1/4 分位	中位数	3/4 分位	最大值
rOJN	7378	0.13	0.037	0.056	0.106	0.127	0.151	0.251
rPEG	7378	0.11	0.037	0.032	0.081	0.101	0.125	0.224
ESG	7378	0.48	0.214	0.202	0.319	0.376	0.598	1.137
AL	7378	0.46	0.197	0.070	0.309	0.465	0.614	0.856
F	7378	0.56	0.776	-0.433	0.084	0.363	0.773	4.258
IV	7378	0.21	0.187	0.014	0.094	0.163	0.266	1.102
SV	7378	0.48	0.271	0.104	0.295	0.415	0.592	1.490
SIZE	7378	22.65	1.039	20.454	21.950	22.561	23.252	25.707
TR	7378	328.65	229.300	33.534	163.147	269.609	432.071	1146.506
BM	7378	0.62	0.242	0.138	0.432	0.623	0.809	1.129
BETA	7378	1.16	0.282	0.461	0.978	1.161	1.332	1.952
GR	7378	0.24	0.445	-0.339	0.035	0.153	0.313	3.073

表 4 相关性分析结果

	rPEG	ESG	SIZE	TR	BM	BETA	GR
rPEG	1						
ESG	-0.016	1					
SIZE	-0.070***	0.179***	1				
TR	-0.157***	-0.116***	-0.150***	1			
BM	0.355***	0.087***	-0.034***	-0.304***	1		
BETA	0.024**	-0.014	-0.143***	0.333***	0.035***	1	
GR	0.071***	-0.039***	-0.029**	0.019*	-0.011	0.021*	1

*** p<0.01, ** p<0.05, * p<0.1

2、多元回归结果

本文采用混合回归、个体效应模型和固定效应模型对数据进行处理。在异方差检验中,结果显示存在异方差,为了缓解这一问题,本文采用了个体聚类,进行多元回归分析。通过 LM 检验和过度识别检验,个体固定效应模型更为适用。如表 5 所示,ESG 与 rPEG 之间存在显著的负相关性,本文的假设 H1 得到验证。

表 5 多元回归结果

变量	混合回归	随机效应	固定效应
	rPEG	rPEG	rPEG
ESG	-0.011*** (-4.98)	-0.011*** (-5.41)	-0.007*** (-2.96)
SIZE	-0.001* (-1.77)	-0.003*** (-6.10)	-0.010*** (-10.97)
TR	-0.000*** (-6.07)	-0.000*** (-9.54)	-0.000*** (-10.42)
BM	0.055*** (21.22)	0.046*** (18.24)	0.018*** (4.72)
BETA	0.002 (1.11)	0.001 (0.54)	0.003* (1.79)
GR	0.005*** (4.84)	0.004*** (3.74)	0.003** (2.52)
SOE	-0.005*** (-4.62)	-0.003*** (-2.72)	-0.005* (-1.66)
IND	控制	控制	控制
_cons	0.104*** (7.72)	0.167*** (12.45)	0.342*** (15.28)

N	7378	7378	7378
r2_a	0.196		0.124
F	58.231		36.878

*** p<0.01, ** p<0.05, * p<0.1

3、中介效应检验

参照(温忠麟, 2004)^[11]的研究,本文选择的中介检验方法是 Sobel 检验。Sobel 检验模型如下: M 指的是中介变量, CONTROLS 为前文选取的控制变量。本文选取的中介变量为经营风险和财务风险。

$$rPEG = h_0 + h_1 ESG + SCONTROLS + e$$

$$M = l_0 + l_1 ESG + SCONTROLS + e$$

$$rPEG = w_0 + w_1 ESG + w_2 M + SCONTROLS + e$$

本文采用会计收益波动性(IV)以及股票收益波动性(SV)来衡量经营风险,会计收益波动性与股票收益波动性越大,则经营风险越大。将上述两个变量分别带入模型进行 Sobel 检验,结果显示均存在显著的部分中介效应。如表 6 所示,第 2 列和第 5 列可以看出,经营风险与 ESG 显著负相关,第 3 列和第 6 列可以看出,经营风险与 rPEG 显著正相关。因此,ESG 表现越好,企业的经营风险和股权成本越低,经营风险在其中可以起到部分中介作用。本文的假设 H2 得到验证。

表 6 经营风险中介检验结果

变量	(1)	(2)	(3)	(4)	(5)	(6)
	rPEG	IV	rPEG	rPEG	SV	rPEG
ESG	-0.011*** (-5.74)	-0.033*** (-3.22)	-0.010*** (-5.47)	-0.011*** (-5.74)	-0.133*** (-9.17)	-0.009*** (-4.95)
SIZE	-0.001** (-2.45)	-0.006** (-2.47)	-0.001** (-2.24)	-0.001** (-2.45)	-0.010*** (-3.25)	-0.001** (-2.18)
TR	-0.000*** (-7.54)	-0.000*** (-10.17)	-0.000*** (-6.61)	-0.000*** (-7.54)	0.000** (2.43)	-0.000*** (-7.77)
BM	0.055*** (29.18)	-0.006 (-0.61)	0.055*** (29.36)	0.055*** (29.18)	-0.211*** (-14.37)	0.057*** (30.10)
BETA	0.002 (1.39)	0.044*** (5.45)	0.001 (0.90)	0.002 (1.39)	0.089*** (7.70)	0.001 (0.73)
GR	0.005*** (6.11)	0.054*** (11.44)	0.004*** (5.06)	0.005*** (6.11)	0.090*** (13.40)	0.004*** (4.93)
SOE	-0.005*** (-6.26)	-0.016*** (-3.43)	-0.005*** (-5.97)	-0.005*** (-6.26)	-0.014** (-2.07)	-0.005*** (-6.11)
IV			0.016*** (7.73)			
SV						0.011*** (7.32)
IND	控制	控制	控制	控制	控制	控制
_cons	0.119*** (11.66)	0.346*** (6.15)	0.114*** (11.12)	0.119*** (11.66)	0.640*** (8.04)	0.112*** (10.96)
N	7378	7378	7378	7378	7378	7378
r2_a	0.203	0.073	0.210	0.203	0.111	0.209
F	79.491	25.102	79.313	79.491	39.559	79.001

*** p<0.01, ** p<0.05, * p<0.1

本文采用资产负债率 (AL) 和 F 分数来衡量企业的财务风险, 资产负债率越大或者 F 分数越小, 则财务风险越大。Sobel 检验的结果是拒绝了原假设, 部分中介效应显著。如表 7 所示, 第 2 列和第 5 列回归结果可以看出, ESG 与财务风险显著负相

关。第 3 列和第 6 列可以看出, 财务风险与股权资本成本显著正相关。因此, ESG 表现越好, 财务风险和股权资本成本越低, 财务风险在其中可以起到部分中介作用。本文假设 H3 得到验证。

表 7 财务风险中介效应检验结果

变量	(1)	(2)	(3)	(4)	(5)	(6)
	rPEG	AL	rPEG	rPEG	F	rPEG
ESG	-0.011*** (-5.74)	-0.061*** (-7.07)	-0.008*** (-4.52)	-0.011*** (-5.74)	0.229*** (6.43)	-0.010*** (-5.23)
SIZE	-0.001** (-2.45)	0.039*** (20.72)	-0.003*** (-6.14)	-0.001** (-2.45)	-0.095*** (-12.29)	-0.001*** (-3.41)
TR	-0.000*** (-7.54)	0.000*** (12.16)	-0.000*** (-9.81)	-0.000*** (-7.54)	-0.001*** (-15.08)	-0.000*** (-8.63)
BM	0.055*** (29.18)	0.364*** (41.73)	0.041*** (19.76)	0.055*** (29.18)	-1.744*** (-48.64)	0.048*** (22.10)
BETA	0.002 (1.39)	0.009 (1.36)	0.002 (1.16)	0.002 (1.39)	-0.117*** (-4.14)	0.002 (1.06)
GR	0.005*** (6.11)	0.038*** (9.51)	0.004*** (4.43)	0.005*** (6.11)	0.007 (0.41)	0.005*** (6.16)
SOE	-0.005*** (-6.26)	0.043*** (10.93)	-0.007*** (-8.32)	-0.005*** (-6.26)	-0.130*** (-7.96)	-0.006*** (-6.89)
AL			0.039*** (15.82)			
F						-0.004*** (-6.82)
IND	控制	控制	控制	控制	控制	控制
_cons	0.119*** (11.66)	-0.700*** (-14.75)	0.147*** (14.36)	0.119*** (11.66)	3.792*** (19.45)	0.135*** (12.91)
N	7378	7378	7378	7378	7378	7378
r2_a	0.203	0.404	0.230	0.203	0.353	0.208
F	79.491	209.405	88.909	79.491	168.692	78.645

*** p<0.01, ** p<0.05, * p<0.1

4、内生性讨论及稳健性检验

(1) 工具变量法

ESG 表现与股权资本成本可能存在逆向因果问题。一方面,企业的 ESG 表现越好,股权资本成本越低;另一方面,企业的股权资本成本越低,企业便可以得到更多的资源,从而提高企业的 ESG 表现。借鉴(周方召, 2020)^[12], 本文采用同省份同行业同年度其他企业的 ESG 表现均值作为工具变量(average_iv), 进行两阶段最小二乘法回归(2sls)。首先, 企业所在省份及行业的政策具有高度相似性, 因此工具变量与解释变量(ESG)之间具有相关性。

其次, 其他企业的 ESG 表现并不会对本企业的股权资本成本产生影响, 因此该工具变量具有外生性。本文采用个体聚类, 进行两阶段回归。如表 8 所示, ESG 与工具变量显著正相关, 同时股权资本成本与 ESG 显著负相关。在控制了内生性因素之后, 工具变量方法的回归结果与之前的回归结果保持一致。

表 8 工具变量法两阶段回归结果

变量	一阶段回归	二阶段回归	
	ESG	rPEG	rOJN
average_iv	0.530*** (14.67)		
SIZE	0.030*** (8.15)	0.001** (1.96)	0.001** (2.12)
TR	-0.000*** (-4.29)	-0.000*** (-6.69)	-0.000*** (-6.41)
BM	0.111*** (6.97)	0.056*** (19.60)	0.050*** (17.07)
BETA	0.007 (0.64)	0.002 (1.59)	0.001 (0.58)
GR	-0.014*** (-2.75)	0.006*** (5.44)	0.006*** (4.87)
BC	-0.037* (-1.67)	0.021*** (5.94)	0.024*** (6.58)
SOE	-0.036*** (-4.44)	-0.009*** (-6.69)	-0.009*** (-6.88)
ESG		-0.052*** (-5.32)	-0.038*** (-3.84)
IND	控制	控制	控制
_cons	-0.507*** (-5.56)	0.071*** (4.52)	0.092*** (5.85)
N	8584	8584	8584
r2_a	0.122	0.134	0.141

*** p<0.01, ** p<0.05, * p<0.1

(2) 倾向得分匹配法

ESG 表现会内生于其所处的环境和自身特征,如公司规模等因素,可能同时与股权资本成本相关,从而产生内生性问题。公司规模越大,政府和公众要求其承担的社会责任也就越多,公司在 ESG 方面的投入也就越高,ESG 表现越好。公司规模越大,股权资本成本也越低。国有企业相比非国有企业,股权资本成本更低,同时国有企业需要承担更多的社会责任,从而 ESG 表现更高。因此本文采用倾向得分匹配法来降低干扰因素对研究结果的影响。首先构建与 ESG 表现水平相关的虚拟变量,如果企业属于国证 ESG 300 成分股,则取值为 1,说明企业

具有优秀的 ESG 表现,否则取值为 0。借鉴(晓 芳,兰风云等, 2021) [13] 本文选择企业规模 (SIZE), 盈利能力 (ROA) 以及产权性质 (SOE) 这三个变量,进行最近邻 1:1 匹配。匹配后变量的标准化偏差均小于 10%。根据 t 检验结果,匹配后样本的处理组和控制组不存在显著差异。将 PSM 匹配成功的样本进行多元回归分析,如表 9 所示,股权资本成本与 ESG 表现显著负相关,其他控制变量符号基本不变,结果与前文一致。

表 9 PSM 匹配后样本多元回归结果

变量	混合回归	随机效应	固定效应
	rPEG	rPEG	rPEG
ESG	-0.027*** (-4.32)	-0.020*** (-3.25)	-0.013* (-1.88)
SIZE	0.001 (0.46)	-0.002 (-0.88)	-0.016*** (-3.90)
TR	-0.000** (-2.18)	-0.000** (-2.41)	-0.000* (-1.94)
BM	0.040*** (5.47)	0.042*** (5.61)	0.003 (0.19)
BETA	0.017*** (2.95)	0.011** (2.12)	-0.003 (-0.42)
GR	0.015** (2.49)	0.016*** (2.59)	0.007 (1.00)
SOE	-0.008* (-1.97)	-0.006 (-1.49)	0.001 (0.12)
IND	控制	控制	控制
_cons	0.080 (1.54)	0.151*** (2.81)	0.565*** (5.43)
N	634	567	567
r2_a	0.254		0.165

*** p<0.01, ** p<0.05, * p<0.1

(3) 替换被解释变量

为了进一步验证结果的稳健性,本文将被解释变量替换为 rOJN,重复前文的步骤。结果显示, rOJN 与 ESG 显著负相关,控制变量的符号方向基本不变,与前文结果一致。本文采用替换后的被解释变量再次进行中介效应检验,结果均拒绝了 Sobel 检验的原假设,部分中介效应显著,与

前文结果一致, 表略。

六、研究结论与建议

本文选取 A 股全部上市公司, 构建 ESG 评价体系, 利用熵权法计算得到企业的 ESG 得分, 通过多元回归分析以及中介效应检验, 研究 ESG 表现对股权资本成本的影响及路径。主要研究结论如下: 第一, 股权资本成本与 ESG 显著负相关, ESG 表现越好, 股权资本成本越低。第二, ESG 与经营风险, 财务风险显著负相关, 经营风险及财务风险可以起到部分中介作用, 从而降低股权资本成本。本文采用工具变量法, 倾向得分匹配法等稳健性检验后研究结论仍然成立。

结合研究, 本文提出如下建议: 一是对于上市公司来说, 一方面企业要提高自身 ESG 表现, 包括积极承担和履行社会、环境责任, 提高公司治理水平等, 与各利益相关者建立长久而稳定的关系, 从而降低企业的股权资本成本, 另一方面, 大部分企业的 ESG 信息披露不足, 导致投资者对企业的 ESG 表现无法做出准确判断, 企业要做好 ESG 信息披露工作, 降低信息不对称程度。二是在碳中和的背景下, 政府应当发挥监督职能, 加快完善 ESG 信息披露制度, 尤其是加强对企业碳信息披露的管控, 建立统一规范的 ESG 评价体系, 及时发布评级信息, 为投资者决策提供真实有效的数据参考。相关部门还可以建立奖惩机制, 对于 ESG 信息披露不足的企业进行处罚, 推动投资者及企业管理者更加重视企业的可持续发展。三是根据研究结果, ESG 表现好的企业经营风险和财务风险较低, 因此投资者在投资项目时, 不仅要关注企业的经济绩效, 也要关注企业所承担的社会责任, 环境责任等, 将 ESG 纳入投资决策之中, 将资金投向 ESG 表现更优秀的企业, 从而更好地规避风险, 实现投资的价值最大化。

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中国制造业上市公司存货非对称投资研究

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摘要：自 2008 年经济危机导致库存积压到 2015 年国家发布的“去库存”经济任务，存货行为决策对企业而言都是一个重要的命题。本文选取 2007-2020 年中国制造业 A 股上市公司作为样本，考察企业存货投资行为。研究发现，企业存货投资存在不对称性，即业绩下降时存货投资减少的幅度小于同等业绩量上升时存货投资增加的幅度。进一步研究发现，在业绩下降时，调整成本越大、管理者对未来需求预期越积极、供不应求导致的缺货成本越大，企业维持生产投入的动机越大，从而导致了更大程度的非对称存货投资。以上结果表明，高昂的调整成本、管理者对未来需求的积极预期与缺货成本促使企业进行非对称存货投资。本研究不仅丰富了国内对存货投资影响因素的研究，还为管理者在应对业绩变化时如何调整和利用承诺生产资源提供了决策参考。

关键词：存货投资；业绩变化；调整成本；管理者预期；缺货成本

Asymmetric Inventory Investment—Evidence from the Chinese Manufacturing Sector

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Abstract: Since the Economic Crisis in 2008 which led to overstocking of inventory to the economic task of "Destocking" issued by the state in 2015, inventory behavior decision-making has become an important proposition for enterprises. We select Chinese manufacturing A-share listed companies from 2007 to 2020 as the research object to investigate the investment behavior of corporate inventory. We find that there exist an asymmetric relation between inventory investment and sales changes, take it in another way, the decrease in inventory investment when sales decrease is less than that of an increase in inventory investment for an equivalent sales increase. In addition, we find that when sales decrease, the greater the cost of adjustment, the more positive managers' expectations for future demand, the greater the cost of stockout due to short supply, and the greater the motivation of enterprises to maintain production inputs, which lead to a greater degree of asymmetric inventory investment. The above results show that high costs of adjustment, managers' positive expectations for future demand and high out-of-stock costs prompt companies to make asymmetric inventory investments. Our findings not only enrich domestic research on factors affecting inventory investment, but also provide reference for how managers adjust and utilize committed production resources to make inventory decisions in response to sales changes.

Key Words: inventory investment, sales change, adjustment costs, managers' expectation, stockout

一、引言

存货是企业经营活动中必不可少的组成部分，存货投资是指某一时期内非价格因素导致的存货变化，对企业而言是至关重要的战略性决策，有研究表明，存货波动较大的公司在股市中的表现也不尽如人意（Allen et al., 2013^[1]）。传统文献分析在

面对业务量增加或减少时，企业管理者在确定存货生产时往往做出对称的线性反应（Lovell 1961^[2]；Bernard and Stober 1989^[3]；Dechow et al.1998^[4]），自 Anderson（2003）^[5]发现企业的销售、一般和管理费用（SG&A）存在粘性开始，对“成本粘性”的研究开始拓展至多类成本，但是鲜少有学者研究

企业生产存货投入的成本是否存在粘性。由于以往的研究主要集中在 SG&A 成本上,因此管理者如何根据经营活动水平的变化综合调整生产资源和生产决策,学术界对此还尚未有定论。

基于以上研究,本文聚焦 2007-2020 年中国制造业 A 股上市公司,考察企业存货投资行为与业绩变化的关系,检验企业在业绩下降时,是否会保持平滑生产以减少平均生产成本,是否会出于避免高昂调整成本、拥挤成本与缺货成本的目的维持生产投入,从而导致业绩下降时存货投资的减少幅度小于同等业绩量上升时存货投资的增加幅度。实证结果表明,企业存货投资与业绩变化为非线性关系,管理者在应对不同业绩变化方向时做出的生产决策是不对称的。研究还发现,企业管理者对未来需求预期越积极、供不应求导致的缺货成本越严重,在业绩下降时,企业维持生产投入的动机越大,从而导致了更大程度的非对称存货投资。

本文可能的研究贡献在于:(1)现有文献对“成本粘性”的研究包括管理费用(Anderson 等, 2003^[5]; Banker 和 Byzlov, 2014^[6])、运营成本(Kama 和 Weiss, 2013^[7])、销售成本、广告费用和研发费用(Banker et al., 2014^[8]),但鲜少有学者探究企业生产存货时投入的成本是否存在不对称性。基于此,本文将研究焦点集中于企业的存货投资行为,探讨在业绩下降时,企业是否会延迟削减生产投入从而导致存货投资的不对称性;(2)现有文献大多从横截面静态研究单一方向上存货投资的影响因素,缺少基于不同业绩变化方向,对存货投资的影响因素研究,本文分开探讨企业业绩上升或下降时,调整成本、管理者积极预期与缺货成本对企业存货投资的影响,这有助于更好的理解企业的存货生产行为;(3)本文发现了存货投资和业绩变化之间的非线性关系,对管理者在应对业绩变化时如何调整和利用承诺生产资源的管理决策提供了新的见解,对企业存货投资管理具有现实意义。

二、存货投资文献综述

以往对存货投资的研究可以分为宏观和微观两个层面。宏观层面上,国内外学者主要研究经济

周期、利率和通货膨胀对存货投资的影响。Ramey and West (1999)^[9]总结出企业存货的波动是顺周期且持久的。易纲与吴任昊(2000)^[10]对西方存货理论进行了梳理,并结合中国情况具体分析后发现:中国的存货投资从 1979-1989 年整个周期来看是顺周期的,但如果划分为几个时间区间来看,存货投资的波动呈现“顺周期-逆周期-顺周期”的趋势。许志伟等(2012)^[11]利用采购经理人指数(PMI)分别对产成品存货投资和原材料存货投资进行研究,结果发现产成品存货投资表现为逆周期性,而原材料存货投资呈现出顺周期性。

关于利率对存货投资影响的研究, Maccini et al. (2004)^[12]最早发现,当企业处于一个长期高利率的环境下,其存货投资水平逐渐降低。Benati and Thomas (2014)^[13]使用贝叶斯时变 VAR 模型,研究发现存货投资与利率水平是正相关的。戴严科与林曙(2017)^[14]探讨了利率波动对制造业存货投资的影响,发现利率波动对企业存货投资的影响具有异质性。以上文献表明,学术界对利率波动对存货投资影响为正面还是负面尚未达成一致。

国内学者较多关注通货膨胀与存货投资的关系,俞静等(2005)^[15]利用中国 1978-2002 年的年度经济数据,研究发现我国的通货膨胀率和存货投资之间呈负相关关系。长期内,通货膨胀率的变动会引起存货投资的变化;而在短期内,存货投资波动和通货膨胀波动互为因果。饶品贵等(2016)^[16]、翟光宇与王晓辉(2020)^[17]的研究则表明通货膨胀水平越高,企业存货投资水平越高。

另外,还有学者探讨货币政策(刘树海, 2018^[18]; 张鸿儒与莫琼辉, 2019^[19])、外部冲击(张鸿儒与杨泽民, 2020^[20]; 李雨浓等, 2020^[21])、经济政策不确定性(郭德兵等, 2020^[22]; 黄晓红 2020^[23])、基础设施(李涵与唐丽淼, 2015^[24]; 张彬斌与陆万军, 2018^[25])、自然环境(张勋等, 2018^[26]; 李超与李涵, 2017^[27])等对企业存货投资的影响。

相比于宏观层面,国内外学者在微观层面对存货投资影响因素的研究成果相对较少, Carpenter et al., (1998)^[28]、Guariglia (2010)^[29]、唐婧倩等(2017)

^[30]研究发现相比于其他财务指标,存货投资对企业内部现金流的敏感性更大, Jones et al. (2013)^[31]研究发现企业存货投资于资本成本为负相关关系, Robb et al. (2012)^[32]基于中国制造业企业数据,研究发现企业存货存在规模经济, 徐志平与姚明安 (2008)^[33]、Eroglu (2011)^[34]的研究发现存货和企业绩效关系呈倒 U 型, Casalin et al. (2017)^[35]分行业探究供应商、客户集中度与中国制造业企业存货投资的影响,发现供应商集中度越高,企业存货投资越大,而客户集中度越高,存货投资越小。

以上研究主要从横截面静态研究单一方向上存货投资的影响因素,缺少基于动态关系的检验,而企业的存货投资行为是动态的过程,管理者会依据不同时期的销售情况做出相应的调整。基于此,本文考察企业在业绩上升及下降时期对存货投资的增加与缩减幅度是否一致。

三、理论分析与研究假设

存货是少数几个主要由公司内部决策决定的变量之一,公司持有存货的原因有很多,如满足日常生产经营所需、应对未来市场的需求波动性、产生规模经济等等,由于市场需求存在不确定性,企业的存货投资与生产往往是一个动态调整的过程。Abel(1985)^[36]提出,当生产成本遵循生产水平的凸函数时,平均成本可以通过减少生产相对于销售的变化来降低。因此,为了使生产成本保持相对平稳,企业往往会控制生产波动程度,使其小于需求波动程度。

本文分析有三点原因促使企业做出非对称存货行为决策,第一,企业迎合市场需求变化在短期内调整生产规模会引起高昂的调整成本,如固定产能调整和员工流失 (Iny et al., 2020^[37]),因此,在业绩下降时,企业往往会维持当前生产规模以避免短期调整成本,并在销售恢复后迅速投入生产以达到降低长期生产成本的目的。第二,有研究表明,管理者对未来需求的预期会对企业短期内的资源调整和利用决策产生影响 (Anderson et al., 2003^[5]; Chen et al., 2019^[38]),对未来需求抱有积极预期的管理者会保持产能和生产水平,以避免未来扩大生

产带来的高拥挤成本 (Pindyck, 1982^[39]; Banker et al., 2014^[40])。Abel (1985)^[41]指出生产过程中的高拥挤成本不仅可能来自短期内资源的增加,还可能来自生产过程的滞后。第三,在不确定的需求环境下,管理者的存货投资决策可能会受到存货缺货风险的影响,存货缺货成本是制造企业在竞争产品市场中的潜在成本,其价值通常大于存货持有成本 (Corsten and Gruen, 2004^[42])。因此,企业会选择保留缓冲库存,以防止出现存货缺货导致供应链的中断而将订单拱手相让于竞争对手甚至失去稳定客户的情况。

基于这些考虑,管理者在业绩下降时不会轻易处置闲置资源以削减生产,而在业绩上升时会选择积极响应市场需求而加大投入生产量,由此形成企业的非对称存货投资行为,基于此,本文提出假设 1 (H1):

H1: 企业的存货投资行为是非对称的,业绩下降时存货投资的减少量小于同等业绩上升时存货投资的增加量。

四、研究设计

1、样本选择与数据来源

本文财务数据主要来自国泰安数据库,由于我国上市公司自 2007 年开始选用新会计准则,因此选取了 2007-2020 年中国制造业 A 股上市公司作为研究样本,因为样本数据计算需滞后一期,实际样本期间为 2008-2020 年。样本筛选过程如下: ①剔除数据缺失的样本; ②剔除 ST 公司; ③为防止兼并和重组的影响剔除样本区间内总资产增长率大于 1 的样本; ④剔除资产负债率大于 1 的样本; ⑤由于回归需要控制滞后一期的销售额增长率,仅保留至少存续 3 年以上的企业。最后,为避免异常值对本文研究结果的影响,本文对公司层面的连续变量进行 1%水平的 Winsorize 缩尾处理,最终得到 13825 个非平衡面板数据,本文相关实证分析使用 stata15.1 完成。

2、模型构建与变量定义

本文借鉴 Gunny (2010)^[43]的方法,利用模型 1 验证假设 1 以度量企业的非对称存货投资是否存

在:

$$\begin{aligned}\Delta INVENT_{it} = & \beta_1 \left(\frac{1}{A_{it-1}} \right) + \beta_2 SALES_{it} \\ & + \beta_3 \Delta SALES_{it-1} + \beta_4 DEC_{it-1} \\ & + \beta_5 DEC_{it-1} \times \Delta SALES_{it-1} \\ & + \beta_6 \Delta SALES_{it} + \beta_7 DEC_{it} \\ & + \beta_8 DEC_{it} \times \Delta SALES_{it} + \beta_9 SIZE_{it} \\ & + \beta_{10} Q_{it} + \beta_{11} AI_{it} + \beta_{12} EI_{it} \\ & + \beta_{13} ROA_{it} + \beta_{14} OPLEV_{it} \\ & + \sum Industry + \sum Year + \varepsilon_{it}\end{aligned}$$

其中, $\Delta INVENT_{it}$ 表示存货投资变化幅度; $SALES_{it}$ 表示企业 i 在第 t 年的销售收入总和, $\Delta SALES_{it}$ 表示销售收入的变化幅度。DEC 为企业业绩下降的虚拟变量, 如果企业营业收入低于上一年取值为 1, 否则为 0。本文构建了业绩下降 (DEC) 和销售收入变化 $\Delta SALES_{it}$ 的交互项以探究库存投资应对销售收入的变化是否取决于销售收入的变化方向。此外, 考虑到重要缺失变量会引起缺失变

量误差, 参考 Iny et al. (2020) [37] 的研究, 本文设置如下控制变量: (1) 企业规模 SIZE; (2) 托宾 Q 值 Q; (3) 企业资产强度 AI; (4) 企业员工强度 EI; (5) 企业经营资产回报率 ROA; (6) 经营杠杆 OPLEV。

本文预计 β_6 为正值, 因为当销售增加 (减少) 时, 管理者会相应的增加 (减少) 库存水平。根据假设 1, 本文预期 β_8 为负。也就是说, 当销售下降时, 存货投资减少的幅度并不等于销售收入增加的幅度。因此, β_2 的变化反映了存货投资的不对称程度, 而 $\beta_6 + \beta_8$ 衡量了存货投资在销售收入下降时减少的比率。此外, 考虑到企业存货行为对销售变化的延迟响应, 模型中还加入了滞后销售收入变化 $\Delta SALES_{it-1}$ 与其下降指标 DEC_{it-1} 的交互项 (Rumyantsev and Netessine 2007^[44])。

本文计量模型均控制行业固定效应与年份固定效应以控制不同年度宏观层面和不同行业特征对检验结果的影响。

表 1 主要变量定义

变量名称	变量简称	计算方法
存货投资变化率	$\Delta INVENT_{it}$	存货变动总额/滞后资产总额
营业收入变化率	$\Delta SALES_{it}$	营业收入/滞后资产总额
营业收入下降	DEC	企业营业收入低于上一年赋值为 1, 否则赋值为 0
高学历员工占比	Edu	研究生及以上员工数/员工总数
情感语调	OUTLOOK	(报表正面词汇数量-报表负面词汇数量)/报表词汇总量
缺货成本	SCIC	具体计算方法见注释
股权市值	SIZE	\ln (资产总额)
托宾 Q 值	Q	托宾 Q 值
资产密集度	AI	资产总额/营业收入
劳动力密集度	EI	员工总数/营业收入*100000
盈利能力	ROA	EBIT/资产总额
经营杠杆	OPLEV	边际贡献/EBIT
大股东控股比例	SHARE	大股东持股数/总股数

五、实证结果分析

1、描述性统计

表 2 报告了本文主要变量的描述性统计。存货投资变化幅度的平均值 (中位数) 为 0.015 (0.009),

销售变化幅度的平均值 (中位数) 为 0.066 (0.051), 表明随着业绩的上升, 存货投资也相应的增长, 但两者增长幅度并不一致, 初步证实了假设 1, 其他变量描述性统计如表 2 所示, 此处不再赘述。

表 2 描述性统计

variable	N	mean	SD	min	P50	max
$\Delta INVENT_{it}$	13825	0.015	0.059	-0.249	0.009	0.361
$1/A_{it-1}$	13825	0.046	0.002	0.038	0.046	0.051
$SIZE_{it}$	13825	0.740	0.481	0.020	0.639	3.330
$\Delta SALES_{it-1}$	13825	0.070	0.229	-0.851	0.055	1.351
$\Delta SALES_{it}$	13825	0.066	0.230	-0.851	0.051	1.351
DEC_{it-1}	13825	0.283	0.450	0	0	1
DEC_{it}	13825	0.296	0.457	0	0	1
$SIZE_{it}$	13825	22.53	1.072	20.63	22.38	26.23
Q_{it}	13825	2.101	1.313	0.870	1.677	8.606
AI_{it}	13825	2.066	1.441	0.386	1.733	13.55
EI_{it}	13825	1.501	1.080	0.055	1.262	7.021
ROA_{it}	13825	0.040	0.063	-0.261	0.040	0.206
$OPLEV_{it}$	13825	1.646	0.819	1.008	1.382	6.166

表 3 Pearson 相关系数

	$\Delta INVENT_{it}$	$1/A_{it-1}$	$SALES_{it}$	$\Delta SALES_{it-1}$	$\Delta SALES_{it}$	DEC_{it-1}
$1/A_{it-1}$	0.041***					
$SALES_{it}$	0.260***	-0.105***				
$\Delta SALES_{it-1}$	0.077***	-0.121***	0.344***			
$\Delta SALES_{it}$	0.446***	-0.002	0.557***	0.188***		
DEC_{it-1}	-0.075***	0.065***	-0.136***	-0.580***	-0.120***	
DEC_{it}	-0.254***	-0.010	-0.248***	-0.100***	-0.582***	0.145***
$SIZE_{it}$	0.078***	-0.891***	0.157***	0.142***	0.133***	-0.086***
Q_{it}	-0.011	0.378***	-0.049***	-0.030***	0.008	0.017**
AI_{it}	-0.038***	0.103***	-0.585***	-0.210***	-0.220***	0.155***
EI_{it}	-0.019**	0.390***	-0.311***	-0.152***	-0.157***	0.106***
ROA_{it}	0.142***	0.009	0.216***	0.161***	0.244***	-0.205***
$OPLEV_{it}$	-0.085***	-0.018***	-0.098***	-0.114***	-0.129***	0.158***

续表:

	DEC_{it}	$SIZE_{it}$	Q_{it}	AI_{it}	EI_{it}	ROA_{it}
$SIZE_{it}$	-0.086***					
Q_{it}	-0.026***	0.056***				
AI_{it}	0.166***	-0.072***	0.092***			
EI_{it}	0.109***	-0.350***	0.142***	0.340***		
ROA_{it}	-0.297***	0.102***	0.155***	-0.222***	-0.155***	
$OPLEV_{it}$	0.169***	-0.015**	-0.077***	0.071***	0.105***	-0.508***

注: ***, **, *分别表示在 1%、5%、10%的水平下显著。

2、相关性分析

表 3 报告了主要变量的 Pearson 相关系数。结果显示, 存货投资变化 $\Delta INVENT_{it}$ 与销售收入变化 $\Delta SALES_{it}$ 的 Pearson 相关系数为 0.446, 在 1%的水

平上显著为正, 存货投资变化 $\Delta INVENT_{it}$ 与业绩下降虚拟变量 DEC 的 Pearson 相关系数为-0.254, 在 1%的水平上显著, 表明业绩下降时的库存变化幅度小于业绩上升时的变化幅度, 进一步证实了假设 1。

3、回归结果

表4报告了营业收入变化对存货投资影响的回归结果。列(1)没有加入业绩下降及其与业绩变化的交互项,可以发现业绩变化的系数是0.056,在1%水平上显著为正,这表明企业营业收入每增长1%,存货投资就会增长0.056%;列(2)加入业绩下降及其与业绩变化交互项后,业绩变化系数是0.074,在1%水平上显著为正, $DEC_{it} \times \Delta SALES_{it}$ 的回归系数为-0.064,在1%水平下显著为负,这表明企业业绩每减少1%,库存投资降低0.01% (0.074%-0.064%)。

表4 非对称存货投资回归结果

	$\Delta INVENT_{it}$	
	(1)	(2)
$1/A_{it-1}$	27.712*** (1.185)	27.350*** (1.187)
$SALES_{it}$	0.003* (0.002)	-0.001 (0.002)
$\Delta SALES_{it-1}$	-0.002 (0.002)	-0.002 (0.003)
DEC_{it-1}		-0.003** (0.001)
DEC_{it-1}		-0.010* (0.005)
$\times \Delta SALES_{it-1}$		
$\Delta SALES_{it}$	0.056*** (0.004)	0.074*** (0.006)
DEC_{it}		-0.001 (0.001)
DEC_{it}		-0.064*** (0.010)
$\times \Delta SALES_{it}$		
$SIZE_{it}$	0.059*** (0.002)	0.058*** (0.002)
Q_{it}	-0.019*** (0.001)	-0.019*** (0.001)
AI_{it}	0.001***	0.001**

	(0.000)	(0.000)
EI_{it}	0.001 (0.001)	0.001** (0.001)
ROA_{it}	-0.066*** (0.013)	-0.068*** (0.013)
$OPLEV_{it}$	-0.003*** (0.000)	-0.002*** (0.000)
industry	YES	YES
year	YES	YES
N	13825	13825
Adjusted R ²	0.190	0.195

注: **、*、*分别表示在1%、5%、10%的水平下显著,括号内为稳健标准误。

以上结果表明,在业绩下降时,为了减少高昂的调整成本、拥挤成本与供不应求导致的缺货成本对企业造成的消极影响,企业不会立即削减生产投入与生产规模,而在业绩上升时加大生产以响应市场需求,从而导致业绩下降时存货投资的减少幅度小于业绩上升时存货投资的增加幅度,由此产生非对称存货投资行为。

4、稳健性检验

(1) 将样本扩展到全行业

为保证本文结果在全行业的可适性,本文将回归样本从制造业扩展到全行业。回归结果(见表5列(1))显示,业绩上升时 $\Delta SALES_{it}$ 的系数依旧显著为正,业绩下降时 $\Delta SALES_{it}$ 的系数为显著为负,表明企业的非对称存货行为存在于全行业,说明本文研究结论是稳健的。

(2) 增加控制变量

为了缓解因遗漏变量导致的内生性问题,本文在稳健性检验中加入大股东持股比例 ($SHARE_{it}$) 作为控制变量,结果如表5列(2)所示,回归结果与前文研究结论基本保持一致,验证了假设1。

表 5 稳健性检验结果

	$\Delta INVENT_{it}$		
	全行业检验	增加控制变量检验	固定效应检验
	(1)	(2)	(3)
$1/A_{it-1}$	34.102*** (1.118)	27.090*** (1.199)	27.926*** (1.121)
$SALES_{it}$	0.001 (0.002)	-0.002 (0.002)	0.007** (0.003)
$\Delta SALES_{it-1}$	-0.003 (0.003)	-0.002 (0.003)	-0.007** (0.003)
DEC_{it-1}	-0.004*** (0.001)	-0.003*** (0.001)	-0.003*** (0.001)
$DEC_{it-1} \times \Delta SALES_{it-1}$	-0.008 (0.005)	-0.014*** (0.005)	-0.009 (0.006)
$\Delta SALES_{it}$	0.055*** (0.005)	0.079*** (0.006)	0.070*** (0.004)
DEC_{it}	-0.002** (0.001)	-0.001 (0.001)	-0.002* (0.001)
$DEC_{it} \times \Delta SALES_{it}$	-0.052*** (0.009)	-0.076*** (0.010)	-0.067*** (0.009)
$SIZE_{it}$	0.073*** (0.002)	0.058*** (0.003)	0.058*** (0.002)
Q_{it}	-0.024*** (0.001)	-0.018*** (0.001)	-0.020*** (0.001)
AI_{it}	0.002*** (0.000)	0.001*** (0.001)	0.002*** (0.001)
EI_{it}	-0.000 (0.000)	0.001** (0.001)	0.005*** (0.001)
ROA_{it}	-0.099*** (0.012)	-0.072*** (0.013)	-0.050*** (0.017)
$OPLEV_{it}$	-0.003*** (0.000)	-0.003*** (0.001)	-0.001** (0.001)
$SHARE_{it}$		0.001 (0.003)	
industry	YES	YES	YES
year	YES	YES	YES
N	22192	13318	13825
Adjusted R ²	0.185	0.201	0.161

注：***、**、*分别表示在 1%、5%、10%的水平下显著，括号内为稳健标准误。

(3) 使用固定效应模型

为解决遗漏变量带来的内生性问题，本文在回归中使用固定效应面板模型，固定公司个体和时间，回归结果如表 5 列 (3)， $DEC_{it} \times \Delta SALES_{it}$ 在 1% 水平上显著，进一步验证了企业非对称存货投资的稳健性。

六、进一步分析

为进一步检验企业非对称存货投资行为的内在机理，本文在模型 (1) 的基础上提出模型 (2)，从调整成本、管理者积极预期和缺货成本三方面考

察企业应对业绩变化时存货投资不对称程度的横截面差异，其中 $PART_{it}$ 代表衡量调整成本、管理者积极预期与缺货成本的变量，根据之前的文献 (Banker et al., 2014^[45])，在估计以下模型时同时包括了业绩上升和业绩下降的交互项。

$$\Delta INVENT_{it} = \beta_1 \left(\frac{1}{A_{it-1}} \right) + \beta_2 SALES_{it}$$

$$+ \beta_3 \Delta SALES_{it-1} + \beta_4 DEC_{it-1}$$

$$+ \beta_4 DEC_{it-1} \times \Delta SALES_{it-1}$$

$$+ \beta_6 \Delta SALES_{it} + \beta_7 DEC_{it}$$

$$\begin{aligned}
& +\beta_8 DEC_{it} \times \Delta SALES_{it} + \beta_9 PART_{it} \\
& +\beta_{10} PART_{it} \times \Delta SALES_{it} \\
& +\beta_{11} PART_{it} \times DEC_{it} \times \Delta SALES_{it} \\
& +\beta_{12} SIZE_{it} + \beta_{13} Q_{it} + \beta_{14} AI_{it} \\
& +\beta_{15} EI_{it} + \beta_{16} ROA_{it} + \beta_{17} OPLEV_{it} \\
& + \sum Industry + \sum Year + \varepsilon_{it} \quad (2)
\end{aligned}$$

1、调整成本

存货投资成本包括调整生产能力的成本,如工厂车间、机器和工人,如果一家公司在业绩下降时选择调整承诺资源将机器卖出,那么之后业绩回升时,企业会花费更高昂的价格购买机器;如果其削减产量并解雇工厂员工,那么它会在终止劳动合同时支付遣散费,并在之后重新雇用员工时支付培训费用。因此,为避免这种短期内由业绩变化带来的资源调整成本,企业在业绩下降时会保持相对平稳生产,使其生产量的波动小于其需求波动(Blanchard, 1983^[46]; Anderson et al., 2003^[5])。综上所述,在业绩下降时,企业会有强烈的动机保持平滑生产以减少调整成本,由此导致了更大程度的非对称存货投资。

参照 Anderson et al. (2003)^[5]的研究,本文将资产密集度(AI_{it})作为衡量资产调整成本的变量;由于高学历员工工资较高,终止合同支付的遣散费也较高,本文使用研究生及以上员工数作为衡量员工调整成本的代理变量,该数据来源于 wind 金融终端。由于高学历员工数自 2011 年才开始披露,因此本文该变量数据期间为 2011-2020。表 6 列(1)

中 $PART_{it} \times DEC_{it} \times \Delta SALES_{it}$ 的结果在 1%水平上显著为负,列(2)中 $PART_{it} \times DEC_{it} \times \Delta SALES_{it}$ 的系数在 5%水平上显著为负,表明企业在业绩下降时,调整生产规模导致的调整成本越高昂,企业维持承诺生产资源的动机越大,从而导致存货投资的不对称程度更大。

2、管理者积极预期

根据前文分析,管理者对未来需求的积极预期是企业进行非对称存货投资的诱因之一。市场对产品需求的变化要求管理者决定是否调整生产水平,如果其预测需求在不久的将来会反弹,考虑到未来扩大产量会带来高拥挤成本,以及在需求低时保持平滑生产可以在长期范围内降低平均生产成本,管理者在业绩下降时往往会选择维持当前生产水平。因此,本文预测,存货投资的不对称程度随着管理者对未来需求预期的增加而增加。

本文选用两个指标衡量管理者对未来需求的预期,其一为 CSMAR 数据库中情感语调($OUTLOOK_{it}$),其定义为:(报表正面词汇数量-报表负面词汇数量)/报表词汇总量,情感语调数值越大,表明管理者情感倾向越偏向正面积极。其二,参考 Iny et al. (2020)^[37]的研究,如果管理者将对未来需求的预测纳入至当前存货决策中,并对近期的未来需求有一个相当准确的预测,那么预计在业绩下降后需求会反弹的管理者很可能会选择生产平滑以积累库存。因此,本文使用 $t+1$ 年实现的未来销售增长($\Delta SALES_{it+1}$)衡量管理者对未来需求的预期。

表 6 考虑缺货成本、管理者积极预期、缺货成本的检验

	$\Delta INVENT_{it}$				
	<i>PART</i>				
	<i>ADJUSTMENT</i>		<i>EXPECTION</i>		<i>STOCKOUT</i>
	AI_{it}	Edu_{it}	$OUTLOOK_{it}$	$\Delta SALES_{it+1}$	$SCIC_{it}$
	(1)	(2)	(3)	(4)	(5)
$1/A_{it-1}$	22.878*** (1.161)	24.668*** (1.408)	22.450*** (1.152)	27.349*** (0.995)	25.084*** (1.251)
$SALES_{it}$	0.010*** (0.002)	-0.001 (0.002)	0.001 (0.002)	-0.005*** (0.002)	0.002 (0.002)
$\Delta SALES_{it-1}$	-0.001 (0.003)	-0.003 (0.003)	-0.005 (0.003)	0.000 (0.003)	-0.010*** (0.004)
DEC_{it-1}	-0.003*** (0.001)	-0.003** (0.001)	-0.003** (0.001)	-0.003*** (0.001)	-0.005*** (0.001)
$DEC_{it-1} \times \Delta SALES_{it-1}$	-0.012** (0.005)	-0.001 (0.006)	-0.001 (0.007)	-0.013** (0.005)	0.003 (0.009)
$\Delta SALES_{it}$	0.001 (0.011)	0.064*** (0.009)	0.073*** (0.009)	0.072*** (0.004)	0.056*** (0.008)
DEC_{it}	0.005*** (0.001)	-0.002 (0.001)	0.001 (0.002)	-0.000 (0.001)	0.000 (0.001)
$DEC_{it} \times \Delta SALES_{it}$	0.024 (0.016)	-0.035*** (0.014)	-0.035* (0.018)	-0.064*** (0.009)	-0.025* (0.014)
<i>PART</i>	0.001** (0.000)	-0.000 (0.000)	0.054 (0.043)	0.037*** (0.003)	0.002 (0.001)
$PART_{it} \times \Delta SALES_{it}$	0.072*** (0.008)	0.003** (0.001)	0.325 (0.238)	-0.006 (0.008)	0.037*** (0.009)
$PART_{it} \times DEC_{it} \times \Delta SALES_{it}$	-0.074*** (0.010)	-0.004** (0.002)	-1.165* (0.597)	-0.039* (0.023)	-0.064** (0.032)
$SIZE_{it}$	0.049*** (0.002)	0.052*** (0.003)	0.047*** (0.002)	0.058*** (0.002)	0.052*** (0.003)
Q_{it}	-0.016*** (0.001)	-0.017*** (0.001)	-0.015*** (0.001)	-0.019*** (0.001)	-0.017*** (0.001)
AI_{it}		0.001 (0.001)	0.001 (0.001)	0.001*** (0.000)	0.001** (0.000)
EI_{it}	0.002*** (0.001)	0.002*** (0.001)	0.002** (0.001)	0.001* (0.001)	0.001** (0.001)
ROA_{it}	-0.067*** (0.013)	-0.040** (0.016)	-0.050*** (0.015)	-0.067*** (0.012)	-0.079*** (0.014)
$OPLEV_{it}$	-0.002*** (0.000)	-0.002** (0.001)	-0.002*** (0.001)	-0.002*** (0.001)	-0.002*** (0.001)
industry	YES	YES	YES	YES	YES
year	YES	YES	YES	YES	YES
N	13825	8713	6563	11396	12380
Adjusted R ²	0.209	0.192	0.205	0.216	0.209

注：***、**、*分别表示在 1%、5%、10%的水平下显著，括号内为稳健标准误。

表 6 列 (3) 列 (4) 报告了考虑管理者对未来需求预期的非对称存货投资回归结果，列 (3) 中 $OUTLOOK_{it} \times DEC_{it} \times \Delta SALES_{it}$ 的系数为负且在

10%水平下显著，表明管理者对未来需求的乐观预期与更大程度的非对称存货投资相关。列 (4) 中 $\Delta SALES_{it+1} \times DEC_{it} \times \Delta SALES_{it}$ 的系数为-0.039 且

在 10%水平下显著为负,表明企业后一年业绩实现的增长越多,其存货投资行为的不对称性越大。综上所述,以上结果表明管理者对未来需求的预期越积极,企业在业绩下降时越不会选择缩减生产,而是保持平滑生产以应对市场未来需求的上升,这种动机促成了企业更大程度的非对称存货投资。

3、缺货成本

在激烈的竞争市场环境下,有经验的企业会选择维持适量的缓冲库存以应对市场需求不确定性,若企业在业绩上升、订单增多时,仓库中存货量无法应付订单量,就会导致收入下降甚至流失主要客户的风险。因此,即使业绩下降,企业也不会立即做出反应改变生产投入,而是选择维持生产水平以积累缓冲库存应对下一次需求量的增加。基于以上分析,本文预测企业在供小于求时产生的缺货成本越大,其在业绩下降时越不会缩减存货生产,从而导致更大程度的非对称存货投资。

在日常的会计核算中,缺货成本的价值往往难以具体衡量,本文参考 Kesavan and Kushwaha(2014)^[47]的实证研究,以毛利率与加权资本成本的比值(SCIC)衡量企业存货缺货成本。其中,毛利率为营业收入与营业成本的差额,加权资本成本为权益资本成本与债务资本成本的加权平均数²⁵。其中,权益资本成本由资本资产定价模型算得, β 为无风险系数,市场无风险报酬率使用一年期国债利率衡量;债务资本成本参考陈汉文与周中胜(2014)^[48]的研究,用财务费用与借款总额的比值衡量。SCIC 数值越大,表明企业缺货成本越大。

表 6 列(5)报告了缺货成本对企业非对称存货投资影响的回归结果,其中交互项 $STOCKOUT_{it} \times DEC_{it} \times \Delta SALES_{it}$ 的系数为-0.064 并在 5%水平上显著,这表明缺货成本越高,企业避免需求上升时供不应求的动机越大,企业在业绩下降时越会维持生产以扩充缓冲库存,进一步引起企业更大程度的非对称存货投资行为。

七、结论与启示

²⁵ 资本成本 = $\frac{\text{权益资本}}{\text{总资本}} \times \text{市场无风险报酬率} + \beta(\text{平均股票报酬率} - \text{市场无风险报酬率}) + \frac{\text{债务资本}}{\text{总资本}} \times$

本文聚焦中国制造业 A 股上市公司 2007-2020 年的数据,探究企业在业绩上升及下降时期存货投资的不对称变化行为。研究结果表明,企业管理者在业绩变化时会进行非对称存货投资,在业绩下降时存货投资的减少量小于业绩上升时存货投资的增加量。进一步研究发现,管理者未来积极预期、缺货成本三者与企业的非对称存货行为存在负相关关系,即管理者对未来预期越积极、缺货成本越大,企业存货投资的不对称程度越大。

本文基于业绩上升及下降时企业做出的不同存货投资决策,深入考察企业的非对称存货投资行为,扩充了“粘性”现象存在的范畴,发现其不仅存在于成本与费用的耗费中,企业的存货投资决策也具有不对称性;同时,本文深入探讨导致非对称存货投资行为的原因,并做了异质性分析,进一步补充了微观层面存货投资影响因素的相关文献。本文的研究对管理者在应对业绩变化时如何调整和利用承诺生产资源的管理决策提供了新的见解,对企业存货投资管理具有重要的现实意义。

本文的研究结论基于中国制造业上市公司研究获得,但不同行业的存货投资行为差异较大,且企业存货投资种类也存在差异,包括原材料、在产品与产成品,未来条件成熟时,可以展开具体考察不同行业不同种类的存货投资非对称性的差异。

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媒体视角下异质性煤炭企业漂绿治理的演化博弈研究

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摘要：基于资源基础理论，聚焦异质性煤炭企业漂绿行为的治理系统，将煤炭市场划分为优势和劣势企业，并构建了企业与媒体间的演化博弈模型，分析不同决策主体之间复杂行为的相互作用机制，同时选取煤炭企业漂绿案例，使用 MATLAB 对媒体受贿程度、漂绿挤占收益、媒体虚假报道风险、政府规制效果四类关键系数进行不同情境下的系统仿真模拟。研究发现：煤炭企业异质性在企业和媒体在治理系统中的策略选择具有不可忽视的影响，同时政府规制中惩罚力度与甄别能力的同步提升不仅可以引导企业和媒体选择真绿和真实报道，还可以有效治理其背后的合谋漂绿。本研究旨在立足煤炭企业异质性，厘清企业与媒体合谋构筑的利益链条，为多方治理企业漂绿行为提供决策参考。

关键词：煤炭企业；漂绿治理；虚假报道；政府规制；演化博弈

Evolutionary Game Research on Greenwashing Governance of Heterogeneous Coal Enterprises from the Perspective of Media

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Abstract : Based on the resource-based theory, this study focuses on the governance system of the greenwashing behavior of heterogeneous coal enterprises, and divides the coal market into advantaged and disadvantaged enterprises. This paper constructs an evolutionary game model between enterprises and media, and analyzes the interaction mechanism of complex behaviors between different decision-making subjects. At the same time, the greenwashing case of coal enterprises is selected, and MATLAB is used to simulate the four key factors of media bribery, greenwashing income, media false reporting risk, and government regulation effect under different scenarios. The study found that the heterogeneity of coal enterprises has a non-negligible impact on the strategic choices of enterprises and media in the governance system. At the same time, the simultaneous improvement of punishment and screening ability in government regulation can not only guide enterprises and media to choose true green and true reports, but also It can also effectively govern the collusion behind it. Based on the heterogeneity of coal enterprises, this study aims to clarify the interest chain conspired by enterprises and the media to provide decision-making reference for multi-party governance of enterprise greenwashing.

Key words: coal enterprises; greenwashing governance; false reports; government regulation; evolutionary game

关联并购、资产评估机构选择及其经济后果

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摘要：资产评估值通常作为并购重组交易中交易定价的参考依据，而评估值很大程度上受到资产评估机构选择差异的影响。本文以 2011-2019 年聘请资产评估机构的上市公司并购事件为样本，探究上市公司关联并购中的资产评估机构选择行为。研究发现：关联并购更倾向于聘请低声誉的资产评估机构，且关联并购中聘请的资产评估机构声誉越低，其异常评估增值率越高。进一步研究发现：股权集中度越低，关联并购中越倾向于选择低声誉的评估机构；并且关联并购中聘请的评估机构声誉越低，企业并购后两年和后三年的价值越低。

关键词：关联并购；资产评估机构；异常评估增值率；经济后果

Related merger and acquisition, asset appraisal institution selection and its economic consequences

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Abstract: In Mergers and Acquisitions transactions, the asset appraised value provides a value reference for transaction pricing, and the appraised value is largely affected by the difference in the selection of asset evaluation institutions. This paper takes the Mergers and Acquisitions events of listed companies that hired asset evaluation institutions from 2011 to 2019 as samples to explore the selection behavior of asset evaluation institutions in related acquisitions. The study finds that related acquisition is more inclined to hire low-reputation asset evaluation institutions, and the lower the reputation of the asset evaluation institutions hired in related acquisition is, the higher the value-added rate of abnormal evaluation is. Further research finds that lower ownership concentration lead to the result in choosing evaluation agency with low reputation in related acquisitions; and the lower the reputation of the evaluation institution hired in the affiliated merger and acquisition, the lower the value of the two years after the merger and acquisition.

Key Words: Related acquisitions; Asset evaluation institution; Abnormal evaluation value-added rate; Economic consequences

资本市场开放与企业 ESG 表现研究 ——基于“深港通”的经验证据

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摘要: 文章基于“深港通”这一外生政策,运用双重差分模型,以 2012~2020 年深市 A 股上市公司为样本,创建了 ESG 指标体系,运用熵值法构造公司的 ESG 指数,研究资本市场开放对企业 ESG 表现的影响。研究发现:“深港通”实施能够提高“深股通”标的股票 ESG 表现,该结论在使用 PSM 倾向评分匹配等方法后仍然稳健。机制分析发现,“深港通”开启后,分析师跟踪人数的增加是资本市场开放影响标的公司 ESG 表现的重要渠道。进一步分析发现,资本市场开放对企业 ESG 表现的促进作用主要存在于非国有企业、市场化程度较高的公司及非重污染行业的企业中。文章研究表明“深港通”实施对于促进我国企业可持续发展具有重要作用,也为后续资本市场进一步开放政策提供了证据支持。

关键词: 资本市场开放,熵值法,ESG 表现

Capital Market Liberalization and ESG Performance: Evidence from Shenzhen-Hong Kong Stock Connect

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Abstract: Based on the exogenous policy of “Shenzhen-Hong Kong Stock Connect”, this paper studies the impact of stock market liberalization on ESG performance. We estimate the difference-in-difference model, establish an ESG index system and construct the company's ESG index by using the entropy method with the data of the A-share listed companies in Shenzhen Stock Exchange over the period of 2012—2019. The results show that compared with the non-Shenzhen-Connect stock, the implementation of the Shenzhen-Hong Kong Stock Connect significantly improves the ESG performance of Shenzhen-Connect firms listed in Shenzhen Stock Exchange. These findings are robust after using the PSM method to revise the sample selection bias. Mechanism analysis shows that the increase of analysts' tracking number is an important channel for the opening of the stock market to affect the ESG performance of target companies after the policy of “Shenzhen-Hong Kong Stock Connect”. Further analysis shows that the promotion effect of capital market opening on ESG performance mainly exists in non-state-owned enterprises, companies with high degree of marketization and companies in non-heavy-polluted industries. This study shows that the implementation of “Shenzhen-Hong Kong Stock Connect” plays an important role in promoting the sustainable development of Chinese enterprises, and also provides some support for the follow-up capital market opening policy.

Keywords: stock market liberalization, entropy method, ESG performance

其他权益工具投资与其他债权投资的会税处理问题探讨

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摘要：财政部最新出台的金融工具准则，自 2018 年起开始施行。然而在实践中，上市公司执行新金融工具准则进行会计处理时出现了一些困惑和混乱。其中就包括其他权益工具投资出售时增值税应计入投资收益还是其他综合收益科目，以及其他债权投资计提信用减值损失时是否需要进行所得税递延处理。本文将对上述两个争议进行讨论，最后呼吁管理当局尽快对 22 号企业会计准则进行修改完善，出台相关指引文件。

关键词：新金融工具准则；金融资产会税处理

Discussion on the tax treatment of investments in other equity instruments and other debt investments

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Abstract: The Ministry of Finance's latest financial instruments standards have been in force since 2018. However, in practice, there has been some confusion and puzzle in the accounting treatment of listed companies in implementing the new financial instruments standard. This includes whether value added tax should be included in investment income or other comprehensive income accounts when investments in other equity instruments are sold, and whether income tax deferral treatment is required when other debt investments make credit impairment losses. This article will discuss the above two disputes, and finally call on the management authorities to revise and improve The No. 22 Corporate Accounting Standard as soon as possible and issue relevant guidance documents.

Key Words: New financial instruments standard; financial assets' accounting treatment and tax treatment

业绩期望落差与企业“漂绿”行为

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摘要：针对企业“漂绿”问题屡禁不止的现状，分析了业绩期望落差对企业“漂绿”行为的影响机理，并以 2010–2019 年 A 股重污染行业上市公司为样本进行实证检验。研究发现，业绩期望落差会诱发企业“漂绿”行为，且主要表现为对环境实践的选择性披露；业绩期望落差持续的时间越长，其对企业“漂绿”行为的影响越显著。路径检验表明，业绩期望落差会恶化企业融资约束和加剧管理层短视，进而导致“漂绿”行为。此外，不同类型规制工具对“漂绿”的治理效应存在差异，命令控制型环境规制及本地媒体监督能够抑制业绩期望落差驱动的企业“漂绿”行为，但市场激励型、公众参与型环境规制以及异地媒体监督的治理效应不明显。

关键词：漂绿；业绩期望落差；环境规制；媒体监督

Performance Expectation Gap and Enterprise's "Greenwashing" Behavior

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Abstract: Aiming at the status quo of repeated "greenwashing" behavior in enterprises, this paper empirically tests the impact of performance expectation gap on enterprises' "greenwashing" behavior, using Chinese's A-share listed companies in heavy pollution industries from 2010 to 2019 as samples. The results show that performance expectation gap could induce enterprise "greenwashing" behavior, which mainly manifested as the selective disclosure of environmental activities. Moreover, with the extension of performance expectation gap duration, the impact of performance expectation gap on enterprise's "greenwashing" behavior would be more significant. Further mechanism test results show that the performance expectation gap could worsen enterprise's financing constraints and exacerbate managers' short-sightedness, thereby affecting "greenwashing" behavior. In addition, different types of regulatory tools have different governance effects on "greenwashing". Specifically, command-and-control environmental regulations and local media supervision can curb enterprises' "greenwashing" behavior driven by performance expectation gap, while the governance effects of market incentives and public participation environmental regulations, and off-site media supervision are not significant.

Keywords: Greenwashing; Performance Expectation Gap; Environmental Regulation; Media Supervision

董事海外背景与资产评估机构选择——来自中国上市公司并购事件的经验证据

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摘要：在并购重组交易中董事会对资产评估机构的聘任选择起着重要作用，基于 2010-2020 年我国资本市场发生的并购事件，考察上市公司董事海外背景特征对资产评估机构选择的影响。结果发现，上市公司董事具有海外背景时倾向于选择高声誉的资产评估机构；且董事长具有海外背景时会更倾向于选择高声誉资产评估机构；进一步研究发现，相较于海外工作经历或大陆法系国家经历背景，上市公司董事具有海外学习经历或英美法系国家经历背景时更倾向于选择高声誉资产评估机构。

关键词：董事海外背景；董事长海外背景；董事海外学习经历；董事海外英美法系经历；资产评估机构声誉

Director's Foreign Experience and Asset Evaluation Institutions Selection ——Empirical Evidence from M&A Events of Chinese Listed Companies

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Abstract: The board of directors plays an important role in the selection of asset evaluation institutions in mergers and acquisitions. This article takes the listed companies that undergo mergers and acquisitions in my country's capital market from 2010 to 2020 as a sample, to examine the influence of the foreign experience of the listed companies' directors on the selection of asset evaluation institutions. The results found that directors of listed companies with foreign experience tend to choose high-reputation asset evaluation institutions; and the chairman of the board is more inclined to choose high-reputation asset evaluation institutions when he has a foreign experience. Further research found that, compared with foreign work experience and civil law country background, directors with foreign study experience and common law foreign experience are more inclined to choose high-reputation asset evaluation institutions.

Key Words: director's foreign experience; chairman's foreign experience; director's foreign study experience; director's civil law country experience; reputation of asset evaluation institutions;

三方演化博弈视角下增值税税率下调的影响研究

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摘要：增值税在保障财政收入和国家经济秩序稳定方面发挥着举足轻重的作用。在增值税税率下调的情况下，为探究增值税减税红利流向问题，构建了上游企业、下游企业与市场监督管理局的三方演化博弈模型。增值税税率下调后，上游企业可能维持原价或相应下调价格，同时下游企业可能接受原价或者接受下调后的价格。通过模型求解和数值仿真发现：上游企业选择维持原价的额外收益和受到的行政处罚大小都不会影响其最终向选择下调价格策略方向演化，但额外收益与演化达到稳定所需的时间正相关，处罚力度越大演化达到稳定所需的时间越短；下游企业选择接受原价的额外成本不会对其最终向接受下调价格方向演化产生影响，上下游企业对价格产生意见分歧时的额外谈判成本会对下游企业的策略选择产生影响；无论市场监督管理局选择高质量监督时查处上游企业变相抬价的额外收益和未能有效发现并查处的信用损失的大小如何，其最终都会向选择高质量监督策略演化，且额外收益和信用损失均与达到演化稳定所需时间成反比。

关键词：三方演化博弈；增值税改革；税率下调；演化博弈均衡

Research on the Impact of the Reduction of Value-added Tax Rate Based on the Perspective of Tripartite Evolutionary Game

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Abstract: Value-added tax plays a pivotal role in ensuring fiscal revenue and the stability of the country's economic order. In the case of the downward adjustment of the value-added tax rate, in order to explore the flow of value-added tax reduction dividends, a tripartite evolutionary game model of upstream enterprises, downstream enterprises and the market supervision and management bureau was constructed. After the value-added tax rate is reduced, upstream companies may maintain the original price or lower the price accordingly, while downstream companies may accept the original price or accept the reduced price. Through model solution and numerical simulation, it is found that the additional benefits of upstream companies choosing to maintain the original price and the size of administrative penalties will not affect their final evolution toward the choice of price reduction strategy, but the additional benefits are positively correlated with the time required for the evolution to stabilize. The greater the penalties, the shorter the time required for evolution to stabilize; the additional cost of downstream companies choosing to accept the original price will not have an impact on their ultimate evolution towards accepting lower prices, and the additional negotiation costs when upstream and downstream companies disagree on prices will It has an impact on the strategic choices of downstream companies; regardless of the amount of extra income gained by the upstream companies when they choose high-quality supervision and the amount of credit losses they fail to find and investigate effectively, they will eventually choose high-quality supervision. The strategy evolves, and the additional gains and credit losses are inversely proportional to the time required to achieve evolutionary stability.

Key Words: Market Orientation; Accounting Function; Accounting Curriculum System

并购业绩承诺的同行效应研究 ——来自中国上市公司定向增发并购标的企业的经验证据

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摘要：近年来，高估值高业绩承诺（“双高”）并购呈现爆发式增长，“双高”背后是否存在同行之间竞相模仿的非理性因素。文章采用 2013-2018 年间中小板和创业板发生的签订业绩补偿协议的定向增发并购事件为样本，对并购业绩承诺的同行效应及其影响因素和行业地位进行研究，结果发现，标的企业业绩承诺存在竞相模仿的同行效应；且同行效应受到行业环境不确定性的影响，当标的企业所处行业环境不确定性越强时，会增强同行的学习行为，且这种同行效应的主要模仿对象是行业领先者。进一步研究发现，监管政策的趋严减弱了并购业绩承诺的同行学习行为。

关键词：业绩承诺，标的企业，同行效应，环境不确定性；行业地位

Research on the peer effect of M & A performance compensation commitment ——Empirical evidence from private placement and M & A target enterprises of Chinese Listed Companies

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Abstract: In recent years, the mergers and acquisition with high value and high performance commitment ("double high") has shown explosive growth, and whether are there irrational factors of imitation among peers behind the "double high". This paper studies the peer effect of performance commitment and its influencing factors and industry status based on the sample of private placement M & A with performance compensation agreement between SME board and gem from 2013 to 2018. It turns out that the performance commitment of the target enterprise exists the peer effect of competitive imitation, and the peer effect is affected by the uncertainty of the industry environment. The stronger the uncertainty of the industry environment, the stronger the peer learning behavior, and the main imitators of this peer effect are the industry leaders. Further research shows that the stricter regulatory policy weakens the peer learning behavior of M & A performance commitment.

Key Words: performance commitment, target company, peer effect, environmental uncertainty; industry status

大股东异质性、退出威胁与企业费用粘性

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摘要：本文以沪深 A 股上市企业 2010-2020 年的样本，实证检验了外部大股东退出威胁对企业费用粘性的影响，研究发现（1）外部大股东的退出威胁能够有效抑制企业的费用粘性；（2）当企业存在机构外部大股东和不存在国有外部大股东时，退出威胁对费用粘性的抑制作用更加显著，说明外部大股东对企业费用粘性的影响具有异质性；（3）在非国有企业中外部大股东的退出威胁表现出更强的治理作用；此外当大股东减持受到管制时，大股东的退出威胁对费用粘性的抑制作用减弱。

关键词：大股东；退出威胁；费用粘性；异质性；代理问题

The Heterogeneity of Large Shareholders, Exit Threats and Corporate Expense Stickiness

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Abstract: In this paper, the sample of listed companies in Shanghai and Shenzhen A-shares in 2010-2020 is used to empirically test the influence of the exit threat of major external shareholders on the cost stickiness of enterprises. The results show that (1) the exit threat of major external shareholders can effectively restrain the cost stickiness of enterprises; (2) When there are outside shareholders and there are no state-owned outside shareholders in the enterprise, the threat of exit has a more significant effect on the expense stickiness, which shows that the influence of outside shareholders on the enterprise expense stickiness is heterogeneous; (3) In non-state-owned enterprises, the exit threat of major external shareholders shows stronger governance effect; In addition, when the major shareholder's reduction is controlled, the restraining effect of the major shareholder's withdrawal threat on expense stickiness is weakened.

Key words: Large shareholder; Exit threat; Expense Stickiness; heterogeneousness; agency problem

责任文化对企业慈善捐赠的影响——来自中国市值 500 强 A 股公司的证据

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摘要：慈善捐赠作为第三次分配的主要实现形式，对调节社会贫富差距、实现共同富裕有重要意义。本文以 2016-2020 年国内 A 股市值 500 强公司为样本，采用文本分析、Tobit 回归、分位数回归等方法验证了企业责任文化对慈善捐赠的影响，并进一步考虑了在各种不同股权特征下这种关系的差异性。研究结果表明，企业对责任文化的重视程度与慈善捐赠水平显著正相关，这种关系受股权结构的调节影响，即在非国有企业中正相关关系更显著，股权集中度提高和管理者持股比例提高都进一步加强了两者的正相关关系。本文尝试将企业责任文化引入慈善捐赠研究框架，拓宽了慈善捐赠影响因素的研究视角，并为企业文化影响企业行为提供了新的证据支撑。

关键词：第三次分配 慈善捐赠 责任文化 股权结构

The influence of responsibility culture on corporate charitable donation ——Evidence from China's top 500 A-share companies

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Abstract: As the main form of the third distribution, charitable donation is of great significance to adjust the gap between the rich and the poor and achieve common prosperity. Taking the domestic top 500 companies with A-share market value from 2016 to 2020 as a sample, this paper uses text analysis, tobit regression, quantile regression and other methods to verify the impact of corporate responsibility culture on charitable donation, and further considers the differences of this relationship under various equity characteristics. The results show that the importance of corporate responsibility culture is significantly positively correlated with the level of charitable donation. This relationship is affected by the regulation of ownership structure, that is, the positive correlation is more significant in non-state-owned enterprises. The improvement of ownership concentration and the proportion of managers' shareholding further strengthen the positive correlation between them. This paper attempts to introduce corporate responsibility culture into the research framework of charitable donation, broaden the research perspective of the influencing factors of charitable donation, and provide new evidence support for the influence of corporate culture on corporate behavior.

Key words: the third distribution charitable donation responsibility culture ownership structure

区块链技术可以提高企业风险承担吗？——基于信息不对称的中介效应检验

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摘要：基于 2013-2020 年间 A 股上市企业的样本，本文从信息不对称这一视角出发，分析企业应用区块链技术后是否会提高企业风险承担。研究发现：区块链技术的应用有助于提高企业风险承担水平；进一步研究表明，区块链技术通过信息不对称这一中介变量影响企业风险承担水平，弥补了区块链技术对企业风险承担影响因素的空白。在非国企样本和中小企业样本中，区块链技术的应用与企业风险承担水平的关系表现出更强的效果。本文认为企业应积极开展产业数字化转型，使区块链技术发挥正效用，为企业风险承担水平注入动能。

关键词：区块链技术；企业风险承担；信息不对称；中介效应

Can blockchain technology improve corporate risk-taking? -- Mediating effect test based on information asymmetry

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Abstract: Based on the samples of A-share listed companies from 2013 to 2020, this paper analyzes whether the application of blockchain technology will improve enterprise risk taking from the perspective of information asymmetry. Research findings: the application of blockchain technology helps to improve the level of enterprise risk taking; Further research shows that blockchain technology influences the level of enterprise risk taking through information asymmetry, which is a mediating variable, and makes up for the gap of influencing factors of blockchain technology on enterprise risk taking. In the samples of non-state-owned enterprises and smes, the relationship between the application of blockchain technology and the level of enterprise risk taking shows a stronger effect. This paper argues that enterprises should actively carry out industrial digital transformation, make blockchain technology play a positive role, and inject momentum into the level of enterprise risk taking.

Key words: Blockchain technology; Enterprise risk taking; Information asymmetry; Mediating effect

产业政策、企业家精神与创新产出——基于创新迎合型企业视角

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摘要：为了提高企业自主创新能力，克服市场失灵，我国政府出台了高企资质认定政策，但是政策的实施效果仍存在争议。本文以《高新技术企业认定管理办法》为研究对象，以2012—2019年A股高新技术企业为样本，采用多时点DID方法研究产业政策的消极影响，同时使用熵权法构建企业家精神指标体系，探究企业家精神对产业政策消极影响的弱化作用。研究表明：产业政策存在消极影响，表现为诱发企业出现创新迎合行为，进而减少企业创新成果产出；企业家精神能够弱化产业政策的消极影响，促使创新迎合型企业充分利用政策资源增加创新产出。

关键词：产业政策，企业家精神，创新迎合行为，创新产出

Industrial Policy, Entrepreneurship and Innovation Output: A Perspective of Innovation Catering Firms

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Abstract: In order to improve enterprises' independent innovation ability and overcome market failure, China's government has introduced the policy of high technology enterprise qualification recognition, but the implementation effect of the policy is still controversial. This paper takes the Management Measures for High and New Technology Enterprise Recognition as the research object, takes A-share high-tech enterprises from 2012-2019 as the sample, and adopts the multi-temporal DID method to study the negative impact of industrial policy, and also adopts the entropy power method to construct the entrepreneurship index system to explore the weakening effect of entrepreneurship on the negative impact of industrial policy. The research results show that: industrial policy has a negative impact, which is manifested in inducing innovation catering behavior of enterprises and thus reducing their innovation output; entrepreneurship can weaken the negative impact of industrial policy and promote innovation catering enterprises to make full use of policy resources to increase their innovation output.

Key Words: industrial policy, entrepreneurship, innovation catering behavior, innovation output

CEO 任期、CEO 受教育水平与企业绿色创新

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摘要：作为企业的实际经营者，CEO 可以显著影响企业行为。因此，在绿色创新背景下，探究 CEO 异质性对于企业绿色创新的影响具有显著意义。本文以 2010–2019 年中国上市公司为样本，实证检验了 CEO 任期对于企业绿色创新的影响以及 CEO 受教育水平在其中的调节作用。研究结果表明：（1）CEO 任期和企业绿色创新呈显著正相关关系；（2）CEO 受教育水平对 CEO 任期和企业绿色创新之间的关系具有正向调节作用，会加强 CEO 任期与绿色创新之间的正相关关系。进一步研究发现，目前上市公司的绿色创新偏向于绿色发明专利创新，对于不同年龄段的 CEO，其任期与企业绿色创新的关系呈显著正相关，但是其任期与实质性创新的关系存在差异。本文补充了绿色创新方向的理论研究，对于企业的长期发展以及实现“碳达峰”、“碳中和”目标具有实际意义。

关键词：CEO 任期；CEO 受教育水平；绿色创新

CEO Tenure, CEO Education Level and Executive Green Innovation

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Abstract: As the actual operator of the business, the CEO can significantly influence the behavior of the enterprise. Therefore, in the context of green innovation, it is significant to explore the impact of CEO heterogeneity on green innovation. Based on a sample of Chinese listed companies from 2010 to 2019, this paper empirically examines the impact of CEO tenure on green innovation and the moderating effect of CEO education level. The results show that : (1) there is a significant positive correlation between CEO tenure and green innovation; (2) CEO education level has a positive moderating effect on the relationship between CEO tenure and green innovation, and strengthens the positive correlation between CEO tenure and green innovation. Further research shows that green innovation of listed companies tends to green invention patent innovation. For CEOs of different age groups, the relationship between their tenure and green innovation is significantly positive, but the relationship between their tenure and substantive innovation is different. The research supplements the theoretical research of green innovation, and has practical significance for the long-term development of enterprises and the realization of "carbon peak" and "carbon neutral" goals.

Key words: CEO tenure, CEO education level, green innovation

企业绿色治理水平对股权融资成本的影响 ——基于媒体关注度的调节作用

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摘要：本文主要研究企业绿色治理水平对其股权融资成本的影响，同时加入媒体关注度作为调节变量。本篇文章研究发现：企业的绿色治理水平的高低会影响企业的股权融资成本，二者呈负相关关系。在媒体关注度较高的企业，两个变量之间的关系更加显著。进一步研究发现国有企业的绿色治理水平更高，但在非国有企业中，绿色治理水平对股权融资成本的影响更加显著。该研究结论有助于企业更好地了解企业绿色治理水平引起的经济后果，帮助企业更准确地看待绿色发展。

关键词：绿色治理，股权融资成本，媒体关注度，产权性质

The influence of enterprise green governance level on equity financing cost

——Based on the regulation of media attention

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Abstract: This paper mainly studies the influence of enterprises' green governance level on their equity financing costs, and adds media attention as a moderating variable. This paper finds that the level of green governance of enterprises will affect the cost of equity financing, and the two are negatively correlated. In enterprises with high media attention, the relationship between the two variables is more significant. Further research shows that state-owned enterprises have a higher level of green governance, but in non-state-owned enterprises, green governance has a more significant impact on the cost of equity financing. The conclusion of this study is helpful for enterprises to better understand the economic consequences caused by the level of corporate green governance and help enterprises to view green development more accurately.

Key Words: Green governance, equity financing costs, media attention, property rights

基于函数型 logistic 模型的上市公司财务困境研究

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摘要：探究影响第 t 年上市公司财务困境的影响因素并分析影响因素的动态差异性。基于 2016–2018 年上市公司财务指标数据以及 2020 年企业财务情况，利用传统 logistic 模型分析单时间维度和双时间维度的财务指标影响因素；主要运用函数型 logistic 模型刻画主要影响因素的时间动态变化特征。结果表明净利润增长率对企业财务困境判别非常显著，在判定 ST 的前三年有负向作用；资产报酬率也保持负向作用，但这种作用在判别 ST 的前两年逐渐减弱；营业利润率和净资产收益率、资产负债率和存货周转率在三年中前期具有正向作用，后期转为负向作用，说明前期企业偿债能力对企业困境判别占据主导，后期更加注重企业盈利能力；同时发现每年开始和末期流动资产周转率具有负向作用，此时企业营运能力占据主导。本文构建面向上市公司的财务困境判别体系，评估企业发展出现经营困境的可能性，为管理者和监管机构提出建议。

关键词：企业困境 财务指标 函数型 logistic 模型 动态影响

Research on financial distress of listed companies based on functional logistic model

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Abstract: This paper explores the influencing factors that affect the financial distress of listed companies in the t year and analyzes the dynamic differences of the influencing factors. Based on the financial indicators data of listed companies from 2016 to 2018 and the financial situation of enterprises in 2020, the traditional logistic model is used to analyze the influencing factors of financial indicators in the single time dimension and dual time dimension; the functional logistic model is used to describe the time dynamic characteristics of the main influencing factors. The results show that the growth rate of net profit is very significant for the judgment of financial distress of enterprises, and has a negative effect in the first three years of the year; the return on assets also maintains a negative effect, but this effect gradually weakens in the first two years of judging ST; operating profit ratio, return on equity, asset-liability ratio and inventory turnover ratio have a positive effect in the early stage of the three-year period, and turn to a negative effect in the later stage, indicating that the solvency of the company in the early stage dominates the judgment of the company's distress, and the later stage pays more attention to the profitability of the company. At the same time, it is found that the turnover rate of current assets at the beginning and end of each year has a negative effect, and the operating capacity of the enterprise dominates at this time. This paper constructs a financial distress discrimination system for listed companies, evaluates the possibility of business distress in the development of enterprises, and makes recommendations for managers and regulators.

Key words: corporate distress financial indicators functional logistic model dynamic impact

How and when participative leadership influence employee learning

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Abstract: Based on self-determination theory and contingency theory, we construct and test a cross-level model depicting the relationships among participative leadership, work meaningfulness, organizational identification and employee explorative and exploitative learning. Using data collected from 318 participants in 89 teams, we conducted a multilevel analysis, which demonstrated that participative leadership promotes work meaningfulness which, in turn, enhances employee explorative learning and exploitative learning. In addition, our study suggests that the organizational identification moderated the relationship between participative leadership and work meaningfulness. Finally, organizational identification moderates the mediating mechanism of participative leadership → work meaningfulness → employee explorative learning and exploitative learning.

Keywords: Participative leadership, Work meaningfulness, Explorative learning, Exploitative learning, Organizational identification.

1 Introduction

In today's competitive global business environment, employee learning plays a critical role in facilitating organizational development, as well as employees' personal success ^[1]. On the one hand, employee learning may enable companies to acquire new knowledge, assets, and new competitive advantages to compete with their business rivals. On the other hand, employee learning may enable employees to obtain competence in resolving work-related problems, and to develop positive attitudes toward their work ^[2]. Accordingly, researchers on organizational behavior are increasingly paying attention to employee learning ^[3]. Especially, the antecedents of employees learning in work settings, as well as the contextual factors impact this facilitation, have attracted substantial research interest.

Employee learning involves various learning activities. Prior studies have identified a number of activities, such as reflective learning ^[4], failure learning ^[5], formal and informal learning ^[6]. Nevertheless, the aforementioned studies do not differentiate between employee learning of new and existing knowledge in organizations. In the current study, we intend to address this gap. In the context of

organizational learning, ^[7] proposed a well-accepted taxonomy, which consists of two type of learning activities, namely, exploitative learning and explorative learning. Explorative learning concentrates on acquiring and creating new knowledge, whereas exploitative learning focusing on the utilization and transformation of existing knowledge ^[7]. For this study, we extend this taxonomy from the organization to the individual level, and distinguish between the two type of employee learning.

Furthermore, prior studies on the antecedents of employee learning mainly focus on employees' personal characteristics, for example, proactive personality ^[4] or their job characteristics, for example, high-involvement human resources practices ^[1]. These studies, however, often pay little attention to external forces that influence employee behaviors. Leadership as a key environmental factor has an important impact on employees' learning behavior. However, the studies on this effect are rare, and researchers seldom delineated the specific behaviors and mechanisms for such learning activities ^[8].

In the current study, we focus on the effect of participative leadership. Such leadership has received substantial attention from academia and industry, As

teamwork becomes increasingly prevalent in organizations in the past several decades ^[9]. Participative leadership focuses on sharing information and resources with employees and encouraging employees to express their opinions on decisions. It aims to increase employee participation by offering them greater discretion, personal attention, more autonomy, and influence on organizational decisions. Additionally, participative leaders often consult employees before making a decision, thereby enabling them to participate in problem solving ^[10]. Prior studies show that such leadership could enhance employee exploratory innovation ^[11], job satisfaction ^[12], knowledge sharing ^[9], and proactive behavior. However, few researchers have examined the mechanism through which participative leadership affect employees' learning behavior. Therefore, one purpose of the current study is to investigate the relationship between participative leadership and employees' explorative and exploitative learning.

Specifically, we draw on self-determination theory to develop our theoretical framework. This theory suggests that the attitude and behavior of employees are derived from their intrinsic motivation, which are affected by their external environment ^[13]. In other words, there exist a linkage of external environment → intrinsic motivation → employee behavior. For this study, we focus on participative leadership as a critical element of employees' external environment, and employee learning as the behavior that we study. Additionally, we study employees' perception of work meaningfulness, which reflects their intrinsic motivation, as a mediator between participative leadership and employee learning. The perception of work meaningfulness refers to the perceived or felt significance and value that employees relate to their work situation ^[14, 15]. Soane et al (2013) argue that it is a critical stepping stone for

employees to engage in proactive behaviors, including learning ^[16]. Several previous studies also show that work meaning is an important mediator between leadership and results ^[17, 18]. Accordingly, we maintain that, when employees view their work as meaningful (i.e., they are intrinsically motivated), they are satisfied with their working situation, and thus tend to engage in proactive behaviors, such as explorative and exploitative learning. Therefore, we also intend to investigate the mediating effects of work meaningfulness in the relationship between participative leadership and employees' explorative and exploitative learning behavior.

Finally, we also intend to examine the moderating effect of organizational identification on the aforementioned relationship. The contingency theory of leadership suggests that leadership is socially constructed and one could only fully examine its effects in specific contexts ^[19]. Recall that we propose a linkage of participative leadership → work meaningfulness → employee learning. The mediator of this model, work meaningfulness, is related to subjective experience ^[20]. Arguably, the effect of participative leadership on employees work meaningfulness is greatly determined by to what extent employees perceive and recognize their organizations ^[12], i.e., organizational identification. Organizational identification refers to employees' perception of oneness with or belongingness to their organizations ^[21]. Prior studies have reported that organizational identification greatly affect the effectiveness of leadership ^[22, 23]. For example, Zhu et al. (2020) proposed that organizational identification concerns moderated the effects of servant leadership on knowledge sharing ^[22]. Specifically, employees with a strong organizational identification may view their organization favorably. Thus, they tend to show more positive disposition to

their organizations than those with weak organizational identification ^[24]. In this article, we argue that, with a strong organizational identification, employees are able to act quickly and accurately, will participative leader offer them opportunities and information resources. As a result, they experience more responsibility and meaningfulness. In other words, organizational identification moderates the effects of participative leadership on work meaningfulness, which subsequently affect employee learning. Therefore, we intend to investigate such moderating effects of organizational identification in the current study.

Our study contributes to literature in several ways. First, as one of the first studies to extend the concept of exploitative and explorative learning from organizational to individual level, we have enriched the understanding of employee learning from the new and existing knowledge aspects. Second, by investigating the effects of participative leadership on the two type of employee learning, we have enriched the research on participative leadership, and shed more light on the antecedents of exploitative and explorative learning. Third, we show that work meaningfulness mediates the positive relationship between participative leadership and exploitative and explorative learning. This provides a more nuanced understanding of the mechanism through which participative leadership affect employees' behaviors. Finally, we propose and verify that organizational identification moderates the linkage between participative leadership and work meaningfulness. This enriches our understanding of the context that shapes the effectiveness of participative leadership.

2 Theory and hypotheses

2.1 Self-determination theory

Self-determination theory ^[25] maintains that all individuals have three basic and the universal needs,

namely, autonomy (i.e., a person's sense of choice in deciding his/her own actions), competence (i.e., a person's confidence in what he/she does), and relatedness (i.e., a person's feeling of belongingness and social connection with others) ^[26]. Arguably, these three psychological needs could be greatly determined by one's social environment. A favorable social environment can enhance a person's internal motivation and promote the internalization of external motivation by satisfying the three psychological needs of individuals in autonomy, competence and relatedness needs, thereby facilitating proper work behavior and enhancing performance ^[27]. Prior studies show that leaders may serve as an important environment factor satisfying the basic needs of employees, and consequently affect employee performance and behavior. For example, transformational leadership can indirectly influence volunteer satisfaction and contribution by facilitating work meaning ^[28]. Empowering leadership enhances employees' harmonious passion, which leads to employee voice behavior ^[29]. Ethical leadership facilitates employees' job performance relationship by enhancing their motivation ^[30]. Spiritual leadership provide employees with a sense of psychological safety and thus facilitate proactive and learning behaviors ^[31].

2.2 Participative leadership and explorative learning and exploitative learning behavior

Participative leadership is a leadership style that focuses on providing employees with decision making and problem-solving opportunities through means such as encouragement, support and influence ^[32]. Unlike many other positive leadership styles, participative leaders focus on consultation rather than direction ^[33]. They encourage employees to creatively to proactively share their views with leaders and other organizational members, thereby creatively engaging

in organizational decision-making ^[10]. It is found that participative leaders could lead to various important psychological behaviors and behavioral outcomes. The psychological behaviors include psychologically empower ^[34], work engagement ^[12]. Its behavioral outcomes often involve extra-role behaviors, such as exploratory innovation behavior ^[11], organizational citizenship behavior ^[35], voice behavior, knowledge sharing behavior ^[9].

March (1991) proposed the widely accepted taxonomy of explorative and exploitative learning. The exploitative learning focuses on refining and extending existing competences, technologies and paradigms in organizations ^[7]. It requires ability to develop a clear understanding of how to create value in the short term and how to coordinate and rationalize activities in order to add value ^[36]. In contrast, explorative learning focuses on developing new alternatives ^[7] and seeks knowledge from the domain outside an organization, which enables the organization to deal with future challenges ^[37]. It is suggested that an organization needs exploitative learning to handle current challenges and streamline existing business processes, while it needs explorative learning for its long-term success ^[37]. As such, both types of learning are critical for an organization to obtain a sustainable competitive advantage. Prior studies have identified various factors that affect the two types of learning in an organization, for example, personal characteristics such as cognitive load ^[38] and academic identity ^[39], and contextual factors such as relational embeddedness ^[40] and leadership ^[41]. In this study, we maintain that at personal level, an employee's explorative learning and exploitative learning behavior could be greatly affected by participative leadership.

Specifically, participative leaders are committed

to collective decision-making, which could lead to close contact, communication, and knowledge sharing between leaders and members, thereby reducing the searching cost for new knowledge and technology within the organization ^[42]. First, such leadership could motivate employees to find ways to improve their work ^[11], and thus enhance the effectiveness of exploitative learning. Second, participative leadership encourages employees to think critically, challenge the status quo and proactively identify problems ^[43]. Arguably, this could cultivate their exploratory thinking abilities. In addition, as participative leadership offers employees opportunities to participate in decision making, it may encourage them to take courses or programs to develop additional knowledge and skills, in order to contribute valuable ideas in future decision-making processes. As such, participative leadership enhance the effectiveness of explorative learning. Based on the preceding discussions, we hypothesize that:

H1a: Participative leadership is positively related to employee explorative learning.

H1b: Participative leadership is positively related to employee exploitative learning.

2.3 The mediating roles of work meaningfulness

Work meaningfulness is defined as the extent to which people view their work as significant and experience a sense of self-worth ^[14, 15]. From the perspective of positive psychology, Steger et al. (2012) maintain that work meaningfulness is determined by an individual's subjective interpretations of his or her work experiences, as well as interactions with others ^[20]. Prior studies show that work meaningfulness affects various employee outcomes, including organizational commitment, in-role and extra-role performance, psychological wellbeing, work and life satisfaction, etc. ^[44]. On the

other hand, it is reported that work meaningfulness is affected by various leadership styles, such as ethical leadership ^[17], empowering leadership ^[45] and authentic leadership ^[46]. In this study, we suggest that participative leadership influence work meaningfulness.

According to self-determination theory, to what extent the three basic psychological motives, such as autonomy (experiencing choice), competence (experiencing effectiveness), and relatedness (experiencing connected with others), are satisfied could greatly affect one's psychological perception ^[47]. In this study, we maintain that participative leadership positively influences work meaningfulness, as such leaders respect employees and offer them support and encouragement. First, participative leadership provides employees with sufficient job autonomy by providing support to employees and encouraging them to participate in decision-making. Such job autonomy could enable employees to obtain an important source of work meaningfulness ^[48]. Furthermore, by providing the opportunities for employees to participate in decision-making, such leaders signal to employees that they are trustworthy and valuable members of the organization. When employees realize their importance to the organization, they are more likely to perceive their work as meaningful ^[49]. Finally, by supporting employees' self-development and growth, participative leaders also send employees a signal that the care about employees, which is conducive to employees' sense of belonging. ^[14] shows that the sense of belonging is an important factor in constructing employees' sense of work significance. In sum, participative leadership could enhance employees' sense of work meaningfulness. Therefore, we hypothesize that:

H2: Participative leadership positively affects

work meaningfulness.

According to self-determination theory, work meaningfulness is a fundamental human need, which could greatly determine employee motivation ^[26,50]. Specifically, work meaningfulness fulfills psychological needs, and consequently satisfy and motivate employees as they carry out their jobs. Accordingly, we argue that employees' work meaningfulness could promote their explorative and exploitative learning behaviors. In particular, with work meaningfulness, employees are able to recognize purpose, significance, and importance of their jobs ^[51]. It also enables employees to take ownership of their job tasks and gain a feeling of responsibility, thereby empowering them in their work ^[52]. As such, with work meaningfulness, employees are often confident that they are able to achieve better work outcomes. Thus, they tend to take their work more seriously, and invest full energy in researching existing and external resources and knowledge, in order to provide better advice and promote the development of the organization ^[45]. Therefore, we maintain that work meaningfulness lead to employees' explorative learning and exploitative learning behavior.

H3a: Work meaningfulness is positively related to explorative learning.

H3b: Work meaningfulness is positively related to exploitative learning.

Our hypotheses 1-3 suggest a linkage from participative leadership to employees' learning behaviors. By sharing information resources with employees and encouraging employees to participate in decision-making, participative leaders provide a positive work environment for employees, and offer them respect and support. This subsequently enhances their sense of work meaningfulness, which motivate employees to engage in extra-role activities,

such as explorative and exploitative learning, in order to make meaningful decisions for the organization. Taken together, we hypothesize that:

H4a: Work meaningfulness mediates the cross-level relationship between participative leadership and explorative learning.

H4b: Work meaningfulness mediates the cross-level relationship between participative leadership and exploitative learning.

2.4 The moderating role of organizational identification

Organizational identification refers to the extent to which an individual defines himself/herself with reference to his/her organizational membership [53]. Such identification is related to a person's identification scope, which involves awareness of his/her membership, value and goal congruence with the organization, shared characteristics, and emotional investment producing consistent behavior [54]. It is argued that organizational identification constitutes a salient domain in modern society. Therefore, such identification is an important factor that explains individual attitudes and behavior, as it forms the basis of those attitudes and behavior. Prior studies have revealed that employees' organizational identification affect their personal outcome, such as work engagement [55], voice [56], creativity [57], pro-environmental behavior [58], extra-role performance [59]. Similarly, organizational identification can also affect the effectiveness of leadership. For example, [60] showed that organizational identification moderates the effects of authentic leadership on organizational dehumanization. Zhu & Zhang (2020) and Mostafa (2018) demonstrated that organizational identification moderates the effects of servant leadership on knowledge-sharing [22,23]. In the current study, we argue that the relationship between participative leadership and work meaningfulness is

influenced by organizational identification. This argument is based on the contingency leadership theory [61], which suggests that the effectiveness of a particular leadership is determined not only by its quality and behavior, but also by work situational conditions like organizational identification.

With strong organizational identification, employees not only view themselves as more members and representatives of an organization, but would also adjust their own values according to the collective value of the organization [22]. Therefore, such employees are more likely to fully understand the behavior of participatory leaders and effectively use the resource information and decision-making opportunities provided by the leaders. During the process, they have the right to speak out and put forward valuable suggestions for organizational decision-making. On the contrary, with a low level of organizational identification, employees tend to feel detached from the organization [62]. They may reduce their work engagement, and thus participate less or do not participate in organizational discussion activities unless absolutely necessary. Therefore, we maintain that organizational identification facilitates the influences of participative leadership on employees' work meaningfulness. Therefore, it is hypothesized that:

H5: Organizational identification positively moderates the relationship between participative leadership and work meaningfulness.

Our H3 and H4 suggest that work meaningfulness mediates the effects of participative leadership on employee explorative and exploitative learning, while organizational identification moderates the influence of participative leadership on work meaningfulness. Accordingly, we maintain that, with a strong organizational identification, an employee's exploitative and explorative learning

behavior is more likely to be affected by participative leadership, and vice versa. Therefore, we propose an overall mediated moderation model, in which the joint effect of participative leadership and organizational identification affects exploitative and explorative learning behavior through work meaningfulness. It is hypothesized that:

H6a: The positive moderating effect of organizational identification on the relationship

between participative leadership and employee exploitative learning is mediated by work meaningfulness.

H6b: The positive moderating effect of organizational identification on the relationship between participative leadership and employee explorative learning is mediated by work meaningfulness

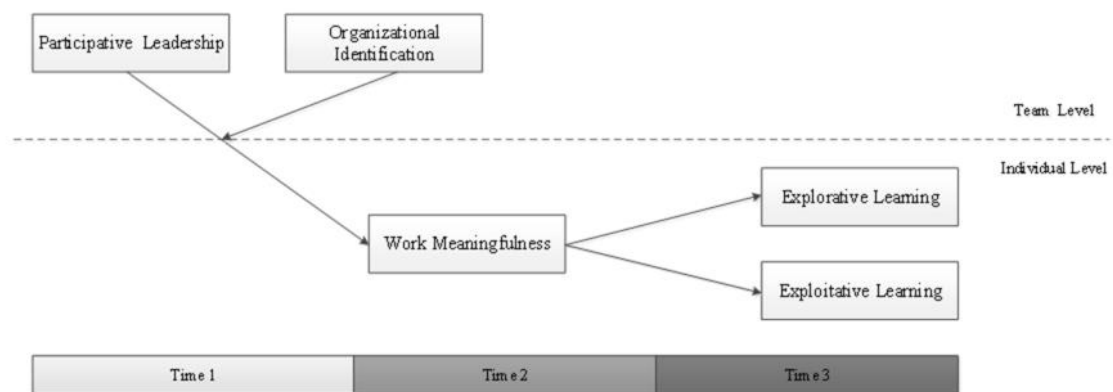


Figure 1. Research Model.

3 Method

3.1 Sample and procedures

For the current study, we surveyed 318 employees in 89 teams from 23 Chinese firms. The firms operate in various industries, including education, services, and telecommunications. We collected data from employees, as well as their direct supervisors. The questionnaire for employees includes items measuring participative leadership, work meaningfulness, organizational identification, and controls variables for our study, whereas the questionnaire for their direct supervisors includes items that measure employee exploitative and explorative learning.

We conducted three waves of surveys. At time point 1, we administered questionnaires to 467 employees in 122 teams, along with a letter explaining basic information about this project. The

questionnaire items ask respondents their organizational identification and that the extent to which their leaders exhibit participative leadership style. For this wave, 410 completed questionnaires were returned. At time point 2 (8 weeks later), we conducted a follow-up survey on individuals who responded at first wave. The survey items are related to their work meaningfulness. A total of 352 team members responded. At time point 3 (8 weeks after time point 2), we surveyed the direct supervisors of these 352 employees, requesting them to evaluate these employees' exploitative learning and explorative learning behavior. For the purpose of matching data, we asked employees to provide the name of their intermediate supervisor. Similarly, we also requested the leaders to provide the names of the employees that they rated. After matching and encoding the data, we removed the respondents' name

from the data set. In total, 318 employees from 89 teams were matched with their supervisors. The overall response rate is 68.09%.

Among the employees, 47.8% were male while 45.0% were married. Regarding the age, 24.2% were under 20 years old; 25.5% between 21 and 30 years old, 20.4% between 31 and 40 years old, and 29.9% over 41 years old. As for their education, 23.6% attended junior college, or below, 28.0% received undergraduate education, 23.9% received graduate education, 24.5% received doctoral education or above. As for their tenure, 18.9% had less than one year, 23.9% between 1 and 3 years, 20.1% between 3 and 5 years, 25.5% between 5 and 7 years, 11.6% over 7 years.

3.2 Measure

All the items for the current study were measured by using a five-point Likert-type scale, with 1 = strongly disagree to 5 = strongly agree.

Participative Leadership. We adapted Arnold et al. (2000) [63] six-item scale to measure participative leadership. A sample item was “Encourages work group members to express ideas/suggestions”. (Cronbach’s $\alpha=0.93$).

Work Meaningfulness. We used six items from Spreitzer et al. (1995) [64] work meaningfulness scale. A sample item is “The work I do is meaningful to me.” (Cronbach’s $\alpha=0.87$).

Exploitative and Explorative Learning. We adapted ten items from Bezuijen et al. (2010) [65] and Liu (2018) [1]. The scale includes five items measuring exploitative learning behavior. A sample item is “He\She continually acquire new knowledge about his\her job.” (Cronbach’s $\alpha=0.89$). The scale includes five items measuring explorative learning behavior. A sample item is “He\She spend time planning and realizing his\her career.” (Cronbach’s $\alpha=0.92$).

Organizational Identification. We adapted six items from Mael & Ashforth (1992) [21] to assess organizational identification. The organizational identification scale contained items such as “When someone criticizes this organization, it feels like a personal insult.” (Cronbach’s $\alpha=0.94$).

Control Variables. Following recent studies on exploitative and explorative learning, such as Asif (2020) [37], we include six control variables in our study: gender, age, marriage, education, tenure and team size.

3.3 Data aggregation

To examine whether it is appropriate to aggregate the scores of participative leadership and organizational identification at individual level to team level, we computed RWG and ICC (intraclass correlation coefficient). The RWG values of participative leadership and organizational identification are 0.97 and 0.97, respectively, suggesting that individual scores of participative leadership and organizational identification could be aggregated for the team-level analyses.

As for ICC, we calculated both ICC (1) and ICC (2). The ICC (1) score is related to the proportion of variance explained by team membership, while ICC (2) score reflects reliability of the difference between group means. A cutoff value of 0.70 is suggested for ICC (2) [66]. The two indicators are calculated based on the following formula:

$$ICC(1) = \frac{MSB - MSW}{MSB + (k - 1) MSW};$$

$$ICC(2) = \frac{MSB - MSW}{MSB}$$

where MSB refers to the mean square between team and refers to the mean square within team.

The ICC (1) values of participative leadership and organizational identification are 0.40 and 0.42, respectively. The ICC (2) values of two constructs are 0.70 and 0.72, respectively. Those scores all

supported aggregation of individual level scores.

4 Result

4.1 Confirmatory Factor Analyses (CFA)

We conducted a multilevel confirmatory factor analysis to evaluate measurement models. The five-factor model, consisting of all the constructs in our research model, fit the data well ($\chi^2 = 353.35$, $df = 265$, $CFI = 0.98$, $TLI = 0.98$, $RMSEA = 0.03$, $SRMR = 0.03$). The model performed better than alternative models, including a four-factor model where participative leadership and work meaningfulness loaded onto one factor ($\chi^2 = 883.06$, $df = 269$, $CFI = 0.89$, $TLI = 0.88$, $RMSEA = 0.09$, $SRMR = 0.10$); or a three-factor model where participative leadership,

work meaningfulness and exploitative learning loaded onto one factor ($\chi^2 = 1701.40$, $df = 272$, $CFI = 0.75$, $TLI = 0.73$, $RMSEA = 0.13$, $SRMR = 0.13$); or a two-factor model where participative leadership, work meaningfulness, exploitative and explorative learning loaded onto one factor ($\chi^2 = 2713.73$, $df = 274$, $CFI = 0.58$, $TLI = 0.54$, $RMSEA = 0.17$, $SRMR = 0.16$); or a one-factor model where all items loaded onto one factor ($\chi^2 = 4237.49$, $df = 275$, $CFI = 0.31$, $TLI = 0.25$, $RMSEA = 0.21$, $SRMR = 0.21$). These findings support the discriminant validity of the five constructors. Therefore, it is appropriate to test the multilevel structure of the data [67]

Table 1. Measurement model comparison

	χ^2	df	χ^2/df	RMSEA	CFI	TLI	SRMR
Five –factor Model (M1)	353.35	265	1.33	.03	.98	.98	.03
Four –factor Model (M2)	883.06	269	3.28	.09	.89	.88	.10
Three –factor Model (M3)	1701.40	272	6.26	.13	.75	.73	.13
Two-factor Model (M4)	2713.73	274	9.90	.17	.58	.54	.16
Single-factor Model (M5)	4237.49	275	15.41	.21	.31	.25	.21

4.2 Descriptive Statistics

The descriptive statistics, correlations and Cronbach alphas of the constructs are presented in Table 2. Participative leadership is found to be positively related to work meaningfulness ($r = 0.44$, p

< 0.01), exploitative learning ($r = 0.24$, $p < 0.01$) and explorative learning ($r = 0.30$, $p < 0.01$); work meaningfulness is found to be positively related to exploitative learning ($r = 0.34$, $p < 0.01$) and explorative learning ($r = 0.49$, $p < 0.01$).

Table 2. Descriptive Statistics

Variable	Individual		Team		1	2	3	4	5	6	7	8	9	10	11
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>											
1. Team size	—	—	5.20	.96	—	—	—	—	—	—	.14*	.14*	.12*	.01	.17**
2. Employee gender	.52	.50	—	—	—	—	—	—	—	—	—	—	—	—	—
3. Employee marriage	.45	.50	—	—	—	.03	—	—	—	—	—	—	—	—	—
4. Employee age	1.56	1.15	—	—	—	-.01	.06	—	—	—	—	—	—	—	—
5. Employee education	1.49	1.10	—	—	—	-.01	-.16**	.00	—	—	—	—	—	—	—
6. Employee tenure	1.87	1.31	—	—	—	.04	-.02	-.03	-.08	—	—	—	—	—	—
7. Participative	3.61	.80	3.61	.55	—	-.08	.02	-.01	.09	-.05	.93	.54**	.40**	.48**	.27**
8. Work	3.70	.80	3.70	.65	—	-.11*	-.02	.02	.16**	-.04	.33**	.87	.59**	.64**	.21**
9. Exploitative	3.63	.69	3.63	.41	—	-.08	.14*	.00	.05	.08	.23**	.38**	.89	.50**	.12*
10. Explorative	3.66	.77	3.66	.47	—	-.05	-.02	-.02	.03	-.00	.25**	.49**	.17**	.92	.21**
11. Organizational	3.68	.84	3.68	.59	—	-.11	.00	.06	.07	-.06	.21**	.11*	.07	.08	.94

Notes. Team level, $n = 89$; individual level, $n = 318$. Individual- and team-level correlations are below and above the diagonal, respectively. Bold values on the diagonal are Cronbach's alpha. * $p < .05$, ** $p < .01$.

4.3 Hypotheses testing

We tested our research model in Mplus Version 8.3. As shown in Figure 1, Participative leadership positively affects employee exploitative learning behavior ($b = 0.26$, $se = 0.06$, $p = 0.03$), supporting H1a; it also positively affects explorative learning behavior ($b = 0.41$, $se = 0.09$, $p = 0.00$), supporting Hypothesis 1b.

Participative leadership positively affects work meaningfulness ($b = 0.57$, $se = 0.16$, $p = 0.00$), supporting H2. Work meaningfulness positively influences employee exploitative learning behavior ($b = 0.40$, $se = 0.14$, $p = 0.00$) and explorative learning behavior ($b = 0.39$, $se = 0.12$, $p = 0.00$), supporting H3a and H3b.

Work meaningfulness mediates the linkage between participative leadership and employee exploitative learning behavior ($b = 0.23$, $se = 0.11$, $p = 0.04$), supporting H4a. It also mediates the relationship between participative leadership and employee explorative learning behavior ($b = 0.22$, $se = 0.08$, $p = 0.00$), supporting Hypothesis 4b.

The interaction term between participative

leadership and organizational identification positively affect work meaningfulness ($b = 0.53$, $se = 0.18$, $p = 0.00$). We present the simple slope test for this interaction in Figure 2. With a lower level of organizational identification, the relationship between participative leadership and work meaningfulness was weaker ($b = 0.25$, $se = 0.17$, $p = 0.13$) than it was with a higher level of organizational identification ($b = 0.88$, $se = 0.21$, $p = 0.00$). This finding supports H5.

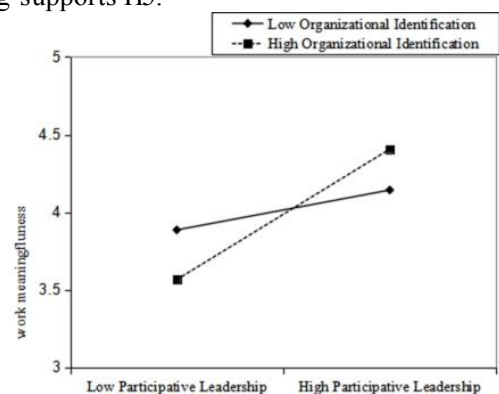


Figure 2 Interaction of participative leadership and organizational identification on work meaningfulness.

Finally, we found that the linkages of “participative leadership → work meaningfulness → employee exploitative learning behavior” differ

significantly across different levels of organizational identification (diff = 0.25, se = 0.13, p = 0.04). Specifically, the indirect effect of participative leadership on employee exploitative learning behavior is stronger higher levels of organizational identification (b = 0.35, se = 0.16, p = 0.03) than that with lower levels of organizational identification (b = 0.10, se = 0.08, p = 0.22), supporting H6a. Similarly, the linkages of “team reflexivity → work meaningfulness → employee explorative learning behavior” differ significantly across different levels of organizational identification (diff = 0.24, se = 0.11, p = 0.02). Specifically, the indirect effect of participative leadership on employee exploitative learning behavior is stronger with higher levels of organizational identification (b = 0.34, se = 0.12, p = 0.00) than that with lower levels of organizational identification (b = 0.10, se = 0.07, p = 0.14), supporting H6b.

Table 3. Results of Hypothesis Testing

	Direct effect								whole model											
	Employee exploitative learning				Employee explorative learning				Work meaningfulness				Employee exploitative learning				Employee explorative learning			
	Estimate	S.E.	P	95% CI	Estimate	S.E.	P	95% CI	Estimate	S.E.	P	95% CI	Estimate	S.E.	P	95% CI	Estimate	S.E.	P	95% CI
Within level																				
1. Gender	-.10	.08	.25	[-.25, .06]	-.04	.08	.61	[-.20, .12]	-.20	.08	.02	[-.36, .04]	-.07	.08	.35	[-.22, .08]	.05	.07	.49	[-.09, .19]
2. Marriage	.21	.07	.00	[.07, .35]	-.03	.07	.61	[-.16, .09]	.02	.06	.73	[-.10, .15]	.21	.07	.00	[.07, .35]	-.04	.06	.56	[-.16, .09]
3. Age	-.01	.03	.65	[-.07, .05]	-.03	.03	.43	[-.09, .04]	-.01	.03	.68	[-.07, .04]	-.02	.03	.58	[-.07, .04]	-.02	.03	.53	[-.08, .04]
4. Education	.02	.04	.49	[-.04, .09]	-.01	.03	.70	[-.08, .05]	.05	.04	.15	[-.02, .12]	.01	.03	.82	[-.06, .07]	-.04	.03	.22	[-.10, .02]
5. Tenure	.05	.03	.09	[-.01, .10]	-.01	.03	.70	[-.06, .04]	-.03	.02	.16	[-.07, .01]	.05	.03	.07	[-.00, .10]	.00	.03	.87	[-.05, .05]
6. WM													.20	.08	.01	[.04, .36]	.49	.07	.00	[.35, .63]
Between level																				
7. Team size	.06	.06	.31	[-.05, .16]	-.04	.06	.54	[-.15, .08]	.01	.07	.91	[-.12, .14]	.04	.05	.40	[-.05, .13]	-.05	.04	.23	[-.14, .03]
8. WM													.40	.14	.00	[.13, .67]	.39	.12	.00	[.16, .61]
9. PL	.26	.12	.03	[.03, .50]	.41	.09	.00	[.24, .59]	.57	.16	.00	[.26, .87]	.03	.11	.77	[-.18, .24]	.19	.10	.07	[-.02, .39]
10. OI									.11	.09	.20	[-.06, .28]								
11. PL*OI									.53	.18	.00	[.18, .89]								

Notes. WM = work meaningfulness; PL = participative leadership; OI = organizational identification. Team level, n = 89; individual level, n = 318. * $p < .05$, ** $p < .01$.

Table 4. Analysis of moderated mediation effect.

Moderator		Participative leadership → Work meaningfulness → Employee exploitative learning			
		Estimate	S.E.	<i>P</i>	95%CI
Organizational identification	High	.35*	.16	.03	[.03, .67]
	Low	.10	.08	.22	[-.06, .26]
	Diff	.25*	.13	.04	[.01, .50]

Notes. N = 318; ** $p < .01$, * $p < .05$.

Table 5. Analysis of moderated mediation effect.

Moderator		Participative leadership → Work meaningfulness → Employee explorative learning			
		Estimate	S.E.	<i>P</i>	95%CI
Organizational identification	High	.34**	.11	.00	[.12, .57]
	Low	.10	.07	.14	[-.03, .23]
	Diff	.24*	.11	.02	[.04, .45]

Notes. N = 318; ** $p < .01$, * $p < .05$.

5 Discussion

In this study, we draw on self-determination theory to develop a research model and empirically show that participative leadership affects employee exploitative and explorative learning behavior. The relationships are mediated by work meaningfulness. Additionally, organizational identification positively moderates the relationship among participative leadership, work meaningfulness and employee learning behavior. We present theoretical and practical implications of our findings in the following sections.

5.1 Theoretical contribution

This study makes several important theoretical contributions. First, while there are an increasing number of studies focusing on participative leadership and employee learning respectively, researchers have paid little attention to investigate possible linkage between them. To fill this gap, we draw on self-determination theory to explore how participative leadership affect two types of employee learning, namely, explorative and exploitative learning behaviors. The mechanism identified by the current study has expanded the scope of cross-cultural application of participative leadership, enriched the literature on the influence of leadership,

and deepened our understanding of antecedents of employees' learning behavior.

Second, many scholars have downplayed the importance of meaningfulness for employee learning [68]. Specifically, researchers on organizational behavior often focus on autonomy or job control rather than work meaningfulness [69]. While there is substantial studies on participative management in leadership field [9], researchers seldom pay attention to the role of meaningfulness. Therefore, our findings on the relationships among participative leadership, work meaningfulness and employee learning behavior also contribute to the literature on work meaningfulness. Prior studies have shown that leaders or supervisors constitute critical environmental factors for work meaningfulness [46, 70]. Our findings support and extends the literatures by specifically showing the positive effect of participative leadership on work meaningfulness. Additionally, we reveal that work meaningfulness enhances explorative and exploitative learning behaviors. Our findings are similar to those of Chaudhary (2020) [46] and Wang & Xu (2019) [70], which demonstrate that work meaningfulness facilitate employee initiative performance. As such, our study further confirms the critical role of work meaningfulness in individual and organizational development.

Finally, this study further reveals the boundary conditions for participative leadership to affect employees' learning behavior through work meaningfulness. Our findings support the earlier research arguments made by Knippenberg et al. (2004) [71] on the relationship between leadership effectiveness and identity. To date, researchers mostly investigate this relationship by focusing on the influence of leadership on subordinates' sense of identity. That is, leadership first influence

subordinates' sense of identity to leaders, which subsequently affects their behaviors [72, 73]. We find that the relationship between leadership and individual organizational identity is complicated. The organizational identity may not only transmit the influence of leader behavior on subordinates (mediating effect), but also serve as a moderator affecting effectiveness of some leadership styles on employee behaviors. This provides a new insight into the relationship between leadership and organizational identity.

5.2 Practical Implications

This study offers several practical implications for organizations. First, we should that participative leadership enhances employees' work meaningfulness, which subsequently facilitates their learning behaviors. Therefore, firms may need to provide participative leadership training to their unit managers. Through the training, the managers could learn how to better encourage their employees to express their thoughts, and how to effectively involve employees in decision-making.

Second, our findings emphasize that the linkage between work meaningfulness and employee learning behavior. Therefore, in addition to promote participative leadership, organizations may also take other actions to stimulate employees' sense of work meaningfulness. For example, they may clearly communicate internal opportunities related to meaningful work, especially job tasks that allow employees to realize their full potential in the organization's. They may also redesign jobs to make them more meaningful and challenging. Moreover, organizations could proactively involve employees in decision making, which could enhance the influence and the significance of their work. Finally, organizations need to make efforts to establish deeper social connections among the employees so that they

can fully understand each other.

Third, this study found that organizational identification increased the positive impact of participative leadership on work meaningfulness. Therefore, managers should take actions to enhance employees' identification with the organization. Specifically, leaders should adopt the "people-oriented" management concept, implement humanized management, and pay attention to the feelings and needs of employees. Organizations should also effectively communicate organizational purpose, vision and values to the employees, and make efforts to enable employees to internalize organizational values into personal values.

5.3 Research limitations and prospects

This current study has two major limitations. First, we conducted a cross-sectional study, which only reveals correlational significant relationships. Therefore, our findings do not necessarily suggest causal relationships among the constructs. Especially, the relationships among constructs such as participative leadership, work meaningfulness, and employee learning could change over time. It is recommended that future researchers adopt experimental design or conduct longitudinal study to further explore the causal relationships among these constructs.

Second, there is only one single mediator (work meaningfulness) and one single moderator (organizational identification) in our research model. However, the relationship between participative leadership and employee learning behavior could be mediated or moderated by some other team level or contextual factors. Therefore, future researchers may identify other potential mediators and moderators that could be included in this model. This could further offer more insights into the relationship between leadership's influence on

employee learning across multiple levels.

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The Impact of Nutritional Content Equivalent Labels on Consumer Perceived Healthiness: A Mental Imagery Perspective

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Abstract: Designing Nutrition labels scientifically is a powerful strategy for companies to increase product sales. Previous research has examined nutritional content equivalent labels within numerical, but little research focuses on the visual equivalent labels. To fill this research void, our study explores the influences of Nutritional Content Equivalent (NCE) labels (visualized vs. numerical) on consumer perceived healthiness. Results show that the visualized nutrition label is more likely to induce mental imagery than the numerical nutrition label, which in turn results in higher perceived healthiness. Further, we introduce advertising appeals as the boundary condition of the mediating effect of mental imagery. This research provides a novel explaining the mechanism for the impact of NCE labels on perceived healthiness from a mental imagery perspective. Meanwhile, this paper not only offers new insight into nutrition label optimization for food companies but also is favorable to design advertisements strategically for marketing managers.

Keywords: Nutritional Content Equivalent (NCE) labels, mental imagery, perceived healthiness, advertising appeals

1. Introduction

With the issue of obesity and various diseases is rising worldwide, consumers are committed to choosing healthier foods to improve health. Further, public health organizations have also begun to convey nutrition information by nutrition labels to guide people's food choices and nudge consumers to make a thoughtful decision^[1]. Nutrition labels are labels that adopt a clear, simple format to display nutritional information on food packaging. However, due to the complexity of traditional nutrition labeling information and the differences in cognitive ability among individuals^[2], customers still show confusion and doubt in understanding nutrition information^[2-4].

To make consumers comprehend the content of nutrition equivalent labels much easier, recently some marketers employ visualized equivalent nutrition labels to convey nutrition information. For example, "the grams of dietary fiber was equal to two apples (apple pictures)" is clearly displayed on the front packaging of *Sprite* (i.e., a popular carbonated drink brand in China). Some other marketers take numerical format to show nutritional equivalent content on the product packaging.

For instance, a beverage named *Ugly Tangerie oquat Favored Water* is labelled "5.7 grams of dietary fiber per bottle" on packaging. Given this, we probe into which equivalent nutrition label (visualized vs. numerical) could be favorable to improve consumer perceived healthiness. In addition, a certain type of product emerges in the market rapidly and consumers hold an ambivalent attitude on its healthy attribute. For instance, Coca-Cola is regarded as unhealthy but also wholesome when it claims to contain dietary fiber valuable nutrients. Consumers may have both positive and negative attitudes (e.g., ambivalent attitude) toward specific food. We define such ambivalent healthy food as a food that makes people have both positive and negative cognitive evaluations towards its health attributes. The health elevation of ambivalent healthy food is especially crucial, so it is important to investigate how the presentation of the equivalent nutrition labels (visualized vs. numerical) affects consumers' perceived healthiness of ambivalent healthy food.

Prior research about equivalent labels has been focused on abstract numerical labels^[5-7], while visual

nutrition equivalent labels are largely under explored. In light of this, this paper aims to investigate the effect of the different types of “Nutritional Content Equivalent (NCE)” labels (visualized vs. numerical) on consumer perceived healthiness. Further, drawing on mental imagery theory, this research explores how the distinct presentation of NCE labels exert an influence on consumer health perception by introducing the mediating role of mental imagery. Mental imagery reflects a process by which sensory information is represented in working memory^[8]. Research has found that visual cues as antecedents can induce mental imagery to impact cognitive, affective, and behavioral responses^[9–11]. Furthermore, the “Picture Superiority Effect” supposes that images have been examined as antecedents of mental imagery^[12], and mental imagery relies on image vividness^[8]. Thus, we assume that the vividness of visualized NCE labels can easily activate the imagery related to equivalent nutrition compared with numerical NCE labels, leading to higher consumers’ perceived healthiness. Moreover, prior studies have proved that the match between product characteristics and advertisement appeals can elicit better responses^[13]. It suggests the NCE labels as a product characteristic within product packaging might interact with advertisement appeals to affect mental imagery, resulting in various levels of healthiness perception. Therefore, we propose advertising appeals as the moderating factor of the mediating effect of mental imagery.

Overall, this study makes fourth significant theoretical and managerial contributions. First, we contribute to the nutrition information research by conceptualizing NCE labels and demonstrating the differential effect of the presentation of NCE labels on perceived healthiness. Second, we extend the content of mental imagery research by revealing the role of mental imagery as the underlying mechanism. Third,

this research examines advertising appeals as the boundary condition of the mediating effect of mental imagery, which advances research on the relationship between advertising information and consumers’ psychological perception. Fourth, we provide practical guidelines that can assist marketers to optimize labels designs and promote advertising effectiveness for ambivalent healthy food.

2. Literature Review and Hypotheses

2.1 Nutritional Content Equivalent Labels

Nutrition labeling is a means to improve consumers’ cognition of nutrition information and nudge healthier dietary intakes^[6,7]. Various simplified nutrition labeling has been applied to product packaging, such as percentage daily intake, traffic light system warning labels^[14], but research is relatively scanty about equivalent nutrition labels. In this study, we propose a new construct of nutrition labels- “Nutritional Content Equivalent (NCE)” labels to help consumers to understand product nutrition easily. NCE labels are defined as a certain sort of labels, which quantify nutrition content through the fixed amount of nutrients in the form of picture or numerical. Accordingly. In this research NCE labels are divided into two types, that is, visualized NCE nutrition labels and numerical NCE nutrition labels.

Prior research about NCE labels concentrates on the numerical nutrition labels, such as the percentage Guideline Daily Amount labels (% GDA), which state the amount of nutrients in the form of daily value percentage^[7,14]. Nevertheless, picture or visual equivalent nutrition information receives much less attention. Moreover, existing visual equivalent information literature is limited to physical activity calorie equivalent (PACE) labeling^[15,16] and sugar equivalent labeling^[12,17]. For example, PACE labeling displayed the number of walking (running, biking) minutes to ‘burn off’ the calories in the packaging or on

the menu could affect consumers choice^[15,16]. In another study, some scholar showed PACE can be equivalent to the miles to walk to burn off the calories in menu labeling^[15]. Compared with the Kcal label conditions, the PACE label can drive consumers to reduce the sense of choosing high-energy snack and beverage choices^[18]. Furthermore, Sah (2021)^[17] demonstrates four equivalent sugar labels (i.e., Cookies label, Candies label, Sugar cubes label, and Teaspoon label) of fruit juice have a differential impact on health perception compared with no label condition. These equivalent labels display nutrition content in a salient and easy-to-understand way.

In summary, previous studies have mostly focused on numerical equivalent nutrition labels, and several kinds of research have investigated visual equivalent nutrition labels limited to calories^[15] and negative nutrients (i.e., sugars)^[17]. However, few studies have paid attention to the positive nutrient visual ones among the equivalent labels. To fill this research gap, this research is aimed to examine which NCE labels (visualized vs. numerical) specific to positive nutrition, could produce higher consumers' perceived healthiness and the underlying mechanism for the above effect.

2.2 The Impact of the NCE Labels on Perceived Healthiness

Research has extensively demonstrated nutrition labels (e.g., Stop Sign labels, Traffic-Light labels), which can draw consumers' attention, create a positive effect to improve consumers' health perception inferences^[5,19]. That is to say, health labels or adding health-related images to product packaging positively affect consumers' relevant judgments of product health characteristics^[20]. Moreover, we should explore whether visualized NCE labels are perceived healthier than numerical NCE labels.

According to prior research, individuals can process nutritional information in a graphical (vs.

numerical) manner more effectively to make judgments and decisions^[21]. It is because visual features increase the easiness of individuals' information processing than numerical information^[22]. Previous research has also pointed out that images are more directly related to their connotation, that is, picture comprehensions could be straightly linked to the objects^[12,23]. For instance, it is much simpler for consumers to imagine consuming 28 sugar cubes when the sugar information is conveyed via a photograph of 28-sugar cubes way^[12]. While for the numerical labels, numerical information needs to be transformed to interpret its implication during processing^[24]. Thus, the nutrition equivalent contents of visualized (vs. numerical) NCE labels will be comprehended better and perceived higher healthiness. We put forward our hypothesis as follow:

H1: *Visualized NCE (vs. numerical) labels will trigger consumers' higher perceived healthiness.*

2.3 Mental Imagery as Mediator

Mental imagery is defined as "a process by which nonverbal information is represented in working memory"^[8]. Mental imagery is a three-dimensional model constituting vividness, quantity, and elaboration^[9]. Mental imagery theory posits that individuals mentally represent in their minds what is presented to them through past experience and existing perceptual information^[25]. Moreover, mental imagery could affect consumers' cognitive and affective responses^[9,11,26].

Previous studies have identified different stimuli as the antecedents of mental imagery. These include visual stimuli, such as pictures^[25], contextual image background^[27], and so on. Pictures as visual cues have dominated as influencing factors of mental imagery because pictures can draw more attention and deliver more lively information^[12,28]. On the other hand, mental imagery could be considered as a proxy for actual sensory experiences, because mental imagery

can involve inferring the inherent benefits of the imagined scene ^[29]. For example, when exposed to a cake picture, consumers might mentally simulate earlier experiences associated with the cakes, and recall the sweet taste in their minds. Taking the above literature into consideration, the vividness of the picture probably stimulates consumers to produce a sensory experience to enhance mental imagery. Thus, we predict that the vividness of visualized NCE labels can arouse consumers' imagery about high and abundant nutrition content in their minds.

While abstract information lacks tangible referents, making it more difficult to evoke mental imagery^[11]. For instance, simulating the experience of consuming "70g of sugar" (abstract information) is relatively difficult to stir up concrete sensations (smell, texture) and responses^[12]. Thus, we infer that the vividness of visualized NCE labels is easy for consumers to imagine and comprehend the amount of nutritional content than numerical NCE labels. According to the above discussion, we put forward this hypothesis:

H2a: *Compared with numerical NCE labels, visualized NCE labels will evoke more mental imagery.*

So far, a stream of research has revealed that mental imagery can affect cognition, affection, and behavioral intentions^[9-11]. As one critical cognition towards products, perceived healthiness is consumers' expectation of a product influence on one's health^[11]. We put forward that there may exist a linkage between mental imagery and perceived healthiness. More specifically, imagery can generate health expectations and promote healthy eating^[32]. Furthermore, people could emphasize the healthiness of the product by depicting health-related images (e.g. a heart) ^[20,33]. Thus, we infer the mental imagery about the nutrition of NCE labels could make consumers promote the consumers' perceived healthiness. Therefore, we put

forward this hypothesis:

H2b: *Mental imagery is positively associated with perceived healthiness.*

In previous research, mental imagery has been adopted as a mediator in the impact of various stimuli and consumers' responses^[34]. For example, Yoo and Kim (2014)^[11] have found that a concrete background image evokes more mental imagery than a solid white background for apparel product, thus improving purchases intentions. Therefore, we infer consumers may generate more mental imagery based on visual rather than numerical NCE labels, thus resulting in higher perceived healthiness. Taking H2a, H2b, and the above discussion into consideration, we can conjecture that mental imagery might play a mediating role between NCE labels and perceived healthiness. We put forward the following hypothesis:

H2c: *The effect of NCE labels on perceived healthiness is mediated by mental imagery.*

2.4 The Moderating Role of Advertising

Appeals

Advertising appeals are usually classified into transformational appeals and informational appeals^[35]. Transformational appeals mainly focus on the experience of consuming the brand and associate the experience with an exclusive set of psychological characteristics^[35-36]. This type of advertising is essentially affect-based rather than cognitive-based. The slogan of an advertisement such as "Come and live the magic" (Disney) reflects the transformational appeals^[37]. While informational appeals refer to providing consumers with factual, pertinent brand data clearly and logically, which typically emphasize product features or benefits^[35]. For example, the advertising shows that "the 60% cocoa butter we use in making our chocolate stimulates the secretion of endorphins" ^[37].

According to the match-up hypothesis, the match

between product characteristics and advertisement appeals can elicit better responses^[13]. Furthermore, recent research has demonstrated that the interaction between the visual complexity of apparel design and types of appealing (information versus emotion type) exerts an impact on mental imagery^[34]. Thus, we assume that nutrition labels design as one of the product characteristics might have an interactive effect with the advertising appeals on mental imagery.

More specifically, transformational appeals connect the product with the ability to bring experience to consumers^[35], which could make consumers feel like the main characters of the ads, thus eliciting vivid and elaborate mental imagery^[38]. In this process, transformational appeals emphasize emotions, which can trigger emotional resonance to process information by an intuitive heuristic-based system and a peripheral persuasion route^[39,40]. Intuition refers to “immediate judgment based on feeling and the adoption of a global perspective”^[41]. Thus confronted with transformational appeals advertising, consumers are inclined to adopt intuition thinking to deal with the information. Moreover, intuition thinking is “non-verbal thinking” in nature and “thinking on the visual level”^[42], which is driven by emotions and schemata^[43,41]. In accordance with this, visual cues require a type of unconscious and unintentional processing^[44]. Therefore, we infer that the unconscious and unintentional processing of visualized labels matches with the intuitive thinking under the transformational appeals. Based on the above speculation, we draw a conclusion that it is favorable for the visualized (vs. numerical) NCE label to evoke more mental imagery under transformational appeals.

In contrast, information advertising emphasizes more on the quality and characteristics of products, and under this advertising consumers would tend to use the central persuasion route to deeply process information and systematically think, analyze and summarize

information^[45]. The central path is similar to analytical thinking^[45]. Relevant for this research is that under informational appeals, consumers need a great deal of thought and assessment of the product attribution logically with high elaboration. In this case, the analysis thinking may conflict with the intuitive thinking required by visualized NCE labels processing. That is to say, informational appeal advertising might not be favorable for consumers to generate mental imagery evoked by the visual image. Therefore, we propose under information advertising appeal, the consumer cannot produce significantly more mental imagery for visualized versus numerical NCE labels. According to the above discussion, we hypothesize the following:

H3: *Advertising appeals moderates the effect of NCE labels on mental imagery.*

H3a: *In the transformational appeals condition, visualized nutrition labels evoke more mental imagery than numerical nutrition labels.*

H3b: *In the informational appeals condition, the type of NCE labels has no significant impact on mental imagery.*

Taking the above literature and H1, H2, H3 into consideration, we propose that advertising appeals can moderate the mediating effect of mental imagery in the impact of the NCE labels on perceived healthiness. To be specific, transformational appeals focus more on experience, consumers’ intuitive thinking under such advertising appeals is better aligned with the intuitive thinking triggered by vividness of visualized NCE labels. The congruent thinking style could lead to higher mental imagery and perceived healthiness. Conversely, consumers adopt systematic thinking to analyze product attribute information when exposed to informational appeals advertising. In this case, this systematically thinking is slightly conflicted with the intuitive thinking required by the visualized NCE labels,

hindering the effective generation of mental imagery. Thus, the presentation of NCE labels (visualized vs. numerical) have no significant effect on consumers' mental imagery and perceived healthiness under the informational appeals condition. Taken together, we put forward this hypothesis:

H4: Advertising appeals moderates the mediating effect of mental imagery in the effect of the NCE labels on perceived healthiness.

H4a: Under transformational appeals condition, visualized labels (vs. numerical labels) can lead to higher perceived healthiness via the mediating role of mental imagery.

H4b: Under informational appeals condition, mental imagery can not play a significant mediating

role in the effect of the NCE labels on perceived healthiness.

2.5 Theoretical Framework

Based on the previous discussion, we propose the theoretical framework presented in Figure 1. This paper seeks to investigate the effect of NCE labels types (visualized vs. numerical) on consumers' perceived healthiness. Specifically, Study 1 offers initial evidence that visualized (vs. numerical) NCE labels could cause a higher degree of consumer perceived healthiness (H1). Further, Study 2 explores the underlying process by examining the role of mental imagery (H2). Then Study 3 introduces advertising appeals as the boundary condition of the mediating effect of mental imagery (H3 & H4).

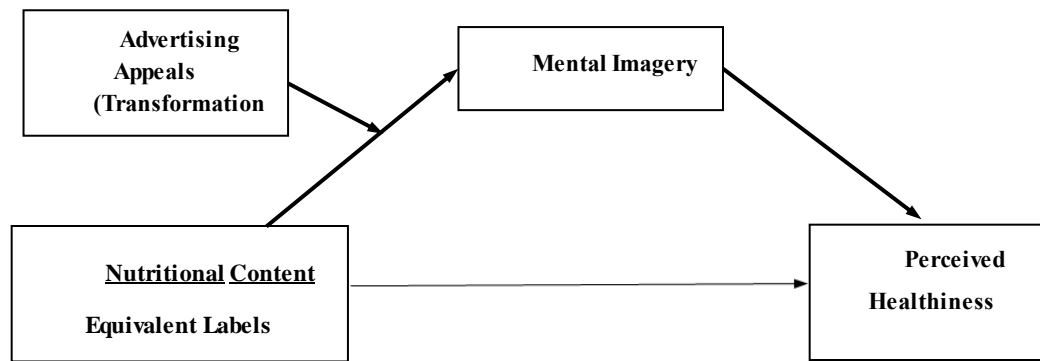


Figure 1 Theoretical Framework

3. Study 1: The Effect of NCE labels on Perceived Healthiness

3.1 Pretest

A pretest was conducted to select the experimental stimuli of ambivalent healthy food. Biscuits as snacks were considered unhealthy to consumers, while it can be considered healthy when providing valuable nutrients (protein or fiber) [46]. In this study, we planned to choose stimulus materials from four types of biscuits (i.e., oatmeal, milk, butter, and soda biscuits). 30 participants (39.02% males, $M_{age} = 19.85$) from a university in China were recruited to evaluate the ambivalent attitudes toward the health of biscuits. We adopt the two independent

sub-scales to capture consumers' mixed attitudes toward the product directly^[47]. First, participants were asked to only consider the healthy aspects of the biscuits and ignore the unhealthy aspects using a 7-point scale ($1 = \text{extremely unhealthy}$, $7 = \text{extremely healthy}$). Then they were required to only consider and indicate the unhealthy aspects of the biscuits by ignoring the healthy aspects ($1 = \text{extremely healthy}$, $7 = \text{extremely unhealthy}$) [48,49]. Based on the literature of ambivalent [50], we adopted the following index as an individual measure of health attitudinal ambivalence:

$$\text{Ambivalence} = (P + N) / 2 - |P - N| / 2$$

Whereby P and N denote the positive and

negative attitude component, respectively.

The results showed that participants exhibited higher ambivalence toward soda biscuits ($M_{\text{Soda biscuits}} = 4.26$, $SD = 1.66$) compared with other biscuits ($M_{\text{Oatmeal biscuits}} = 3.48$, $SD = 1.91$; $M_{\text{Butter biscuits}} = 3.78$, $SD = 1.62$; $M_{\text{Milk biscuits}} = 3.57$, $SD = 1.72$).

3.2 Method

The purpose of this study was to investigate the main effect of NCE labels on perceived healthiness. The independent variable was the type of NCE labels (visualized vs. numerical vs. verbal), and the dependent variable was perceived healthiness. We adopted Gpower software^[51] to do a prior power analysis using effect size = 0.25, $\alpha = 0.05$, and the desired power of 0.90. The result indicated 231 participants would be required.

274 college students (49.30% males, $M_{\text{age}} = 21.37$) were recruited to participate in the study and assigned to three different nutrition labels groups randomly. In this experiment, another verbal NCE labels was introduced as the control group. Especially, verbal NCE labels referred that the equivalent nutrition information was presented through the verbal description. We inferred there existed two possible reasons for the visualized NCE labels advantage over numerical NCE labels: one is the vividness of visualized NCE labels; the other might be the healthy food (the object of quantification) displayed on the visualized NCE labels. In the verbal NCE labels group, the equivalent nutrition information included healthy food but lacked vividness. By comparing the above three groups, we could exclude the superiority of visualized NCE labels was induced by the inclusion of healthy food information.

First, participants were asked to browse the soda biscuits advertising carefully. Visualized nutrition labels displayed that “dietary fiber is about equal to

two apples (Cartoon apple images). Numerical nutrition labels equivalent to the amount of dietary fiber by displaying “dietary fiber $\approx 5.4\text{g}$ ”. The verbal nutrition labels revealed “dietary fiber is about equal to two apples” with verbal descriptions (see Appendix A). The equivalent information was calculated based on China’s largest online weight loss platform (Boohee.com) and the Chinese Dietary Guidelines issued by the Chinese Nutrition Society. The three ads contained the same product package and background, but the descriptions of the NCE labels among them were different.

Participants were then asked to rate their perceived healthiness on a seven-point scale ($1 = \text{strongly disagree}$, $7 = \text{strongly agree}$). It consisted of four statements ($\alpha = 0.93$; “*The consumption of the product can enhance my health,*” “*I think consumption product enable me to live healthily,*” “*I think that the consumption of the product has a health-promoting effect,*” “*The product and a health-conscious lifestyle match well.*”)^[52]. Further, participants rated biscuits’ perceived tastiness^[53] with three items “tasty,” “flavorful,” and “delicious.” ($\alpha = 0.94$, $1 = \text{strongly disagree}$, $7 = \text{strongly agree}$).

3.3 Results

The one-way analysis of variance (ANOVA) showed that visualized NCE labels ($M_{\text{visualized}} = 4.60$, $SD = 1.23$; $F(2, 270) = 4.51$, $p < 0.05$, $\eta_p^2 = 0.03$) produced higher perceived healthiness compared with numerical NCE label and the verbal NCE labels ($M_{\text{numerical}} = 4.05$, $SD = 1.50$; $M_{\text{verbal}} = 4.13$, $SD = 1.28$) (see Figure 2), supporting H1. The result was still significant ($F(2, 270) = 4.38$, $p < 0.05$, $\eta_p^2 = 0.03$) when we controlled perceived tastiness ($F(1, 270) = 58.48$, $p < .001$, $\eta_p^2 = 0.18$) as covariate.

Specifically, visualized NCE labels led to higher perceived healthiness than numerical NCE labels (t

(179) = 2.72, $p = 0.04$) and verbal NCE labels ($t(179) = 2.54$, $p = 0.01$). However, the effect of verbal NCE labels did not trigger significantly higher perceived healthiness than numerical NCE labels ($t(179) = -0.387$, $p = 0.70$). It showed that compared to the numerical NCE labels, the inclusion of text information about healthy food did not lead to higher perceived healthiness, and only the images of healthy food as quantitative objects could improve perceived healthiness.

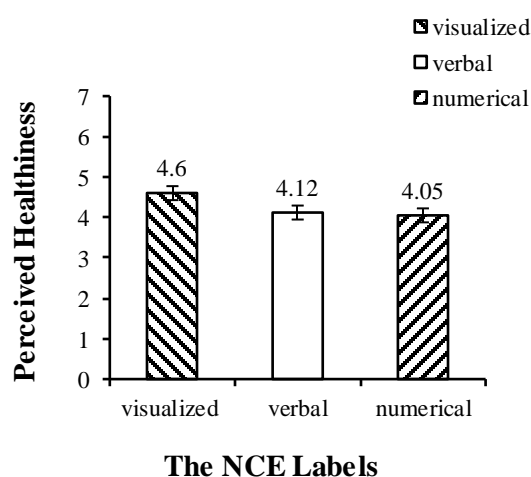


Figure 2 the Influence of NCE Labels on Perceived Healthiness

3.4 Discussion

The results show that the type of NCE labels has a significant effect on perceived healthiness. Specifically, visualized NCE nutrition labels evoke higher perceived healthiness than numerical NCE labels and verbal NCE labels. The effect of numerical labels and verbal labels have no significant differences on perceived healthiness, thus we could exclude the superiority of visualized (vs. numerical) NCE labels were induced by the inclusion of healthy food information.

However, there are some limitations of this experiment. First, this study does not reveal the underlying mechanism, and thus subsequent study aims to introduce mental imagery to explore the

mechanism. Second, we would adopt another product category as the stimulus of the experiment to expand the scope of applicability of the research. Further, in this study, cartoon pictures displayed on the visualized nutrition labels is not realistic enough. Accordingly, the following experiment would adopt real fruit photographs to increase the authenticity of stimuli. Third, the college students' sample is not representative enough. In the following study, young adults (18-30 years old) will be recruited to improve the external validity of this research.

4. Study 2: The Mediating Role of Mental Imagery

4.1 Pretest

A pretest was conducted to select one beverage as the stimuli of ambivalent health food from six beverages (Fresh juice, sparkling water, Coke, Ice tea, Milk tea, Sports drinks) [54]. Participants were asked to indicate their ambivalent attitudes towards the beverage with two items (same as study 1). We recruited 30 individuals (50.00% males; $M_{age} = 25.25$) aged between 18 and 30 years to complete the experiment.

Results showed that participants expressed more ambivalence toward the healthy sparkling beverage ($M_{Sparkling} = 3.97$, $SD = 2.53$) than the other beverages ($M_{Fresh\ juice} = 2.40$, $SD = 2.45$; $M_{Coke} = 3.72$, $SD = 2.46$; $M_{Iced\ tea} = 3.47$, $SD = 2.05$; $M_{Milk\ tea} = 3.52$, $SD = 2.21$; $M_{Sports\ beverage} = 3.88$, $SD = 2.04$).

4.2 Method

In this study, we aimed to examine the mediating role of mental imagery on the type of NCE labels and perceived healthiness. In addition, we sought to exclude one alternative explanation -health accessibility, accounting for the effect of NCE labels on perceived healthiness. External cues (e.g., words or images) can increase the mental accessibility of a goal [55]. Some research provides preliminary support

that food-related television content could affect the accessibility of a hedonic eating goal for different consumers^[56]. Accordingly, the vividness of visualized NCE labels might increase the consumers' health accessibility. Therefore, we infer that health accessibility may also mediate the effect of the type of NCE labels (visualized vs. Numerical) on perceived healthiness.

We first conducted a priori analysis (effect size = 0.25, $\alpha=0.05$, and the desired power of 0.9) by Gpower software^[51]. The result revealed that 172 participants would be required. 182 (46.7% males, $M_{age}=24.64$) participants were recruited through printed advertisements on notice boards. First, participants were randomly assigned to two experimental groups, then they were presented with the stimulus material image and asked to read an instruction *"Suppose that you are planning to buy beverages, and just browse sparkling water beverage in the online shopping platform."*

Based on the pretest study, sparkling beverage was selected as material that stands out on the package. The two different NCE labels (visualized vs. numerical) were displayed on the package to convey the vitamin information. Visualized NCE labels quantified "vitamin content \approx 2.5 orange (photographs)". Numerical NCE labels showed "vitamin content \approx 268 mg". To rule out the influence of brand name, the fictitious brand name "Yi Chen" was adopted on the package (see Appendix B). The layout design and beverage package size were concordant under the two conditions.

Participants then indicated their perceived healthiness ($\alpha = 0.91$) and perceived tastiness ($\alpha = 0.91$). Meanwhile, participants rated the extent to which they thought the beverage was "pricey" and "expensive" ($1 = strongly disagree$, $7 = strongly agree$). These items were combined into a "perceived

price" composite. Perceived tastiness and perceived price ($r = 0.74$) were served as control variables.

Additional, participants were asked to indicate the extent to which they engaged in mental imagery^[57] on a seven-point Likert scale ($1 = not at all$, $7 = very much$) by four items ($\alpha = 0.91$; *"How vividly do you find nutritional label description on the picture of the product?" "To what extent do the pictures bring to mind concrete nutritional content?" "To what extent do the pictures of the product help you imagine nutritional content?" "To what extent do the pictures of product help you visualize nutritional content?"*).

Finally, we measured health goal accessibility as the alternative explanation.

By referring to the relevant research about goal accessibility^[58], we defined health goal accessibility, as the likelihood or availability that individual will achieve health. It was assessed by three items ($\alpha = 0.92$; *"Using this product increases the likelihood to achieve good health," "Consuming this product makes it easier for me to achieve my goal of getting closer to health," "This product ensures that I can get enough nutrients"*) on a 7-point scale ($1 = strongly disagree$, $7 = strongly agree$) (^[58]).

4.3 Results

4.3.1 Main effect

The one-way analysis of variance (ANOVA) revealed that when participants exposed to visualized NCE labels ($M_{visualized} = 4.72$, $SD = 1.29$) were perceived as healthier than when exposed to numerical NCE labels ($M_{numerical} = 3.82$, $SD = 1.32$; $F(1,181) = 21.81$, $p < 0.001$, $\eta_p^2 = 0.11$). The results indicated that consumers would exhibit greater perceived healthiness under the visualized NCE labels (vs. numerical NCE labels) condition, further verifying H1. The results was still significant ($F(1,181) = 13.34$, $p < 0.001$, $\eta_p^2 = 0.07$) when we controlled perceived price ($F(1, 181) = 6.09$, $p = 0.02$,

$\eta_p^2 = 0.03$) and perceived tastiness ($F(1, 181) = 29.96$, $p < 0.001$, $\eta_p^2 = 0.14$) as covariates.

4.3.2 Mediation analysis

The presentation of NCE labels (visualized vs. numerical) was taken as the independent variable, perceived healthiness as the dependent variable, and mental imagery as the mediator. Additionally, we included perceived tastiness and perceived price as control variables. We conducted a mediated analysis (model 4; 5,000 samples) using the PROCESS analysis with the bootstrap method (Preacher & Hayes, 2008). The results indicated that mental imagery could significantly mediate the effect of NCE labels on perceived healthiness ($\beta = 0.20$; 95% CI [0.08, 0.35]). The significance of the result ($\beta = 0.10$; 95% CI [0.01, 0.23]) was not altered when we controlled perceived price ($\beta = 0.3$, $p < 0.001$) and perceived tastiness ($\beta = 0.22$, $p = 0.1$) as covariates.

4.3.3 Alternative explanations

An independent-simple t test revealed that participants exposed the visualized NCE labels have higher health goal accessibility ($M_{\text{visualized}} = 4.09$, $SD = 1.24$; $M_{\text{numerical}} = 3.61$, $SD = 1.20$; $t(155) = 3.86$, $p < 0.05$) than numerical NCE labels.

Parallel mediation analysis (PROCESS Model 4 with 5000 bootstrapped samples) was used to explore the influence mechanism of NCE labels on perceived healthiness. Different types of NCE labels as an independent variable, perceived healthiness as the dependent variables, and mental imagery, health goal accessibility as parallel mediators. The results indicated that the effect of the type of NCE labels on consumers' perceived healthiness was not mediated by health goal accessibility ($\beta = 0.03$; 95% CI [-0.001, 0.103]) but can be mediated by mental imagery ($\beta = 0.18$; 95% CI [0.07, 0.33]).

This mediate effect of mental imagery remained significant even ($\beta = 0.09$; 95% CI [0.01,

0.21]) and the insignificance of the mediate effect of health goal accessibility ($\beta = 0.01$; 95% CI [-0.01, 0.07]) was not altered when we controlled perceived price ($\beta = 0.02$, $p = 0.73$) and perceived tastiness ($\beta = 0.19$, $p < 0.05$).

4.4 Discussion

The results not only offer more evidence for the proposition that the visualization of NCE labels boost perceived healthiness by mental imagery, but also show that health goal accessibility is not a viable alternative explanation. More specifically, the findings testify that compared with numerical NCE labels, visualized NCE labels would elicit more mental imagery, hence generating higher perceived healthiness, conforming to H2.

However, this study has several limitations. First, it is important to investigate the boundary conditions of the mediating effect of mental imagery and to explore the underlying mechanism in depth. Second, the participants of this study recruiting are young adults aged 18-30. In the following study, participants attend to broaden the age range of the subjects by removing age restrictions. Besides, we select another product category to expand the scope of applicability of this research.

5. Study 3: The Moderating Effect of Advertising Appeals

5.1 Pretest

A pretest was conducted to select bread as the stimuli of ambivalent healthy food. It is debatable whether bread is healthy food due to the uncertainty of the nutritional value of bread^[59]. Thus, we choose stimulus material from six kinds of bread (Multigrain Bread, Butter bread, White toast, Sourdough, Croissant, Wholemeal bread)^[30,31].

31 participants (64.52% males; $M_{\text{age}} = 24.65$) were recruited to measure ambivalent attitudes toward healthy food with two items (the same as

experiment pretest1). The finding showed the croissant was judged as the higher ambivalent attitudes of bread ($M_{\text{croissant}} = 4.87$, $SD = 1.66$; $M_{\text{Multigrain bread}} = 3.37$, $SD = 2.50$; $M_{\text{butter bread}} = 4.63$, $SD = 1.57$; $M_{\text{white toast}} = 4.79$, $SD = 1.49$; $M_{\text{sourdough}} = 4.82$, $SD = 1.85$; $M_{\text{Whole meal bread}} = 3.79$, $SD = 2.46$) contrast to other breads.

In addition, we conducted a second pretest to ensure the manipulation of type of advertising appeals successful. 60 participants (48.33% males; $M_{\text{age}} = 31.50$) were randomly assigned to two groups to be presented with different advertisements. Then they rated perceptions of each transformational appeals and informational appeals on a seven-point Likert scale ($1 = \text{strongly disagree}$; $7 = \text{strongly agree}$). It contained four items ($\alpha = 0.83$; “*This advertisement contains a lot of rational information*”, “*This advertisement mainly focuses on product attributes*”, “*This advertisement has a very strong appeal to my emotions*”, “*This advertisement mainly focuses on the experience of using the product*”). The first two items captured informational appeals, which focused on rational information and product attributes. The latter two items measured transformational appeals, which concentrated on emotions and experience^[45,38].

An independent sample t-test showed that participants significantly rated the ad higher on experiential and emotion ($M_{\text{transformational}} = 5.17$, $M_{\text{informational}} = 4.42$, $t(58) = 2.46$, $p < 0.05$, Cohen’s $d = 0.64$) under the transformational appeals condition than informational appeals. While under the informational appeals condition, participants significantly rated the ad higher on product attributes and rationality ($M_{\text{transformational}} = 5.23$, $M_{\text{informational}} = 4.70$, $t(58) = -2.27$, $p < 0.05$, Cohen’s $d = 0.58$) than transformational appeals. Thus, the manipulation of advertising appeals was successful.

5.2 Method

Study 3 was to test whether the advertising appeals might moderate the mediating effect of mental imagery in the impact of the NCE labels on perceived healthiness. We first adopted Gpower software^[51] to do a prior power analysis (effect size = 0.25, $\alpha = 0.05$, desired power = 0.90) and the result indicated 231 participants would be required. 330 participants (51.2% males, $M_{\text{age}} = 28.32$) were assigned to a 2 (advertising appeals: transformational vs. informational) \times 2 (type of NCE labels: visualized vs. numerical) between-subjects design.

All participants were assigned to two groups randomly and were told to browse different advertising. Two types of nutrition labels were displayed on bread packaging. Visualized nutrition label marked “protein \approx two egg (photographs)” advertising to quantify protein content in bread package, and numerical nutrition label marked “protein \approx 15.4g”. Moreover, advertising appeals were displayed by two different slogans. More specially, transformational appeals were depicted as “*Spend good time with your family in the morning and afternoon*”, while the informational appeals depicted as “*Strict selection process to select layers of materials ripe soft*”. To avoid other factors’ interference, the experiment of four group ads used the same layout and background image (see Appendix C).

Participants were then asked to complete the measures of perceived healthiness ($\alpha = 0.85$), mental imagery ($\alpha = 0.85$), perceived price ($r = 0.74$), and perceived tastiness ($\alpha = 0.86$) (the same as Study 2). Considering the effect of mood state on mental imagery processing^[60], we introduced emotions as a control variable. All the participants were asked to indicate their positive emotions ($\alpha = 0.82$; “joy,” “interest,” “surprise”) and negative emotions ($\alpha = 0.81$; “anger,” “disgust,” “contempt”) ^[60] for the

advertising on a seven-point Likert scale ($1 = \text{not at all}$, $7 = \text{to a great extent}$).

5.3. Results

5.3.1 Main effect

The one-way analysis of variance (ANOVA) showed that participants in the visualized NCE label condition reported a higher level of perceived healthiness ($M_{\text{visualized}} = 5.25$, $SD = 0.92$) than in the numerical NCE labels condition ($M_{\text{numerical}} = 4.64$, $SD = 0.97$, $F(1,329) = 33.99$, $p < 0.001$, $\eta_p^2 = 0.09$). Therefore, the visualized NCE nutrition labels (vs. numerical NCE nutrition labels) were more likely to trigger consumers' higher perceived healthiness, further conforming to H1. The significance of the results were not altered ($F(1,329) = 11.79$, $p < 0.001$, $\eta_p^2 = 0.04$) when we controlled perceived price ($F(1,323) = 7.75$, $p < 0.05$, $\eta_p^2 = 0.02$), perceived tastiness ($F(1,329) = 62.10$, $p < 0.001$, $\eta_p^2 = 0.16$), positive emotions ($F(1,329) = 56.21$, $p < 0.001$, $\eta_p^2 = 0.15$) and negative emotions ($F(1,329) = 2.79$, $p = 0.10$, $\eta_p^2 = 0.01$) as covariates.

5.3.2 Mediation analysis

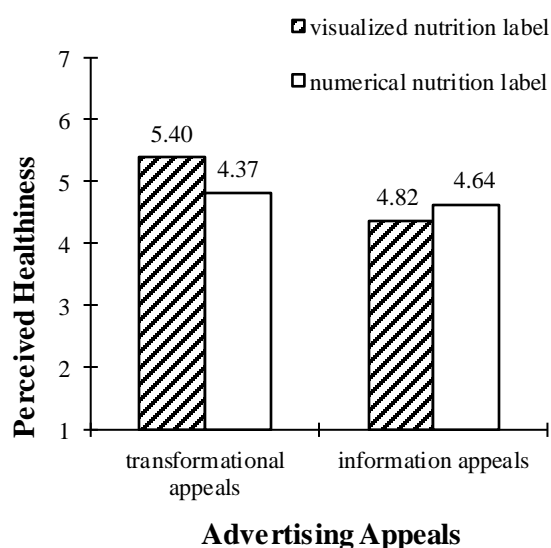


Figure 3 The Moderating Role of Advertising Appeals

The type of NCE labels was taken as the independent variable, perceived healthiness as the

dependent variable, and mental imagery as the mediator. To examine the mediating role of mental imagery in the effect of the NCE labels on perceived healthiness, we adopted the PROCESS model 4 with 5,000 bootstrap samples (Hayes, 2013). The results revealed that a 95% confidence interval (CI) for the indirect effect was significant and excluded zero ($\beta = 0.22$, 95% CI [0.14, 0.30]). Thus, the results demonstrated that mental imagery significantly mediated the impact of the NCE labels on perceived healthiness, further confirming H2. The significance of the results was not altered ($\beta = 0.04$; 95% CI [0.01, 0.08]) when we controlled perceived price ($\beta = 0.05$, $p = 0.13$), perceived tastiness ($\beta = 0.13$, $p < 0.05$), positive emotions ($\beta = 0.23$, $p < 0.001$) and negative emotions ($\beta = -0.03$, $p = 0.15$).

5.3.3 Moderated mediation analysis

A two-way ANOVA analysis indicated that the interaction between the type of NCE labels (visualized vs. numerical) and advertising appeals (transformational appeals vs. informational appeals) on mental imagery was significant ($F(1,329) = 15.07$, $p < 0.001$, $\eta_p^2 = 0.04$). Further simple effect tests showed that in the transformational appeals condition, the mental imagery scores of participants under visualized NCE labels condition were significantly higher than those under the numerical nutrition labels ($M_{\text{visualized}} = 5.40$, $M_{\text{numerical}} = 4.37$, $F(1,326) = 45.30$, $p < 0.001$, $\eta_p^2 = 0.04$). Consumers are more likely to generate mental imagery when they are exposed to visualized NCE labels (vs. numerical NCE labels). In the informational appeals condition, there was no significant difference on mental imagery between the two types of NCE labels ($M_{\text{visualized}} = 4.82$, $M_{\text{numerical}} = 4.64$, $F(1,326) = 1.48$, $p = 0.23$, $\eta_p^2 = 0.01$) (see Figure 3). The significance of the above interaction results was not altered ($F(1,329) = 4.54$, $p < 0.05$, $\eta_p^2 = 0.01$) when we controlled perceived price ($p <$

0.05), perceived tastiness ($p < 0.05$), and emotions ($p < 0.05$) as covariates.

Next, we conducted a moderated mediation analysis through Bootstrap analysis (PROCESS Model 7; 5,000 samples; Hayes, 2013). The results showed that the moderated mediation effect of the advertising appeals was significant ($\beta=0.30$, 95% CI [0.15, 0.47]), which confirmed that the advertising appeals significantly moderated the mediating role of mental imagery in the effect of the type of NCE labels on perceived healthiness. More specifically, the indirect effect of mental imagery was significant under the transformational appeals ($\beta = 0.37$, 95% CI [0.26, 0.49]), while the indirect effect was not significant under the informational appeals ($\beta = 0.07$, 95% CI [-0.05, 0.18]). The significance of the above result was not altered ($\beta=0.06$, 95% CI [0.01, 0.13]) when we controlled perceived price ($\beta = 0.05$, $p < 0.001$), perceived tastiness ($\beta = 0.13$, $p < 0.05$), positive emotions ($\beta = 0.23$, $p < 0.001$) and negative emotions ($\beta = -0.03$, $p = 0.15$) as covariates.

5.4 Discussion

The results confirm that the advertising appeals could serve as a boundary condition of the mediating effect of mental imagery in the impact of the type of NCE labels on perceived healthiness, supporting H3 and H4. Specifically, in the transformational appeals condition, visualized NCE labels induce more mental imagery than numerical NCE labels, which consequently triggers higher perceived healthiness. Nevertheless, in the informational appeals condition, visualized NCE labels have no significant difference on mental imagery and perceived healthiness, compared with numerical NCE labels.

6. General Discussion

In this research, NCE labels are proposed from a unique equivalent perspective, and different types of NCE labels (visualized vs. numerical) exert a

significant impact on perceived healthiness (Study 1). We further investigate the mediating process by which the mental imagery evokes (Study 2). Finally, we also address the boundary condition of this mediating effect (Study 3). Specifically, under the transformational appeals condition, visualized (vs. numerical) NCE labels can induce more mental imagery and further higher healthiness perception; but in the informational appeals ads condition, the two types of NCE labels have no significant difference.

6.1 Theoretical contributions

This research makes several theoretical contributions. First, this study has made the first attempt to propose the concept of NCE labels. Furthermore, we explore which type of NCE labels (visualized vs. numerical) is more effective in improving consumer perceived healthiness, expanding the literature on nutrition information. Prior studies have examined numerical nutritional equivalent labels, few studies focus on the visual equivalent labels and mostly limit to negative nutrition labels, such as sugar^[17] or calories^[16]. Our research addresses this research gap by investigating the effect of NCE labels (visualized vs. numerical) on perceived healthiness. The results showed that visualized NCE labels could lead to higher perceived healthiness than numerical NCE labels. Accordingly, the proposal of type of NCE labels in this study perhaps offers new insights to literature about quantified nutrition labels.

Second, we introduce mental imagery as an inner mechanism underlying the effect of NCE labels on perceived healthiness. Drawing on mental imagery theory, individuals mentally represent recognition presented in terms of past experience and prior perceptual process information^[25], and the mental imagery could affect attitude and behavior^[9,26,11].

Moreover, Existing research has proved that the product presentation form (picture vs. text) as stimulus affects consumers' imaginations^[11]. Taking the above into consideration, we explore the different presentation of NCE labels (visualized vs. numerical) on the perceived healthiness by introducing mental imagery as the mediating mechanism. Our results have demonstrated that, the specifically equivalent nutritional information of visual labels displayed in the form of pictures, can activate the memory in consumers' minds and easily make consumers comprehend the equivalent content than numerical labels. Therefore, this paper bridges the research between nutrition labels and psychological healthy perception from the new perceptive of mental imagery.

Third, we contribute to the match-up hypothesis by revealing the advertising appeals as a boundary condition for the effect of type of NCE labels on mental imagery. Prior studies about moderating roles of mental imagery influence are limited to individual traits^[10,11], mostly overlooking the roles of the advertising aspects. Based on the match-up hypothesis, our evidence suggests that consumers' perceived healthiness responses to the type of NCE labels depend on advertising appeals. More specifically, when transformational (vs. informational) appeals are matched with the visualized (vs. numerical) NCE labels, it could easier to trigger mental imagery and thus enhance perceived healthiness. That is, our research demonstrates that the mediating effect of mental imagery in the impact of the NCE labels on consumers' perceived healthiness is moderated by the relevant advertising appeals. Hence, this study advances the theoretical content of the match-up hypothesis by demonstrating the interaction between advertising appeals and the type of NCE labels.

6.2 Practical implications

This study also has several practical managerial implications. First, marketing managers or manufacturers can adopt NCE labels, especially visualized NCE labels to convey nutrition information. For example, currently, beverage manufacturers provide NFC (not-from-concentrate) juice, such as "Nong fu Spring". It employs visualized labels with packaging describing "Mango blended juice was equal to four mango and two apples", and four mangoes and two apples are shown through cartoon pictures. Nevertheless, numerous marketers still employ numerical presentation to display nutritional content from product packaging. Thus, manufacturers or marketers should be proactive in adopting visualized nutrition labeling strategies to improve consumers' feeling of health towards products.

Second, activating mental imagery of healthy food may be a novel and particularly flexible approach to improve consumer perceived healthiness. Our results show that mental imagery mediates the effect of the type of NCE labels on perceived healthiness. This study helps marketers understand deeply how consumers process nutrient presentation associated with mental imagery cognitively, further improving the perception of healthiness strategically. Enterprises could design NCE labels in packing or advertisements, which benefit to trigger consumers' mental imagery, further improving perceived healthiness. Specifically, marketers could use other visual cues to stimulate consumers' mental imagery. For example, traditional elements, such as Auspicious cloud pattern, traditional craft on the packaging may could trigger more mental imagery on past experience, further improving our healthiness.

Third, our results have identified that the NCE labels and advertising appeals are both important

factors triggering consumers' perceived healthiness. Marketers should stress tailored advertising appeals matching the appropriate type of nutrition labels. For example, a product with visualized nutrition labels could be more consistent with transformational advertising appeals (e.g., "Your home away from home" of Starbucks slogan), which could evoke consumers' mental imagery and enhance perceived healthiness more effectively. Overall, beverage companies should formulate corresponding marketing strategies for different types of advertising appeals and nutrition labels respectively.

Fourth, this study has public policy implications for governments and public health departments in improving consumers' perceived healthiness. As unhealthy eating has become an important factor threatening consumers' health, "nudge" becomes an important and predictable tactic to varying consumer's behavior with no options or economic incentives altered^[61]. Visualized NCE labels as a means of nudge can help consumers select healthier food, and the government and public health departments should extend to adopt this nudge intervention to guide consumers to healthier eating and consumption.

6.3 Limitations and Future Research

This study takes a unique angle about the effects of the type of NCE labels and advertising appeals on mental imagery and perceived healthiness. However, this research has some limitations. First, future research could optimize the design of NCE labels by other methods. It remains open to investigate whether there have other foods (vegetables) to equate to nutrition content. Whether the picture size for the visualized labels could vary and still obtain the same outcome. Beyond that, researchers could extend the NCE labels to other decision-making contexts, such as restaurant menus.

Second, we should investigate more boundary conditions of the mediating effect of mental imagery. For example, several individual factors such as cognitive style^[62], style of processing^[11] or subjective numeracy^[63] might moderate the mediating effect of mental imagery. Prior research has found that consumers' style of processing (SOP) moderates the relationship between the concreteness of pictures and mental imagery^[11]. When consumers are visualizers (the high SOP) could trigger more mental imagery than verbalizers (low SOP) in visualized nutrition labels group than numerical labels. Future research should probe into whether consumers' style of processing moderates the effect of the NCE labels on perceived healthiness.

Further, this research merely takes account of the effect of NCE on perceived healthiness in laboratory environments, not in a real consumption context. In addition, this study only provides the linkage between the nutrition labels and consumers' cognition (perceived healthiness), not on the actual behavior. Future studies would carry out field studies to explore whether the NCE labels can nudge real food choice and purchase behavior to increase external validity. Specifically, we may cooperate with universities or shopping malls to observe the real purchase intention and behavior in the future.

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Research on the Influence Mechanism of Perceived Quality of Subsidy Policy on Consumers' Purchase Intention of Household Photovoltaic -- Based on the Moderating Effect of Peer Effect and the Mediating Effect of Policy Trust

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Abstract: This paper measures the perceived quality of Household Photovoltaic subsidy policy from the two dimensions of perceived benefits and perceived stability of policy, and introduces policy trust as mediating variables and peer effect as moderating variables respectively. Based on 362 samples from 16 provinces and cities from China, combined with scenario simulation and questionnaire survey, this paper explore the intention mechanism of how the perceived quality of HPV subsidy policy impact on consumer purchase intention. The empirical results show that: (1) Perceived benefits and stability of subsidy policy have a significant positive impact on both policy trust and consumer purchase intention, and policy trust plays a partial mediating role between perceived quality of subsidy policy and consumer purchase intention; (2) Peer effect plays a positive moderating role in the two paths of "policy perceived quality—policy trust" and "policy perceived quality—consumer purchase intention"; (3) Compared with the passive peer effect, the positive guidance of the active peer effect is greater; compared with the offline peer effect, the online peer effect is more influential. The research results can provide reference for improving the consumer perception quality of subsidy policy, enhancing the purchase intention and improving policy diffusion efficiency of Household photovoltaic.

Key words: perceived quality of subsidy policy; policy trust; peer effect; purchase intention; household photovoltaic

Introduction

China has pledged to the world in 2020 to achieve carbon peak by 2030 and carbon neutralization by 2060. As the world's largest energy consumer and emitters, high carbon emission intensity results from the unreasonable resource structure^[1]. Clean energy should be developed urgently to replace fossil energy consumption in order to relieve the unprecedented pressure of the emission reduction^[2]. Household energy consumption is an important part of China's energy consumption; using clean and renewable household photovoltaic (HPV) devices to reduce carbon emissions in household energy consumption has become a heated topic for research in energy conservation and environmental protection.

In order to promote HPV devices coverage in the market, China has designed a series of stimulating

policies in recent years. Especially since 2012, Chinese government at all levels have been releasing plenty of subsidiary policies to stimulate HPV device purchase. Yet to their disappointment, though China has the largest installed photovoltaic power (PV) capacity in the world, its HPV installation accounts for only 1‰ of the world, which is only 1/50 of Germany, the United States and other main photovoltaic power using states, far from the expected policy goals and effects^{[3][4]}.

Theoretically, the earliest study on the effects of HPV subsidy policies dates back to 1995, which indicated that high-quality government subsidy policies will promote the HPV diffusion in the market and stimulate companies to develop and innovate on HPV technology at the same time. Subsequent research results of related scholars have maintained such views. However, the latest research findings say that the

effects of the subsidy policies varied significantly depending on the development stage of the PV market, and that not all policies will have positive effects and inappropriate policy promotion may have negative effects. For this, a few scholars have further tried to study the policy effects from the perspective of policy quality, which also led to the conclusion that low-quality policy implementation often results in ineffective or even negative effects. Meanwhile, it remained to be answered for the scholars why there can be negative or even suppressing effects and how the subsidy policy mechanism works.

Unlike traditional energy subsidy policies, which target manufacturers and enterprises, HPV subsidy policies face household consumers, who will be the end users that benefit from the cost and profit of the policy. Therefore, the study of the HPV subsidy policy effects should be based on the consumers' perspective. According to the theory of cognitive psychology, the consumers' judgment on external factors often depend on their psychological perceptions inside, which means that the consumers' perception quality is the main factor influencing their responses and comments of the policies; however, regarding the policy perception quality from the consumers' perspective, there has not been clear definition or empirical research academically, and there is not enough attention to the interaction with consumers in the HPV product diffusion. Based on this, this paper introduces peer effects from the perspective of consumers' perception quality to investigate the microscopic mechanism of how current consumption perception quality of subsidy influences HPV purchase, and is set to improve HPV policy quality, reduce policy implementation loss, and effectively promote the efficiency of HPV diffusion.

1 Review of related studies

There is a general consensus among academics to take the policy receivers' judgment of a policy's value

as a criterion to measure policy quality, and the diversity of their value preference and evaluation criteria will lead to difference in the perception quality of the policy^[5]. Therefore, the academics have looked into the measurement criteria of policy perception quality. Some scholars measure from the perspective of policy characteristics, from the six dimensions of the policy: efficiency, effectiveness, fairness, richness, appropriateness, and responsiveness; while some others take it an important indicator of policy quality to see whether the policy maximizes the social benefits is, and further measures whether the policy meets the recipients' expectations of and whether it has practical effects. However, as the government's macro-control tool to support a specific industry with end-consumers as the recipients, the academics tend to see whether the subsidy policies meet the consumers' expectations and satisfy their needs as the evaluation index of policy perception quality.

The consumers' purchase behavior is influenced by a series of policies introduced by governments at all levels, and the behavior consists of five stages of problem identifying, information collecting, psychological perception, purchase decision, and post-purchase behavior, and perception quality can significantly influence consumers' purchase decision. Therefore, academics have tried to explore the relationship between consumers' perceived value and purchase intention from the perspective of perception quality, and found that consumers' perception quality is positively related to their perceived value and thus enhances the purchase intention. Further findings reveal that perception quality is also positively related to consumers' satisfaction, and the effect of consumers' satisfaction, which act a promoting role on their purchase intention has been generally recognized by the academics. Customers tend to purchase or respond to products or

policies with higher perception quality. Therefore, the consumers' purchase decision is influenced by their perception quality, and the effect of perception quality is more significant when consumers consider to re-purchases.

The effect of policy implementation depends on not only the policy itself, but the degree of policy promotion, and policy trust is a prerequisite for policy promotion. It is the policy receivers' certain psychological expectation of a policy's effectiveness, which is their recognition and support of the policy. Meanwhile, the perceived risk in the purchase process makes trust a concerned topic in marketing. On the relationship marketing level, the academics believe that trust is closely related to consumers' purchase intention, the stronger the trust, the weaker perception of risk and higher purchase intention. As sharing economy and green new energy products emerge, the academics has slowly switched their focus from the relationship between trust and consumers' behavior to green trust in the renewable energy area. The dual attributes and complexity of HPV not only promote the reform the means of policy subsidy, but also make the consumers' psychological cognitive processes about policies and products more complicated. As a result, building trust when the policies are interacting with consumers has become a key step. It requires more attention on whether the policies trusted by consumers can bring benefits to them and what types of policies are easier to build trust in consumers.

The consumers' trust in policies and purchase behavior are both influenced by peer effects, which points out that individual behavior is influenced by peers in equal social relationships to a certain extent. Factors like other people's decisions and the environment around can affect the consumers' purchase decisions. For example, as new technologies spread in the market, the neighbors' adoption of new

technologies makes them spread faster. The academics have further classified peer effects into two dimensions. Some classified the peer effects into positive and negative aspects and argue that the negative one has a more significant impact on the consumers' decision. Some argued that peer effects contain active and passive aspects, but the variables are difficult to define and measure, so only a few have tried to explore the heterogeneity between the active and passive peer effects, and said that the active is more important than the passive.

In summary, the subsidy policies have a significant influence on HPV purchase intention, but consumers' perception as an important antecedent of purchase decision has not been explored academically in depth. During the HPV diffusion, the policy has been focusing on improving the economical performance, but ignored the importance of building trust in the market and in the consumers. The product innovation and upgrade alone will not actively promote HPV diffusion, and the policy intensity or stability cannot measure consumers' perception of the policy favorable aspects and stability. Meanwhile, existing studies have shown that peer effects significantly affect the consumers' HPV purchase behavior, but few have explored how different types of peer effects influence product diffusion while most of them have explored from a single perspective. Therefore, it is necessary to analyze the current HPV subsidy policies effects in China and verify the peer effects' mechanism in innovation products diffusion from the perspective of consumers' perception quality of subsidy policies.

2 Theoretical analysis and research hypothesis

2.1 Subsidy policy perception quality

2.1.1 Subsidy policy perception quality and dimension division

Based on the perspective of maximized the

perceived value, the consumers' perceived value of policies comes from whether the subsidy policies can satisfy their interests and needs, so consumers will pay more attention to how favorable the policies are, which is one important criterion for them to evaluate the policy quality. Meanwhile, based on the perspective of minimize the perceived risk, the public tends to accept the policy with the least perceived risk and measure it by the stability of the policy itself. Unstable policies will make the users to doubt about higher perceived risk for relevant policies; high-quality subsidy policies on the other hand, tend to be stable and will not change too much or too frequently in implementing and adjusting; if there is any damage caused by the change of the new policy, the residents will be compensated to a certain extent. Based on this and relevant studies, this paper defines the policy perception quality as follows: it is a kind of subjective evaluation by consumers on whether the current subsidy policies meet their expectations and satisfy relevant needs, and subsidy policy perception quality is to be evaluated by two dimensions of policy perceived benefit and policy perception quality is measured in two dimensions: policy perceived benefit and policy perceived stability, among which the former refers to whether the policy meets the recipients' needs and interests and whether there is financial or social benefits while the latter refers to whether the policy has a clear period for implementation, whether there are new changes during the implementation and whether such changes have any impact on the original policy recipients.

2.1.2 The impact of subsidy policy perception quality on HPV purchase intention

Wüstenhagen & Bilharz found that the tax exemption policy for green power purchase in the United States has significantly reduced the cost for consumers and successfully stimulated their green consumption behavior and increase the share of

renewable energy utilization; empirical studies from the environmental protection field shows similarly that if subsidies for end-consumers are less than those for research and development and manufacturing sectors, the consumers' policy perception quality will be lower, which affects the energy-efficient and environmentally friendly devices diffusion in the market. At the same time, keeping a policy stable in a long-term in implementation is a key for effective policy frequent policy changes, updates, inconsistency can result in poor policy implementation or even failure. And consumers will have doubts and high-risk perception, which will make them significantly less motivated to be a part and the policy to run at a high cost and low quality. On the contrary, a continuously stable policy reduces the perceived risk of the recipients while accelerating their response to the policy, implementation and gets good policy results.

Based on the above research results, it is clear that policy receivers have different perceived benefits and perceived stability, which leads to different attitudes and consumption behaviors towards policy. Thus, this paper hypothesizes that.

H1: HPV subsidy policy perception quality (perceived benefit and perceived stability) significantly affects consumers' purchase intention of HPV.

2.2 Policy trust

Consumers' support, satisfaction and their degree of belief in the series of governmental policies is called policy trust, which is a psychological expectation and perceived evaluation of the policy target group for the policy effective formulation, implementation and solution of social problems.

Consumers' perception and evaluation of the quality of objective things is one of the antecedents that influences their trust; the higher the perceived value of the policy, the more trust and satisfaction they have for the policy and perception quality and consumers' trust

jointly influence consumers' purchase decision.

Fonseca and other researchers looked into the relationship between consumption behavior and law and government and concluded that national policies and laws greatly influence people's willingness and behavior, and that the public trust in policies largely depends on how much they satisfy public needs and whether they are reasonable and stable. Scholars including Verma and Xie have conducted empirical analysis on new energy product purchase intention, which shows that consumers' trust of relevant policies can greatly promote their purchase or use of new energy products, and the government's improved supporting policies can effectively reduce the resistance and risk perception of the products and thus help a rapid market diffusion.

Drawing on the above research results, this paper argues that residents' perception quality of HPV subsidy policies can have a direct impact on the consumers' purchase intention, and through enhancing the path of policy trust, there can be an indirect impact on the consumers' purchase intention. Thus, this paper hypothesizes that:

H2: HPV subsidy policy perception quality (perceived benefit and perceived stability) has an impact on consumers' purchase intention through policy trust.

2.3 Peer effects

2.3.1 The connotation of peer effects and how it affects purchase intention

In 1983, scholars including Paul found that a person's behavior is influenced by individual's peers such as neighbors or friends, and this is peer effects. Wang defined peer effects as responding similarly when a participant has been influenced by others, which is a self-decision responses in the face of others' influence, a phenomenon in which individual behavior changes to a certain extent along with the changes in

the group behaviors. Peer effects arise mainly from information asymmetry, the difficulty in collecting effective information and the rising cost, and individuals need to rely on the information feedback and behavior of their peers to make decisions. In terms of purchase intention and decision making for green products, Brisol & Mangleburg and Ha & Janda found that peer decision making can significantly influence an individual's decision making, and the ease and frequency of communication among peers allows buyers to have more information about channels, technology, product features, and use; due to the similarity of attributes and external environment among peers, individual decision making tends to refer to or follow peer behavior or even directly duplicate peer behavior.

2.3.2 Active peer effects a negative peer effects

Based on the perspective of active information exchange, peer effects can be divided into two types, active and passive; individual decision makers who actively communicate with peers about relevant products and information are called active while those being aware of peers' relevant activities through observation or in other ways (like seeing a neighbor installing an HPV device) are passive. Since most HPV devices are installed outdoors, the purchase and use of HPV are easily noticed by in the neighborhood, so it's mostly passive in HPV peer effects.

The differences in the influence of different types of peer effects on consumer purchase decision have not been final in research. Rai & Robinsonv found no significant differences, while a comparative study by Palm & Alvar showed that the majority of residents who had installed HPV believed that seeing an HPV (passive) may not lead to changes in their own ideas or attitudes, and proactive communication with other users was more important for their decision to install their own HPV.

Considering HPV's high upfront costs, the various overflow information and complex installation process, passive and active peer communication vary quite much in terms of policy understanding and information collecting, and the effects on policy trust and the final HPV purchase decision may also be very different. So based on the research results of Palm & Alvar et al., this paper further divides the two types of active and passive, and define that in the HPV purchase process, residents are active when they communicate with other community groups, like talking face-to-face, online through WeChat and QQ or in community or village meetings, to learn about the product, the subsidy policies and the purchase experience; individuals who hear or see that the residents in the neighborhood had

purchased and installed HPV but do not communicate with them further are passive. Here are the hypothesis:

H3: peer effects (Active vs. Passive) can adjust the influence of policy trust in HPV subsidy policy perception quality (perceived benefit and perceived stability)

H4: peer effects (Active vs. Passive) can adjust the influence of HPV purchase intention in perception quality (perceived benefit and perceived stability)

Based on the analysis above, this paper uses policy trust as a mediating variable, peer effects as a moderating variable, and gender, age, occupation, and education as control variables to build a theoretical model.(As shown in figure 1)

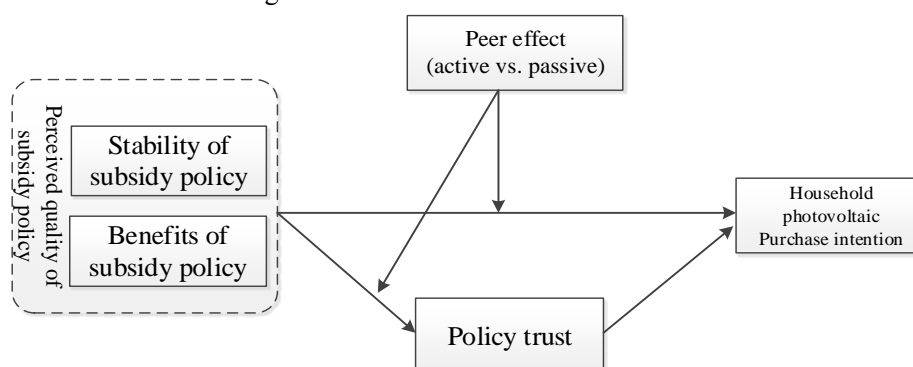


Figure 1 Theoretical model

3 Research design

3.1 Questionnaire design and data collection

3.1.1 Questionnaire design

The main three parts of the questionnaire are scenario simulation, variable measurement, and basic

information statistics. The key variables of concept definition and measurement are borrowed from existing research outcomes. Likert scale is used to measure the research variables, and the specific information borrowed is shown in Table 1.

Table 1 Main variable concepts and measurement reference table

Variable	Content	Reference
policy perception	Concept definition	Fan and Zhang, Peng et al. 、 Zhao and Zheng (2019)
quality	Dimension division	
policy trust	Concept definition and variable measurement	Chen, Zhang
peer effects	Concept definition and type division	Rai & Robinson and Palm & Alvar
HPV purchase intention	questionnaire design and measurement scale	Dodds, Grewal & Monroe

The specific scenarios of the different types of peer effects in this paper are based on existing theoretical research results, internal group discussions, and in-depth interviews with 10 HPV purchasers, and were revised and refined regarding the scenario content, dimensions, and order of the questions.

After the initial questionnaire was completed, we consulted the policy-making and implementation staff of Jiangsu, Henan, Shandong provinces and six experts in the fields of consumer behavior, energy policy, and economic management research to comment on the variable selection, operational definitions, and the specific questions in the questionnaire for a revised questionnaire; finally, we randomly invited 15 household users to fill in the questionnaire for a trial period and revised the wordings and the confusing parts according to their feelings and opinions to form the final questionnaire of this paper.

3.1.2 Data collection

In this paper, we collected 382 questionnaires

from February 2020 to May 2020 by using the online platform of "WIX.cn". After excluding 18 questionnaires with short response time, inconsistent answers and obvious abnormalities, we collected 362 valid questionnaires that covered 16 regions in China including Jiangsu, Anhui, Hebei, Xinjiang, Shanghai, Shaanxi, Heilongjiang, Zhejiang, Ningxia, Chongqing, and Beijing. The proportion of male and female in the valid samples was 52.49% and 47.51%, respectively, and the age covered between 20-60 years old, of which 54.7% were aged 30-55, which are the main age range of HPV purchasers; the proportion of permanent residence in rural and urban areas was 57.46% and 42.54%, respectively; and the proportion of rural self-constructed houses, urban commercial houses and villa was 45.86%, 44.75% and 0.55%.

3.2 Reliability and validity test

This paper uses SPSS for reliability and validity test and the outcome is as follows:

Table 2 Reliability and validity test results

variables	Specific questions	Alpha after deletion	F	α	CPV		
Overall KMO of the questionnaire: 0.913							
policy perception quality	perceived benefit	HPVSP gives me discounts in the purchase	0.734	0.647	0.892	15.737	
		HPVSP lowers my cost of purchase	0.723	0.804			
		HPVSP shortens my investment period	0.798	0.717			
		HPVSP helps with environment protection	0.789	0.582			
		I think HPV subsidy amount won't change randomly	0.818	0.853	0.858	29.000	
	perceived stability		I think HPVSP's period won't change randomly	0.815			0.845
			I think new HPVSP won't affect the benefit for those who have installed	0.835			0.512
			I think HPVSP will last a long time	0.814			0.565
	policy trust		I believe HPVSP to be true	0.865			0.727
			I think HPVSP benefit the society	0.869	0.691		
		I think HPVSP will be performed as planned	0.867	0.733			
		I think HPV governmental subsidies will be given as promised	0.885	0.805			
purchase intention		I'm very interested in HPV products	0.914	0.757	0.892	73.388	
		I'm willing to recommend tommy friends HPV products and policies	0.894	0.817			
		I'm willing to purchase HPV products	0.899	0.871			
		I'm willing to recommend purchase HPV products	0.896	0.855			
		I'm willing to share my use experience	0.923	0.836			
Overall		0.924					

Note: HPV stands for Household Photovoltaic and HPVSP stands for household photovoltaic subsidy policy

Table 2 above shows that, all variants have Cronbach's $\alpha > 0.8$, which indicates the high overall reliability of the questionnaire; the α value of each variable after deleting is smaller than before, which means that the questionnaire is scientifically reasonable. The overall KMO value is 0.913, and the Bartlett's test

of sphericity is 0, indicating that the overall internal consistency of the questionnaire is high; the factor loading coefficient of specific question items was > 0.5 , indicating that there was no collinearity among the variables. The overall interpretation rate of the questionnaire was 73.388%, which means that the

variables in this questionnaire well explain the research questions.

4 Empirical result and discussion

4.1 control variable test

To obtain the influence of the basic characteristics

of the sample statistical variables on the research questions, this paper adds control variables and uses the ANOVA method to explore the control variables effects of different paths in the theoretical model, the results of which are shown below.

Table 3 One way ANOVA of control variable to research variables

variable	Gender		Age		Education		Occupation	
	F	S	F	S	F	S	F	S
Policy perceived benefit	0.035	0.563	3.729	0.120	0.288	0.885	0.744	0.615
Policy perceived stability	0.07	0.792	3.495	0.171	1.603	0.176	1.971	0.172
policy trust	0.002	0.969	0.899	0.132	0.424	0.791	0.604	0.727
purchase intention	0.660	0.418	1.622	0.186	0.678	0.608	1.636	0.140

Table 3 shows that test results for consumers' gender, age, education and occupation are not significant, which means these variables will not affect consumers' policy perceived benefit, policy perceived stability, policy trust and purchase intention, and they will not be included in the analysis later.

4.2 The main effect test for subsidy policy perception quality on consumers purchase intention

The relationship between consumers' HPV subsidy policy perception quality and purchase intention is examined using SPSS22.0 and single-factor regression analysis.

Table 4 Regression analysis of perceived quality of subsidy policy on purchase intention

dependent variable : consumers purchase intention						
Model		Unstandardized Coefficients		Standardized coefficients	t	S
		β	SE			
Model 1	Constant	1.210	0.214		5.664	0.000
	Policy perceived	0.754	0.078	0.588	9.720	0.000
Model 2	Constant	1.600	0.190		8.414	0.000
	Policy perceived	0.660	0.074	0.553	8.882	0.000

According to the test results of Model 1 and Model 2 (Table 4) above, it is clear that subsidy policies perceived benefit, subsidy policies perceived stability both significantly affects consumers purchase intention ($\beta=0.588$, $p=0.000<0.05$; $\beta=0.553$, $P=0.000<0.05$), indicating that the higher the perception quality of HPV-related policies, the greater the purchase intention

of the residents. Further comparison analysis revealed that the promotion effect of policy perceived benefit on consumers' purchase intention was more significant than the promotion effect of policy perceived stability ($0.588>0.533$). This indicates that the degree of benefit brought by policy subsidy to consumers is more significant than the stimulating effect of policy stability

on the purchase of HPV products now.

Bootstrap to test the policy trust' mediating effect and the result follows.

4.3 the mediating effect of policy trust

Based on the test results above, this paper uses

Table 5 Test results of mediating role of policy trust (1)

independent variable	effect coefficient	t	p	lower limit	upper limit	dependent variable
PPB and PC influence on PI						
constant	0.617	2.595	0.010	0.148	1.087	
PPB	0.457	4.724	0.000	0.266	0.648	
PC	0.477	4.708	0.000	0.277	0.677	
PPB's direct influence on PI with mediating control						PI
PPB	0.457	4.724	0.000	0.266	0.648	
PC's indirect influence (mediating effect)						
PC	0.297	-	-	0.143	0.474	
PPB's overall effect on PI						
PPB	0.754	9.72	0.000	0.604	0.907	

Note: Model4 (simple mediation analysis model), Y: PI (purchase intention), X: PPB (policy perceived benefit), M: PC (policy trust).

The analysis results (Table 5) show that the mediating path of PC holds and is significant. Between PPB and PI, the mediating effect of PC does not include 0 in the 95% confidence interval, representing a significant effect of PPB on PI through PC with an indirect effect of 0.297. After controlling for the mediating variable PC, the effect of PPB on PI is also significant with a direct effect of 0.457, so the total

effect of policy PPB on consumers The total effect of PI is 0.754 (0.297+0.457, 95% confidence interval does not include 0), indicating that PC is partially in the process of PPB's effect on consumers' PI. The mediating effect holds, which means the higher the perceived benefit of the policy and the higher the trust of the policy, the more it stimulates higher purchase intention of the consumers.

Table 6 Test results of mediating role of policy trust (2)

independent variable	effect coefficient	t	p	lower limit	upper limit	dependent variable
PPS and PC influence on PI						
constant	0.772	3.296	0.001	0.309	1.234	
PPS	0.366	0.088	0.000	0.193	0.540	
PC	0.534	0.099	0.000	0.338	0.729	PI
PPS's direct influence on PI with mediating control of PC						
PPS	0.366	4.166	0.000	0.193	0.540	
PC's indirect influence (mediating effect)						
PC	0.293	-	-	0.096	0.479	
PPS's overall effect on PI						
PPS	0.659	8.882	0.000	0.513	0.806	

Note: Model 4 (simple mediation analysis model), Y: PI (purchase intention), X: PPB (policy perceived stability), M: PC (policy trust).

The analysis results (Table 6) shows that between PPS and PI, the 95% confidence interval of the mediating effect of PC does not include 0, representing a significant effect of policy perceived stability PPS on consumers purchase intention PI through policy trust PC, with a mediating effect coefficient of 0.293. controlling for the mediating. After PC, the effect of PPS on PI is also significant with a direct effect of 0.366, representing a total effect of PPS on consumers PI of 0.659 (0.293+0.366, 95% confidence interval excluding 0). Thus, PC also plays a partially mediating role in the effect of independent variable PPS on dependent variable consumers PI.

Consumers' perception quality of policy consists of policy perceived stability and perceived benefit, and combining Tables 5 and 6, it is easy to find that policy perception quality not only has a direct effect on consumers' purchase intention, but also indirectly influence HPV product purchase intention through

policy trust, which means policy perceived stability and affordability enhance consumers' purchase intention by positively influencing policy trust.

4.4 Peer effects impact

4.4.1 The regulating effect of peer effects

To examine the regulating effects of peer effects, this paper borrows from the relevant research and built evaluation model of subsidy policy perception quality's influence on policy trust as the following:

$$PC = A_0 + A_x PPB + A_w PE + A_{xw} PPB \times PE + \varepsilon_1 \quad (1)$$

$$PC = A_0 + A_x PPS + A_w PE + A_{xw} PPS \times PE + \varepsilon_1 \quad (2)$$

The model of subsidy policy perception quality's direct effect on consumers purchase intention:

$$PI = \beta_0 + \beta_x PPB + \beta_w PE + \beta_{xw} PPB \times PE + \varepsilon_2 \quad (3)$$

$$PI = \beta_0 + \beta_x PPS + \beta_w PE + \beta_{xw} PPS \times PE + \varepsilon_2 \quad (4)$$

In formula (1)-(4), PE stands for peer effects, while PC, PPB, PPS and PI are the same as mentioned. Bootstrap empirical results are as the following.

Table 7 The results of the moderating effect test of peer effect PE

Y		Policy trust PC				
X		A ₀	A _x	A _w	A _{xw}	R ²
	PPB	3.026***	0.407***	0.800***	0.240***	0.818***
	PPS	3.014***	0.397***	0.752***	0.252***	0.808***
Y		Consumers' purchase intention PI				
X		B ₀	B _x	B _w	B _{xw}	R ²
	PPB	3.344***	0.504***	1.138***	0.189***	0.803***
	PPS	3.333***	0.487***	1.082***	0.206***	0.794***

In the Table7, A_{xw} represents the adjustment effect coefficient of PPB and PPS on PC. according to the test results, the coefficients of PPB×PE、PPS×PE are 0.240 and 0.252 respectively, and the 95% confidence interval does not include 0, indicating that PE positively regulates the impact of PPB and PPS on PC; Similarly, in the impact path of PPB and PPS on PI, the

coefficients of PPB×PE、PPS×PE are 0.189 and 0.206 respectively, and the 95% confidence interval does not include 0, indicating that peer effect positively regulates the impact of policy perceived stability PPS and perceived stability PPS on purchase intention PI.

4.4.2 Active vs. passive peer effect

In this paper, the peer effect is divided into active

peer effect and passive peer effect, and the former is assigned as 1 and the latter is assigned as 0. The differences of different types of peer effects are further analyzed by means of dummy variable and bootstrap test.

Firstly, this paper analyzes the impact of different types of peer effects (passive vs active) on policy trust at different levels of policy perceived benefits (low PPB vs high PPB) and different levels of policy perceived stability (low PPS vs high PPS). Taking policy trust as the dependent variable and PE, PPB and PPS as the fixed factors, the variance analysis models of PE, PPB, PPS and their interaction items are constructed respectively, and the linear model diagrams are drawn with policy perceived benefit ppb and stability PPS as the horizontal axis respectively, as shown in Figure 2.

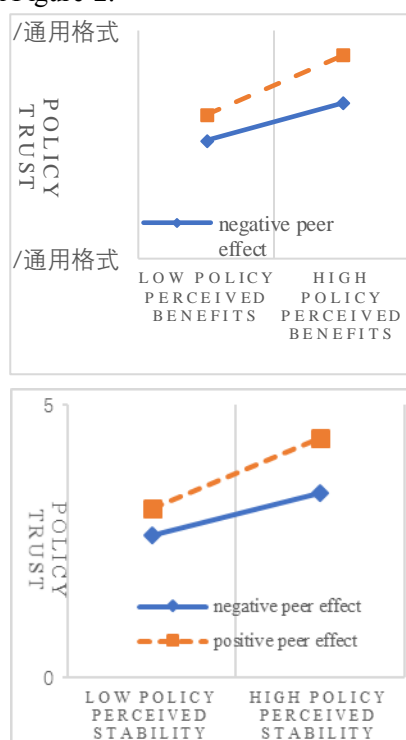


Figure 2 the test of the regulation effect of active vs passive peer effect in the relationship between PPB, PPS and PC

According to Figure 2, the adherence of active PE is higher than passive in both PPB and PPS dimensions, i.e., the facilitation effect of policy perception quality on policy trust is more significant under the moderation

of active peer effects relative to passive peer effects. The results of this study suggest that although peer behavior has an effect on individual policy trust in the HPV purchase decision process, regardless of the level of policy perception affordability and stability (high and low), individuals who communicate and interact deeply with their peer group are more likely to form trust in policy among consumers than merely watching peer group behavior, therefore, promote and formation of interactive communication and sharing among consumers is important for policy perception trust.

Similarly, to analyze the effect of different types of peer effects on purchase intention at different levels of policy perceived benefit (low vs. high) and different levels of policy perceived stability (low vs. high) on purchase intention, with PI as a dependent variable, PE, PPB and PPS as fixed variables. The analysis of variance (ANOVA) models of PE, PPB, PPS and their interaction terms are constructed and plotted with PPB and PPS as the horizontal axes respectively, as shown in Figure 3.

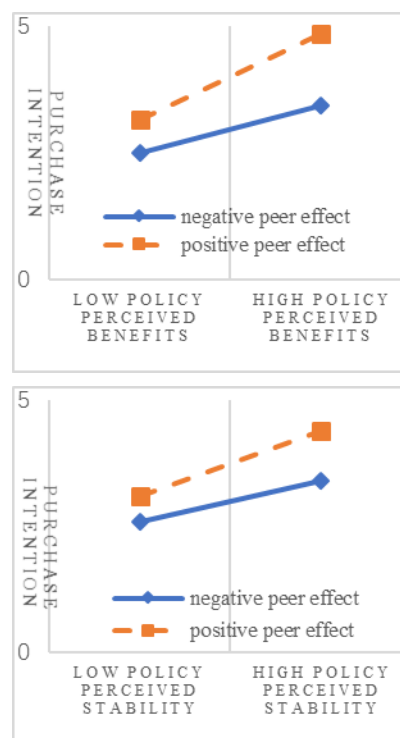


Fig. 3 the moderating effect of active vs. passive peer effect in PPB, PPS and PI

According to Figure 3, the compliance of active PE is higher than passive PE in both PPB and PPS dimensions. Compared to passive peer effects, the promotion of policy perception quality for purchase intention is more significant in active peer effects. It suggests that the promotion effect of policy perception quality on purchase intention is more significant under the regulation of active peer effects. The results of this study suggest that regardless of the level of policy perception afford ability and stability (high and low) in the HPV purchase decision process, individuals who actively communicate and interact deeply with their peer group can enhance the purchase intention of consumers more than just watching the behavior of peer group, thus promoting and forming interactive communication and sharing among consumers. Therefore, the promotion and formation of interactive

communication and sharing among consumers is important for the rapid market diffusion of HPV products.

4.4.3 Online vs. offline peer effects

The survey found that the online channel for residents to obtain information about HPV products and subsidy policies accounted for 71.82% of the 362 samples, while the offline traditional channel was only 28.18%; it can be seen that in the era of self-media and social media, the access channel, access speed and access quality of information for both urban and rural households have changed qualitatively compared with traditional media, and online information dissemination and interactive communication have become the main channels. The details are shown in Table 8.

Table 8 source analysis of residents' information channels

Channel	Information source	Means	Information content	peer effects
online 71.82%	personal social platform 68%	WeChat/ QQ group chat and link distribution through the Moments	receive, collect and forward HPV subsidy policies information	active
	public social platform	Weibo, Zhihu, TikTok, etc	for interaction	
	online media push, company online ads	video news push and ads on TikTok and Toutiao	passive information learning about products and policy	passive
	grassroot organization 11%	Community and village committee publicity	understand HPV and subsidy policies	
offline 28.18%	friends and relatives 50%	Recommendation by friends and relatives	In-depth interaction	active
	self observation 32%	observation of HPV use or installation	understand HPV products	
	commercial sources 7%	company promotion and exhibition; ads on TV, broadcast and newspaper; traffic ads on bus, railway and high-speed railway	understand HPV and subsidy policies	passive

It's easy to see that there are three main ways for residents to obtain HPV information and subsidy policies online: (1) personal social platforms, mainly WeChat, QQ and the moments, whose distinctive features are that the members of the group have deeper communication in various aspects, most of them are offline friends or have communicated offline, and there is basic understanding and knowledge among members. (2) Public social platforms, mainly Weibo, post sites, forums, etc., which are characterized by the fact that members may not be familiar and acquainted with each other, but they can communicate with each other within the platform, and individuals can actively collect and obtain the information they need; (3) Online commercial pushing, such as video and news pushing by headlines, and various online advertisements placed by enterprises, which are often completely open. Information push, the individual generally belongs to the passive recipient can not be interactive communication. Among the above three online channels, "personal social platform" has become the most important information channel, accounting for 68% of the online channels.

Similarly, there are four main offline access: (1) grassroots organizations, mainly community and village committees, which are characterized by the familiarity or acquaintance of members within the community, and a certain "semi-public" nature in residents' perceptions, and more formal channels; (2) introduction and recommendation by friends and relatives, which are characterized by mutual trust and the possibility of interactive communication, and to provide not only product and policy information, but also to pass on the practical experience of product advantages and policy benefits to others; (3) residents' observation and their own understanding of HPV-related information; (4) traditional commercial

channels, i.e., corporate publicity, exhibitions, TV, radio, newspapers, subways, highway and other transportation advertisements, etc. Among the above four information sources, 50% were recommended by "friends and relatives", while 32% were found by themselves but not communicated with others.

Further investigation and comparative analysis found that the main channels for residents to obtain information about PV power generation equipment and related policies are online "personal social platforms" (WeChat, QQ and Moments) and offline "friends and family recommendation". The common feature of these two types of channels is the high frequency of interaction and communication, which are active peer effects; the product features, installation process, cost and benefit, policy subsidy method, application procedure, etc. These are clearly displayed among members through on-site demonstration and video demonstration, which become the main influential channels for consumers to purchase PV products. The main influence channel for consumers to purchase PV products.

Consumers are influenced by their social interactions before making a purchase decision, and they expect reliable information and experience sharing to reduce the perceived risk and increase the perceived value, and then make a more cost-effective purchase. As HPV is a product with a high upfront capital investment and long payback period, a better understanding of the underlying channels of information flow can provide insights to overcome some of the inherent barriers. Although passive peer effects can initially influence people's perceptions for an easily observable product like HPV, experience sharing and further communication of advice from neighbors and friends with similar attributes and living environments can help generate a stronger sense of identification and trust, leading to a greater

willingness of consumers to emulate the green purchasing behavior of their peers, prompting an increase in home. This leads to an increased willingness of consumers to imitate the green purchasing behavior of their peers, to purchase and install PV. Although previous studies have argued that face-to-face communication and information sharing are more reliable, with the rapid development of the Internet, the boom of information technology has greatly changed the communication structure of modern society, and the hierarchy of social networks has become flatter and more complex. Compared with face-to-face offline communication, online interaction, which can be accessed, consulted and shared anytime and anywhere, is more recognized and loved by contemporary people, especially when their neighbors and friends who are closer to them do not have home PV installed and cannot provide them with effective information.

5 Conclusion and Policy Implications

This paper measures HPV subsidy policy perception quality in two dimensions: perceived stability and affordability, and introduces policy trust and peer effects as mediating and moderating variables respectively to look into the mechanism and influence path of subsidy policy perception quality on HPV purchase intention. The empirical analysis was conducted on the basis of 362 samples collected from across the country using in-depth interviews, scenario design and questionnaires, and came to the following main findings:

5.1 Conclusions

(1) Both subsidy policies perceived stability and policy perceived benefit have significant positive effects on policy trust and HPV purchase intention; the more consumers believe that subsidy policies can bring them benefits and the longer they feel so, the better they trust the policy and the consumers

purchase intention will go up. At the same time, compared to the perceived stability, consumers pay more attention to the actual degree of cost reduction and benefit increase from the subsidy, the higher the benefits, the more trust in the policy and the higher purchase intention for HPV products.

(2) Subsidy policy perception quality positively affects HPV purchase intention through two paths, the direct path is "policy perception quality-HPV purchase intention"; the indirect path is "policy perception quality-HPV purchase intention"; i.e., policy trust plays a partial mediating role between subsidy policy perception quality and consumers HPV purchase intention.

(3) Peer effects in "subsidy policy perception quality-policy trust" and "subsidy policy perception quality-HPV purchase intention". policy perception quality-HPV purchase intention", i.e., peer behavior amplifies the stimulating effect of subsidized perception quality on policy trust and HPV purchase intention. The active peer effects amplify the main effect more than the passive peer effects, which means that active communication and interaction among consumers help to reduce the policy rejection of consumers, and purchase intention is higher based on in-depth understanding of policy information and product characteristics. intention is higher.

(4) Whether in urban or rural areas, online channels become the main channel for residents to obtain information about HPV products and subsidy policies, accounting for about 72%; there are 4 and 3 offline and online information acquisition and interaction channels for residents, respectively, among which offline active peer effects, mainly communication with friends and relatives, and online active peer effects groups, mainly WeChat, QQ and moments, become the most important way to influence residents to purchase household PV

products.

5.2 Corresponding suggestion for the strategy

(1) Based on different consumers' needs, the target of policy formulation should effectively settle on the two aspects of subsidy affordability and policy stability to improve the overall policy perception quality.

As HPV is green and renewable, the popularization of HPV equipment is of great significance to China's green energy consumption, energy conservation and emission reduction. Policy makers need to implement multi-dimensional subsidies based on different household characteristics, such as reducing the risk of initial investment and more subsidies for households with low economic income and risk tolerance, especially for some rural households with pretty good installation conditions. One-time cash subsidies or tiered subsidies combined with poverty alleviation programs can be adopted to lower the risk and cost.

For urban residents, policies should focus on the solution of HPV installation conditions, selection of installation site and others, for example, regulating the rights and procedure in use of roofs, walls and other public spaces while introducing relevant policies to encourage fast product development that suits urban housing structure and installation conditions. At the same time, a reasonable policy implementation period should be made based on the actual research to ensure the relative policy stability, avoid frequent changes and market instability caused by conflicts in the policy transitions, and pilot and promote the policy in steps as planned so as to enhance the policy quality and improve market proliferation of HPV products.

(2) Online channels and consumers' personal media should be fully utilized to facilitate interaction within consumers to make the most of the positive

guidance effect and expand the HPV policies and product information coverage in depth, so consumers will be motivated to purchase.

HPV products are large household durable goods, which is an assumption as well as a profit. In the early stage, it requires higher investment and the installation conditions and procedures are quite complicated, so families need a second thought for the purchase. Peer interaction provides potential buyers more information and experience, especially when it seems more reliable coming from a friend or a relative, so it has a significant influence on the residents' HPV purchase decision. In the process, WeChat, QQ and the moments are priorities because it's convenient to use anytime, responsive, in-depth in communication and reliable for the information. In formulating and releasing the policy, in addition to releasing relevant information on official websites and social media platforms, residents' self-media and network groups should be utilized properly. The communication with grassroots organizations should be emphasized, and relevant information can be directly distributed in residents' community WeChat and QQ groups using the intelligent community network platform; HPV users' opinion leaders can be spotted and cultivated through village committees and community managers for profound communication within users, sharing relevant policy information and experience, so as to play a positive role of stimulating online active peer effects and improve the consumers purchase intention for HPV. Besides, the government or the enterprises can also launch more professional analysis and reports on HPV through public media like WeChat and Tik Tok, which gives an in-depth explanation of policy subsidy process, provides professional consulting services and solve in time consumers' questions about the HPV use. Through lifts in public emotion value and

recognition, policy trust can be improved to boost purchase.

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How does exploitative leadership influence employee silence? A moderated mediation framework

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Abstract: We use conservation of resource (COR) theory to explore the cross-level effect of exploitation on employee silence. We particularly examine the mediating impact of work meaningfulness and the moderating role of performance reward expectancy. Data were collected from 351 subordinates and 73 direct managers. We analyzed the data by using multilevel path analysis to examine the cross-level moderated mediation framework. Our results demonstrate that (1) exploitative leadership positively influences employee silence; (2) work meaningfulness plays a mediating role between exploitative leadership and employee silence; (3) the effects of exploitation on work meaningfulness are moderated by performance reward expectancy; (4) performance reward expectancy moderates the linkage of exploitative leadership-> work meaningfulness-> employee silence. The study suggests that organizations should reduce exploitative leadership. To reduce employee silence, managers should make an effort to promote employees' work meaningfulness, and satisfy their performance reward expectancy.

Keywords: exploitative leadership; employee silence; work meaningfulness; performance reward expectancy

1 Introduction

In the field of organizational behavior, a great deal of research has explored 'dark-side' leadership, for instance, abusive supervision^[1], narcissistic leadership^[2], and hubristic leadership^[3]. An emerging strand investigates exploitative leadership^[4, 5], introduced by Schmid et al. (2019)^[5], this self-serving behavior shows the most significant characteristics of dark-side leadership. Such leaders exploit followers by acting selfishly, exerting control, overburdening subordinates, and allowing no development^[5]. The available literature has made a start toward showing that leaders' exploitation hurts job satisfaction, service performance, and innovative behavior in followers^[4, 5], and increased burnout, deviance, and knowledge hiding^[5, 6]. However, little research has focused on understanding whether exploitative leadership affects employee silence—an intentional withholding of information, opinions, or concerns about potentially necessary organizational problems^[7, 8]. Therefore, by examining a mechanism underlying exploitative leadership and employee silence, this study fills the gap between the dark-side leadership and silence literatures.

Based on COR theory, when faced with threats or

actual loss of resources, people will maintain their own resources to protect themselves from further loss of resources^[9]. Exploitation is a stressor in the organization^[5], when employees feel exploited by their managers, they may try to reduce the loss of resources by keeping silent. COR theory also proposes that resource loss causes individuals more vulnerable to further resource loss, especially in negative emotional sequels and lower potential supportive resource availability^[9, 10]. Work meaningfulness refers to the extent to which an individual views the job as worthwhile and valuable^[11], is thus a potential supportive resource. Supervisor exploitation consumes employees' resources^[4]. Employees who suffer exploitative leadership may constantly consume resources, experience low work meaningfulness, and may hence keep silence to protect self-resources^[1]. Thus, based on COR, this study explores the mediating effect of work meaningfulness between exploitative leadership and employee silence.

Moreover, different people react in the different way when faced with leaders' exploitation. Based on COR theory, people response to loss of resources depends on individual differences^[12]. Previous studies

has found that performance reward expectancy, defined as the perceived possibility of receiving material rewards from organization that match their contributions^[13], functions as an accelerator of resource depletion caused by leaders' mistreatment^[14]. Thus, this study propose that performance reward expectancy moderates the relationship between exploitative leadership and work meaningfulness. Figure 1 shows the integrated framework.

There are three contributions in our research. First of all, it enriches the negative consequences of exploitation by introducing silence as an individual-level outcome, and also extends the antecedents of silence behavior in the leadership field. Second, in accordance with COR theory, our study opens the 'black box' to describe how exploitative leadership promotes employee silence by taking work meaningfulness as a mediator. Third, by demonstrating the idea that performance reward expectancy moderates the effect of leaders' exploitation, our study highlights the significance of performance reward expectancy in accelerating the bad influence of leaders' exploitation on employees.

2 Theory and hypothesis

2.1 Conservation of resource theory

Conservation of resource theory (COR) encapsulates a full process of how stress happens and how people respond to it. The most significant principle of the theory is that "people want to preserve, protect and construct resources"^[9] such as time, energy and positive emotions. Resources are valuable because they not only have instrumental value in providing people with the means to achieve their own goals, but also have symbolic value in identifying individuals^[10]. People fundamentally want to create a situation of excess resources and avoid situations that may lead to the loss of valuable resources, resulting in psychological discomfort or stress^[9, 15].

One of the most significant principles of this theory is the reason of the loss of resources, which suggests that losing resources will cause more psychologically harm to people than gaining them^[9]. According to this principle, individual will feel more stressful when (a) his/her resources are threatened, (b) there is an actual loss of resources, or (c) the expected return on his/her resource investment is not realized^[15]. There is also a motivational factor indicating that exhausted people want to take actions to avoid the loss of resources and attempt to minimize potential threats to their resources^[10].

People will try their best to find, gain and invest the indispensable resources to meet their work needs, and accumulate excess resources to cope with potential future pressures when not threatened by stressors^[15]. In contrast, when suffering from stressors, people attempt to protect remaining resources and reduce the possibility of further depletion of self-resources^[16]. Therefore, people are motivated to stay away from stressors by investing resources in passive and defensive behaviors^[17].

2.2 Exploitative leadership and employee silence

Schmid et al. (2018)^[18] point out exploitative leadership is a self-serving leadership style that pursues personal interests at the expense of others. Displayed by acting egoistically, manipulating employees, exerting pressure, taking credit, and undermining development, exploitative leadership acts as a stressor in the workplace, threatening the loss of actual or potential valuable resources for employees in terms of employment benefits and career developments^[5]. It also consumes followers' internal resources that allow thriving at work and relational attachment^[4, 19]. According to COR theory, depleted employees will try their best to conserve their own resources and pay more attention to reduce further resource loss^[9, 15]. In this study, we argue that silence is a likely response for

exploited employees to preserve their remaining resources.

Employee silence is defined as the deliberate withholding of thoughts, ideas, and opinions of employees on issues related to work and organization^[2, 20]. From the COR perspective, voice behavior is both expensive and risky for the individual^[21], which requires effort and energy, as followers must process their thoughts, consider time, and express themselves in an appropriate way^[22, 23]. However, keeping silent in the organization is a safer way to conserve remaining resources when an employee is emotionally depleted. It also saves time and self-resources relative to voice behavior^[21].

As mentioned above, exploitative leaders are selfish and put their own interests at first^[5], which depletes followers' self-resources. Thus, exploited followers are motivated to minimize the detrimental effects of this source of stress. They are more likely to avoid risking their self-resources to change the status quo and improve the current work situation^[23]. By contrast, they prefer to isolate themselves from work in silent ways to protect their limited resources and focus their efforts on preventing further loss of resources^[20, 24, 25]. In addition, exploitative behavior is an unpleasant source of work stress^[5], such that exhausted subordinates are more likely to fall into the dilemma of losing self-resources^[26, 27] and may therefore be inclined to adopt methods to reduce the loss of resources, such as using silence as a coping strategy. Therefore, we assume:

Hypothesis 1. *Exploitative leadership is positively correlated with employee silence.*

2.3 Work meaningfulness

Work meaningfulness is defined as 'the degree to which an individual experiences work that is generally meaningful and valuable'^[11]. Based on COR theory, people experience psychological strain when faced

with threats or actual losses and strive to protect and retain their limited resources^[9]. Therefore, this study suggests that leaders' exploitation can consume subordinates' work meaningfulness, which will then prompt victims to adopt silence as a preventative action. Furthermore, our study argues that subordinates are more likely to hold a negative mental state, which may reduce work meaningfulness, when encountering their leaders' exploitation.

First, leaders' exploitation is a threatening situation, which greatly drains followers' internal resources, such as thriving at work, job satisfaction, and relational attachment^[4, 5, 19]. Thus, leaders' exploitation makes depleted employees feel exhausted and helpless, further weakening their work meaningfulness^[5]. Second, exploitative leaders assign complicated and boring tasks to subordinates^[19]. When this occurs, employees are less likely to see meaning in their work and hence choose not to put resources into these tedious jobs, which gradually weakens their work meaningfulness. Third, exploitative leadership may cause subordinates to worry about their prospects in the organization, because exploitative leaders do not consider subordinates' promotion and development opportunities^[5]. Employees are not given the opportunity to further develop themselves professionally because leaders' goals take priority and they would feel disappointed and helpless, which makes it more difficult to cope with leaders' exploitation. Their work meaningfulness is then further reduced. Therefore, we assume:

Hypothesis 2. *Exploitative leadership is negatively correlated with employee work meaningfulness.*

Further, we argue that work meaningfulness negatively influences employee silence. With fewer resources, employees find it difficult to withstand the threat of further resource losses, which could lead to a

spiral of loss that endangers employees' sense of motivation and general well-being^[28]. Because individuals are more sensitive to resource loss than resource gain^[15], exhausted subordinates are more likely to take a defensive stance to prevent further resource loss or to conserve limited resources^[29-31]. Research has revealed that a low level of work meaningfulness would cause stress, exhaustion^[32, 33] and turnover intention^[34]. In line with these observations, we expect weaker work meaningfulness to be linked with higher employee silence.

The relationship between work meaningfulness and employee silence will be weakest when (a) employees perceive that their work is helping them achieve ultimate value and (b) they experience positive emotions at work^[35]. In these cases, work helps individuals achieve their ultimate goals in life, and individuals feel meaningful while working. Hence, they would like to put more resources into their work and work harder, instead of keeping silent to remove themselves from perceived risk of loss at work. In addition, individuals who report less work meaningfulness may experience higher levels of exhaustion^[36]. This situation is very painful for subordinates because it consciously and unconsciously depletes their psychological resources and they would try their best to protect limited resources^[37]. As a result, followers tend to keep silent in order to relieve the associated psychological discomfort^[38] and conserve their limited resources^[23]. Therefore, we assume:

Hypothesis 3. *Work meaningfulness is negatively correlated with employee silence.*

Integrating the reasoning above, in which we argue exploitative leadership is negatively associated with followers' work meaningfulness and that reduced work meaningfulness motivates subordinates to adopt silence behaviors, we hypothesize a mediated relationship as below:

Hypothesis 4. *Work meaningfulness mediates the relationship between exploitative leadership and employee silence.*

2.4 Performance reward expectancy

Performance reward expectancy refers to "the perceived possibility of obtaining material rewards provided by the organization matching their contributions"^[13]. Research suggests that performance reward expectancy promotes employees' creativity^[39], performance^[40], and innovative behavior^[41] because it tends to increase employees' desire to achieve their own goals, and hence, their allocation of resources to positive actions. However, despite the importance of performance reward expectancy in employee resource depletion, little research studying the moderating effect of performance reward expectancy on the influences of leaders' exploitation on a reduction of employees' resources. Based on COR theory, we argue that performance reward expectancy plays a moderating role in the process of internal resource consumption of individuals^[42].

As an individual cognitive appraisal, performance reward expectancy would enhance the negative influence of leaders' exploitation on work meaningfulness. First, exploitative leaders link employees' performance reward expectancy to organizational high-performance goals. Under the dual performance pressure of high reward expectancy and exploitative leadership, employees strive to constantly improve their skills while dealing with work overload. Meanwhile, high reward expectancy further reduces limited resources of employees who are overloaded by exploitative leaders. This leaves subordinates with even fewer resources to cope with leaders' exploitation. In other words, the bad effect of leaders' exploitation on employees' work meaningfulness becomes more severe with high performance reward expectancy in the workplace.

In addition, when employees have high performance reward expectancy, it is likely that they are motivated to materialize their work efforts and performance^[43]. Therefore, when faced with leaders' exploitation, employees become more sensitive, and their feelings about resource loss are more intense, which leads to stronger negative impacts of exploitation on work meaningfulness. In contrast, when employees have low performance reward expectancy, they do not have high expectations of their contributions being converted into material rewards. When suffering from exploitative leadership, subordinates are accustomed to and thus do not feel strongly about the loss of resources, thus weakening the bad influence of exploitation on work meaningfulness. Therefore, we hypothesize that:

Hypothesis 5. *Performance reward expectancy*

positively moderates the relationship between exploitative leadership and work meaningfulness.

2.5 Integrated model

Hypotheses 4 and 5 argue that performance reward expectancy positively moderates the relationship between exploitation and work meaningfulness, and that work meaningfulness plays a mediating role in the relationship between exploitative leadership and employee silence. Thus, the whole relationship among exploitative leadership, performance reward expectancy, work meaningfulness, and employee silence falls under the moderated mediation framework.

Hypothesis 6. *Performance reward expectancy moderates the mediating impact of work meaningfulness on the relationship between exploitative leadership and employee silence.*

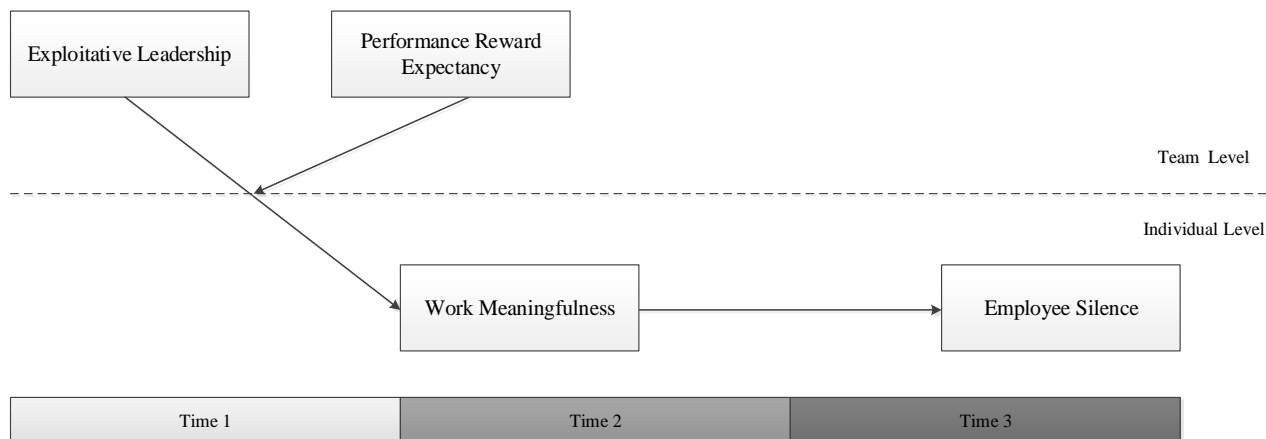


Figure 1. Research Model.

3 Methods

3.1 Sample and procedure

Data were collected from companies operating in manufacturing, high-tech industries and services located in Jiangsu Province. The HR managers of each company were contacted and permission to investigate was obtained. All participants took part voluntarily and confidentiality was assured. We initially developed questionnaires in English and then translated into

Chinese using reverse translation techniques. The employees' questionnaire measured exploitative leadership, work meaningfulness, performance reward expectancy, and control variables; the managers' questionnaire measured employee silence.

In the first round of surveys (May 2021), 550 employees (from 110 teams) were asked to complete the questionnaire, which questions on individual information, perceived leaders' exploitation, and

performance reward expectancy. 463 employees (from 93 teams) finished the survey, a response rate of 84%. In the second round of surveys (2 weeks later), we used a follow-up survey to members who participated at first round, measuring their work meaningfulness; some 397 (from 80 teams) finished surveys were returned, a response rate of 86%. In the third round of surveys (a further 2 weeks later), we gave a survey to the team managers of the 397 employees to the second round survey. Managers were asked to evaluate their subordinates' silence behavior. In this round, 351 completed surveys were returned.

Among the 351 employees, 51.3% were male; 55.3% were unmarried; 22.2% were under 20 years old, 25.4% between 21 and 30 years old, 23.6% between 31 and 40 years old, and 28.8% over 41 years old; 22.8% had attended junior college, vocational education, or below, 28.2% were undergraduates, 24.8% were graduates, and 24.2% had received a doctoral education or above. As for tenure, 16.8% had tenure of less than 1 year, 23.6% between 1 and 3 years, 22.5% between 3 and 5 years, 23.1% between 5 and 7 years, and 14.0% over 7 years.

3.2 Measures

Unless otherwise stated, our study use 7-point Likert-type scales to measure all items, with 1 = "strongly disagree" and 7 = "strongly agree".

Exploitative leadership was measured using the 15-item scale developed by Schmid et al. (2019)^[5]. Sample item includes: "Uses my work for his or her personal gain." The Cronbach's alpha was .92.

Work meaningfulness was measured using the 3-item scale developed by Spreitzer (1995)^[44]. Sample item includes: "The work I do is meaningful to me." The Cronbach's alpha was .88.

Employee silence was measured using the 5-item scale developed by Tangirala and Ramanujam (2008)^[45]. Sample item is: "Although he/she had ideas

for improving patient safety in his/her workgroup, he/she did not speak up." The Cronbach's alpha was .90.

Performance reward expectancy was measured using the 4-item scale developed by Eisenberger and Aselage (2009)^[39]. Sample item is: "Good performance in my job leads to higher pay." The Cronbach's alpha was .91.

Control variables. We used gender (1 = female; 0 = male), marital status (1 = married; 0 = unmarried), age (3 = over 41 years old; 2 = 31–40 years old; 1 = 21–30 years old; 0 = under 20 years old), education (3 = doctor of philosophy or above; 2 = graduate; 1 = undergraduate; 0 = junior college, vocational education or below) and tenure (4 = over 7 years; 3 = 5–7 years; 2 = 3–5 years; 1 = 1–3 years; 0 = under 1 year) as control variables.

3.3 Data aggregation

A one-way random-effects analysis of variance showed that *ICC* (1) values of exploitative leadership and performance reward expectancy were .43 and .36, respectively, and *ICC* (2) values of these variables were .79 and .73, respectively. These results indicate that exploitative leadership and performance reward expectancy differed across teams. The mean of *Rwg* (Reliability of score within group) across teams was also calculated using a uniform null distribution. The values were .99 and .95 for exploitative leadership and performance reward expectancy, respectively. These results suggested that we use multilevel modeling as the analytical strategy.

4 Results

4.1 Confirmatory factor analyses

Our study use Mplus8.3 to perform a confirmatory factor analysis. The four-factor model (M1), which was composed of exploitative leadership, work meaningfulness, employee silence, and performance reward expectancy, fit the data well ($\chi^2[296] = 487.07$, $\chi^2/df = 1.65$, $RMSEA = .04$, $CFI = .97$, $TLI = .96$, $SRMR$

= .04). The results showed that the four-factor model is better than other models, including (1) a three-factor model (M2), which combined employee silence and performance reward expectancy into one factor ($\chi^2[303] = 1459.30$, $\chi^2/df = 4.82$, $RMSEA = .10$, $CFI = .81$, $TLI = .78$, $SRMR = .10$); (2) a two-factor model (M3), which combined employee silence, performance

reward expectancy, and work meaningfulness into one factor ($\chi^2[309] = 1987.49$, $\chi^2/df = 6.43$, $RMSEA = .12$, $CFI = .73$, $TLI = .69$, $SRMR = .12$); and (3) a one-factor model (M4), which combined all the items into a common factor ($\chi^2[324] = 3860.86$, $\chi^2/df = 11.92$, $RMSEA = .18$, $CFI = .42$, $TLI = .37$, $SRMR = .15$).

Table 1. Measurement model comparison.

	χ^2	df	χ^2/df	RMSEA	CFI	TLI	SRMR
Four –factor Model (M1)	487.07	296	1.65	.04	.97	.96	.04
Three –factor Model (M2)	1459.30	303	4.82	.10	.81	.78	.10
Two-factor Model (M3)	1987.49	309	6.43	.12	.73	.69	.12
Single-factor Model (M4)	3860.86	324	11.92	.18	.42	.37	.15

4.2 Descriptive statistics

Table 2 shows the means, standard deviations, internal consistency reliability, and correlations of the variables.

4.3 Hypotheses testing

First, we constructed a complete model, which included the linkage of exploitative leadership \rightarrow work meaningfulness \rightarrow employee silence, as well as the indirect effects from exploitative leadership to work meaningfulness to employee silence. The results show that exploitative leadership is positively related to employee silence ($\beta = .37$, $se = .18$, $p < .05$), supporting H1.

Second, the results indicate that exploitative leadership is negatively related to work meaningfulness ($\beta = -.50$, $se = .22$, $p < .05$), supporting H2. Work meaningfulness is negatively related to employee silence ($\beta = -.34$, $se = .09$, $p < .01$), supporting H3. Work meaningfulness mediated the impacts of exploitative leadership on employee silence (*indirect effect* = .17, $se = .09$, $p < .05$), supporting H4.

Then, our study tested the moderation effect of performance reward expectancy on the relationships between exploitative leadership and work meaningfulness at the team level. As shown in Table 3, the moderating effect is significant ($\beta = -1.31$, $se = .58$, $p < .05$); hence, H5 was supported. Figure 2 depicted the simple slope test of this interaction, which shows that with a high level of performance reward expectancy, the relationship between exploitative leadership and work meaningfulness is stronger ($\beta = -1.29$, $se = .36$, $p < .01$) than that under a low level of performance reward expectancy ($\beta = .29$, $se = .46$, $p = .53$).

Hypothesis 6 predicts that performance reward expectancy moderates the linkage exploitative leadership \rightarrow work meaningfulness \rightarrow employee silence. Results showed significant differences between the linkages among the three variables across different levels of performance reward expectancy (*diff* = .54, $se = .27$, $p < .10$), supporting H6.

Table 2. Descriptive statistics.

Variable	Individual		Team		1	2	3	4	5	6	7	8	9	10
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>										
1. Team size	—	—	5.52	1.09	—	—	—	—	—	—	-.27**	.21**	-.21**	.03
2. Employee gender	.49	.50	—	—	—	—	—	—	—	—	—	—	—	—
3. Employee marriage	.45	.50	—	—	—	.04	—	—	—	—	—	—	—	—
4. Employee age	1.59	1.13	—	—	—	.05	.09	—	—	—	—	—	—	—
5. Employee education	1.50	1.09	—	—	—	-.01	-.19**	.04	—	—	—	—	—	—
6. Employee tenure	1.94	1.30	—	—	—	.09	-.01	-.05	-.03	—	—	—	—	—
7. Exploitative leadership	3.72	.50	3.72	.37	—	-.03	-.03	.04	-.01	-.02	.92	-.56**	.52**	-.00
8. Work meaningfulness	3.67	.77	3.67	.62	—	.09	.00	-.01	.01	-.00	-.38**	.88	-.56**	-.11*
9. Employee silence	3.62	.81	3.62	.51	—	-.02	-.04	.09	.08	-.04	.29**	-.38**	.90	.04
10. Reward expectancy	3.36	.86	3.36	.60	—	.05	-.10	-.01	.05	.05	.04	-.06	.05	.91

Notes. Team level, $n = 73$; individual level, $n = 351$. Individual- and team-level correlations are below and above the diagonal, respectively. Bold values on the diagonal are Cronbach's alpha. * $p < .05$, ** $p < .01$.

Table 3. Results of hypothesis testing.

	Work meaningfulness				Employee silence			
	Estimate	S.E.	P	95% CI	Estimate	S.E.	P	95% CI
Within level								
1. Employee gender	.07	.06	.26	[-.05, .20]	.06	.08	.51	[-.11, .22]
2. Employee marriage	.03	.06	.64	[-.10, .16]	-.06	.07	.40	[-.20, .08]
3. Employee age	-.01	.03	.69	[-.06, .04]	.05	.04	.25	[-.03, .12]
4. Employee education	-.01	.03	.66	[-.08, .05]	.05	.04	.17	[-.02, .13]
5. Employee tenure	-.01	.02	.64	[-.05, .03]	-.02	.03	.58	[-.07, .04]
6. Work meaningfulness					-.28**	.10	.00	[-.47, -.09]
Between level								
7. Team size	.02	.05	.65	[-.07, .11]	-.02	.05	.62	[-.11, .07]
8. Work meaningfulness					-.34**	.09	.00	[-.52, -.17]
9. Exploitative leadership (EL)	-.50*	.22	.03	[-.94, -.06]	.37*	.18	.04	[.01, .73]
10. Performance reward expectancy (PRE)	-.03	.08	.70	[-.19, .13]				
11. EL * PRE	-1.31*	.58	.02	[-2.43, -.18]				

Notes. Team level, $n = 73$; individual level, $n = 351$. * $p < .05$, ** $p < .01$.

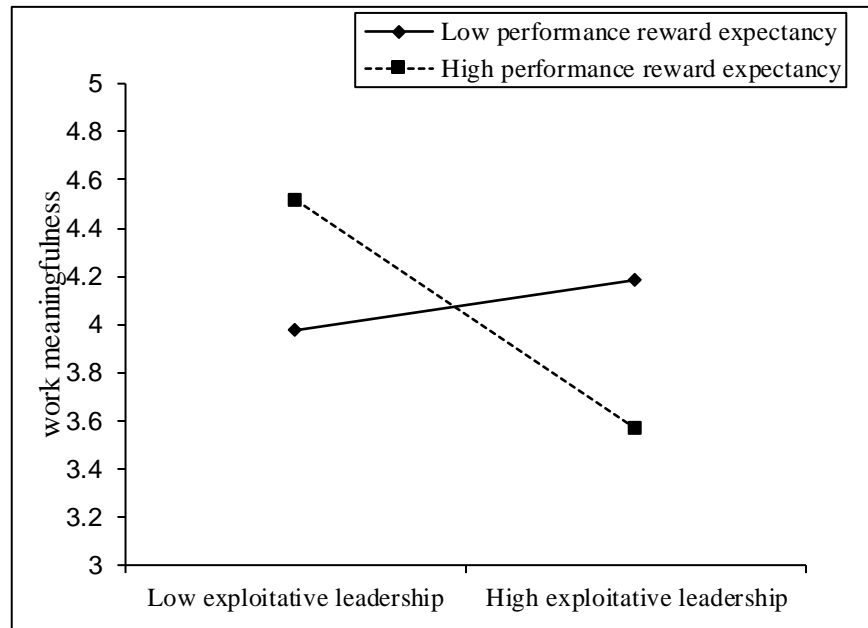


Figure 2. Interaction of exploitative leadership and performance reward expectancy on work meaningfulness.

Table 4. Analysis of moderated mediation effect.

Moderator		Exploitative leadership → Work meaningfulness → Employee silence			
		Estimate	S.E.	P	95%CI
Performance reward expectancy	High	.44**	.17	.01	[.12, .76]
	Low	-.10	.16	.54	[-.41, .21]
	Diff	.54	.27	.05	[.00, 1.07]

Notes. N = 351; * $p < .05$, ** $p < .01$.

5 Discussion

5.1 Theoretical implications

First, from the perspective of COR theory, this study considers the behavioral response of employees when they face dark-side leadership. This addresses an emerging research call concerning how exploitative leadership influences a broader range of employee psychological and behavioral outcomes. Aspects of this have been considered in recent literature^[4, 5]. For instance, Schmid et al. (2019)^[5] revealed that leaders' exploitation leads to reduced affective commitment and job satisfaction, increasing work deviance and burnout, Wang et al. (2021b)^[4] showed that leaders' exploitation hurt employees' innovative behavior, and Guo et al. (2021)^[26] indicated that leaders' exploitation induces knowledge hiding. However, to the best of our knowledge, the impact of leaders' exploitation on

employee silence has been overlooked. Therefore, by exploring the relationship between exploitative leadership and employee silence, our research broadens the range of the existing exploitative leadership literature and responds to the call of Schmid et al. (2019)^[5] for more empirical research to shed new light on exploitative leadership. Our research enriches this knowledge by showing exploitative leadership is a destructive form of leader behaviors that are conducive to employee silence.

Second, this study further deepens our understanding of the underlying mechanisms underlying exploitative leadership and employee silence by demonstrating the mediating role of work meaningfulness. Researchers have demonstrated the direct impact of exploitative leadership on job satisfaction, thriving at work, and relational

attachment^[4, 5, 19]. According to COR theory, our study introduce work meaningfulness as a key mediator in the relationship between exploitative leadership and employee silence. Our findings proved that leaders' exploitation reduces employee work meaningfulness (as a typical form of potential supportive resources), and thus led to silence behavior. This finding draws on previous research by Wang and Xu (2019)^[46], which found that work meaningfulness mediates the impact of ethical leadership on followers' work attitudes. Our finding contributes to explicating the previously "black box" nature of the leaders' exploitation – employee silence relationship and broadens our understanding of how dark-side leadership influences employees' behavior^[5].

Third, by demonstrating the moderating role of performance reward expectancy, our research reveals the boundary conditions that leaders' exploitation is more or less harmful to employees' internal resources and behaviors. Although recent years have witnessed an increasing interest in exploring the influence of exploitative leadership^[5, 18], the boundary conditions of exploitative leadership are not well developed theoretically. To address this gap, we identified that performance reward expectancy is an accelerator of the impact of exploitative leadership on work meaningfulness and subsequent employee silence. Therefore, our study responds to the call for paying greater attention to the role of individual cognitive characteristics in the relationship between dark-side leadership and subordinates' behavior^[47].

5.2 Practical implications

First, our findings suggest that organizations need to take measures to prevent, control, and reduce leaders' exploitation. For example, organizations need to give preference to leader candidates with low levels of selfish tendencies when selecting and promoting managers. What's more, it is recommended that

organizations adopt a zero tolerance policy for leaders' exploitation and link managerial performance and compensation systems to a "no exploitation" policy. At the same time, employee grievance channels should be established, so that organizations receive employee feedback on leader misconduct. Once leaders are accused of exploitative behaviors, organizations need to respond quickly, taking measures to protect subordinates and resolving such problems in a timely and serious-minded manner.

Second, managers should pay attention to the important role of work meaningfulness in reducing employee silence. Research shows that subordinates become more attached to their organization and work more actively when they have stronger work meaningfulness^[46]. Therefore, we suggest that organizations promote work meaningfulness by offering employees the opportunity to realize their potential at work via job design. In addition, our study suggests that organizations would conduct regular surveys to assess the degree to which subordinates perceive their work to be meaningful and take proactive measures by focusing on both personal and contextual factors to enrich their work meaningfulness.

Third, organizations should strive to create an organizational culture of fairness, which allows employees to perceive the possibility of achieving their reward expectancy. Senior managers should serve as a role model to leaders in conforming to organizational regulations, which could augment the trust of employees in their performance-based rewards. In addition, organizations should establish an effective performance reward mechanism, objectively evaluate employees' work contributions, give corresponding rewards in time, and effectively stimulate employees' work meaningfulness.

5.3 Research limitations and prospects

Our research is not free from limitations. First of

all, data only come from one province in China. Given the heterogeneity of China's economic, social, and cultural development across regions, we acknowledge the possibility of overlooking factors prevalent in other regions that substantially differ from those in our sample. Therefore future research could expand the sample size across different cultural contexts. Second, although the data were collected at different points in time to reduce common method bias, this study is cross-sectional in nature, and thus, not sufficient to establish causality. Therefore, longitudinal or experimental designs would be beneficial to future research. Last but not least, when exploring the boundary conditions of the relationship between leaders' exploitation and work meaningfulness, we only examined the moderating role of performance reward expectancy. Further research could consider other individual (e.g. self-evaluation) and situational (e.g. competition climate) moderators as alternative boundary conditions for the impact of exploitative leadership.

5.4 Conclusions

In conclusion, our study has theorized and tested the hypothesis that exploitative leadership significantly affects employee silence by influencing work meaningfulness. The strength of this effect was found to be moderated by performance reward expectancy. Our findings extend the knowledge on exploitative leadership and employee silence by using the COR theory and provide important opinions that organizations can follow to reduce the association between leaders' exploitation and employee silence.

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零售商过度自信视角下制造商的 CSR 投入策略研究

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摘要：过度自信是一种常见的行为认知偏差，对供应链成员的决策有重要影响。鉴于此，运用动态博弈理论，分别构建批发价格契约和成本分担契约模型，讨论零售商的过度自信行为对制造商企业社会责任（CSR）投入和供应链成员利润的影响。研究表明：（1）零售商完全理性时，成本分担契约无法实现供应链的完美协调；（2）成本分担契约下零售商过度自信行为有利于 CSR 投入，价格契约下结果相反；（3）只要零售商存在过度自信行为，他的利益总会随其过度自信程度的增加而减少。但在成本分担契约下，当零售商的过度自信程度低于某一阈值，程度的加深有利于制造商获利；（4）理性的零售商并不总比过度自信的零售商利润多，批发价格契约下，过度自信的零售商比完全理性的零售商利润高。

关键词：过度自信；企业社会责任；成本分担契约；供应链

Research on CSR investment strategies of upstream manufacturers from the perspective of retailer overconfidence

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Abstract: Overconfidence is a common behavioral cognitive bias, which has an important impact on the decision-making of supply chain members. In view of this, this paper uses dynamic game theory to construct models of wholesale price contract and cost sharing contract respectively, solve and conduct data simulation, and discuss the influence of retailers' overconfidence behavior on manufacturers' CSR input and supply chain members' profits. The results show that: (i) when the retailer is completely rational, the cost-sharing contract cannot achieve the perfect coordination of the supply chain; (ii) retailer's overconfidence behavior is beneficial to CSR input under cost sharing contract, but opposite under price contract; (iii) as long as the retailer has overconfidence behavior, his interests will always decrease with the increase of his overconfidence. However, under the cost-sharing contract, when the degree of overconfidence of retailers is lower than a certain threshold, the deepening of the degree is beneficial to the profits of manufacturers. (iv) the rational retailer is not always more profitable than overconfident the retailer. Under the wholesale price contract, the overconfident retailer is more profitable than the completely rational retailer.

Key words: overconfidence; corporate social responsibility; cost sharing contract; the supply chain

Impact of social influence from competing product on focal product adoption. The role of product variety, user experience, and network density

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Abstract: Social influence literature predominantly focuses on investigating the impact of social influence from adopters of a focal product, without considering the potential influence from competing product adopters. In this study, we first examine the effects of social influence from competing product adopters (SICPA) on focal product adoption (FPA). We further hypothesize the moderation effect of SICPA on FPA in terms of competing product variety, focal user experience, and network density. We collected the data from a popular massively multiplayer online role-playing game, which lasted 85 days with 897,765 participants, demonstrate an inverted U-shape effect of SICPA on the FPA: the existence of competing product adopters could elevate focal product adoption when focal users are surrounded by *a small number* of competing product adopters. However, with the increase of competing product adopters, their effects on focal product adoption would be decreased. For the relationship of SICPA and FPA, both competing product variety and focal users' experience exert a negative moderating effect, while the network density of focal users produces a *positive* moderating effect. Our findings have significant theoretical and managerial implications for social influence, product adoption, targeting and seeding strategy.

Key words: social influence from competing product adopters, focal product adoption, competing product variety, focal user's experience, network density

信息搜索下高级别景区游客流的波动模式及驱动机理研究

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摘要：以 2015 年 2 月-2021 年 6 月苏锡常高级别旅游景区（4A 和 5A 级景区）游客量为样本，从高频数据视角分析高级别旅游景区游客流的波动特征，并利用脉冲响应和方差分解，揭示了游客旅行前后信息寻求的四个维度：景点本身特征、环境、旅游成本、配套设施，对旅游周期波动的分解和驱动效应。研究表明：在信息搜索强度较大情况下，游客的网络搜索可以有效高级别缓解游客流的季节波动，游客流的波动特征呈现出平缓的态势，并且旅游网络搜索数据对游客现实行为具有良好的解释作用。并且在信息搜索结构因素的分解效应中，游客在进行旅游信息搜索时，最关注旅游成本，其次是配套设施、景点特征和旅游环境。最后文章包含了对优化高级别旅游景区结构和旅游经济高质量发展的建议。

关键词：高级别景区；旅游流；周期波动；动态效应；贡献率；

Study on the fluctuation pattern and driving mechanism of visitor flow in high-level scenic spots under information search

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Abstract: Taking the visitor arrivals of high-level tourist attractions (4A and 5A grade attractions) in Suzhou, Wuxi and Changzhou from February 2015 to June 2021 as a sample, we analyse the fluctuation characteristics of tourist flows in high-level tourist attractions from a high-frequency data perspective, and use impulse response and variance decomposition to reveal the four dimensions of tourist information seeking before and after travel: the characteristics of the attractions themselves, the environment, tourism costs, and supporting facilities, on the fluctuation of tourism cycles. The decomposition and driving effects of The study shows that with higher information-seeking intensity, tourists' web search can effectively mitigate seasonal fluctuations in tourist flow at a high level, the fluctuation characteristics of tourist flow show a flattening trend, and the tourism web search data has a good explanatory effect on tourists' realistic behaviour. And in the decomposition effect of information search structural factors, tourists are most concerned with tourism cost, followed by supporting facilities, attraction features and tourism environment when conducting tourism information search. Finally the article contains suggestions for optimising the structure of high-level tourism attractions and the high-quality development of the tourism economy.

Key words: high-level scenic areas; tourism flows; cyclical fluctuations; dynamic effects; contribution margin.

相对地位的差异会影响产品扩散吗? ——产品类型的调节作用

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摘要: 在以往分析社会影响的研究中,地位是分析已购买者影响力、未购买者易感程度的重要指标。尽管这两者之间是紧密关联的,但以往的大多数研究只分析了其中的一个方面。因此,本文综合考虑这两方面,从影响者和被影响者地位差异的视角去探究社会影响对产品扩散之间的关系。并且,由于消费者对不同类型产品的诉求是不同的,本文也进一步探究在不同产品类型下,这种关系是否有差异。因此,本文与国内某虚拟世界运行公司进行合作进行一个实地实验来探究以上问题。研究结果证明:对于实用型产品来说,相对地位较高的影响者更能促进产品的扩散,并且影响者与被影响者之间的地位差距越大,效果越大;对于象征型产品来说,地位相似的影响者的更能促进产品扩散,并且影响者与被影响者之间的地位差距越小,效果越大。同时,本研究为企业更好地理解 and 开展病毒营销,促进产品的扩散等有着重要意义。

关键字: 地位; 相对地位; 关键消费者; 产品扩散

Does the difference in relative position affect product diffusion? ——The regulating effect of product type

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Abstract: In previous studies on product diffusion, status is an important index to analyze the influence of existing buyers and the susceptibility of non-buyers. Although the two are closely linked, most previous studies have looked at only one aspect. Therefore, this paper synthesizes these two aspects of consideration, from the perspective of the status difference between the influencer and the affected to explore the relationship between product diffusion. In addition, since consumers have different demands for different types of products, this paper further explores whether there are differences in this relationship under different product types. Therefore, this paper cooperates with a domestic virtual world operation company to conduct a field experiment to explore the above problems. The results show that: for practical products, influencers with higher relative status can promote the diffusion of products, and the greater the status gap between influencers and the affected, the greater the effect; For symbolic products, influencers with similar status can promote product diffusion, and the smaller the status gap between influencer and affected, the greater the effect. At the same time, this study is of great significance for enterprises to better understand and carry out viral marketing and promote the spread of products..

Key Words: Status; Relative position; Key consumers; Product diffusion

缓慢冒险游记分享对潜在旅游者旅游意愿的影响

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摘要：作为对生活节奏加快的一种回应，越来越多的人选择进行沉浸式的缓慢冒险旅游，而旅游企业营销人员如何通过社交媒体这一新兴的营销渠道来吸引旅游者，提高潜在旅游者的旅游意愿已成为亟待解决的问题。本研究通过 2×2 的组间实验，从临场感视角揭示了缓慢冒险游记分享对潜在旅游者旅游意愿的影响路径。研究表明，缓慢冒险游记分享的呈现形式（图文 VS. 视频）和内容属性（功能型 VS. 情感型）对临场感存在交互效应。同时研究还发现，临场感通过唤起和心流体验的链式中介以及心流体验的单中介路径间接影响旅游意愿。因此，在推广缓慢冒险旅游以及目的地社交媒体营销中关注游记呈现形式与内容属性的匹配效应具有重要的现实意义，本文为目的地社交媒体营销宣传实践提供了重要的理论指导。

关键词：缓慢冒险游记分享，临场感，唤起，心流体验，旅游意愿

The Influence of Slow Adventure Travel Notes Sharing on Potential Tourists' Travel Intention

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Abstract: In response to the faster pace of life, more and more people are opting for deep, immersive slow adventure travel. But growing competition in the tourism industry has led slow adventure destinations to constantly seek new ways to attract tourists. And social media is the primary tool for travelers to share travel information, stories and experiences with others. Therefore, how these slow-adventure travelogue sharing on social media captures the attention of potential tourists and influences their decision-making is an interesting research question. This study introduces the concept of presence, and reveals the impact of slow adventure travel journal sharing on social media on potential tourists' travel intentions from the perspective of presence. The study found that in the context of social media, the more vivid the presentation form of slow adventure travel notes, the more obvious the effect on the sense of presence; the information attributes of slow adventure travel notes and their presentation form have an interactive effect on the sense of presence; the sense of presence through flow The single-mediation of experience and the chain-mediated mediation path of arousal and flow experience have indirect effects on travel intention. This article provides important theoretical guidance for slow adventure destination social media marketing practices.

Key Words: Slow adventure travelogue sharing, sense of presence, arousal, flow experience, travel intentio

参照群体对居民绿色消费意愿影响的实证研究

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摘要：构建美丽中国依赖于民众的集体参与，积极践行绿色消费有利于生态文明建设与经济绿色转型发展。本文结合参照群体理论与社会互动理论，将参照群体影响分为信息性与规范性两大维度，探究中国背景下参照群体对居民绿色消费意愿的影响机制。运用结构方程模型对 394 份有效问卷进行实证分析，采用 Bootstrap 法检验中介效应。结果表明：参照群体的信息性影响与规范性影响对居民的绿色消费意愿有显著正向影响。参照群体的信息性影响与规范性影响分别通过知识认知、感知行为控制、消费情感这三条中介路径作用于绿色消费意愿。

关键词：参照群体影响；知识认知；感知行为控制；消费情感；绿色消费意愿

An empirical study of the reference group influence on residents' green consumption intentions

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Abstract: The construction of a beautiful China depends on the collective civil participation, and actively practicing in green consumption is conducive to ecological progress and economic transformation and development. Combining with the reference group theory and the social interaction theory, this paper divided reference group influence into two dimensions: information influence and normative influence to explore the influence mechanism of the reference group on the residents' green consumption intentions in the Chinese context. The research used structural equation model to analyze 394 valid questionnaires and test mediating effect through the Bootstrap method. The results show that the information influence and normative influence of the reference group have a significant positive impact on the residents' green consumption intentions. The information influence and normative influence of the reference group act on the green consumption willingness through the three intermediary paths of knowledge cognition, perceived behavioral control and consumption emotion, respectively.

Key words: reference group influence; knowledge cognition; perceived behavioral control; consumer emotion; green consumption willingness

一、引言

党的十九大指出生态文明建设是中华民族永续发展的千年大计，对于消费导向型经济发展而言，消费的可持续发展尤为重要。在所有环境问题中，人类消费活动引发的问题所占比重高达三分之一以上。绿色消费是经济绿色转型发展过程中推动实现“一带一路”倡议建设和助力完成 2030 年可持续发展目标的必然要求^[1]。绿色消费指个体或组织在产品的选择、购买、使用和处置过程中既满足自

身需求又关注环境可持续发展的消费方式^[2]，狭义绿色消费主要指绿色购买行为。消费者绿色购买行为是“社会人”行为，绿色消费的发展依赖于全民环境共治。生态文明建设与美丽中国的构建离不开民众的集体参与，社会情境中的参照群体对消费者决策有重要影响。在具有高情景特征的中国，参照群体对消费行为影响研究具有更强的现实意义^[3]。参照群体指个体在消费行为决策过程中，被参考比较并对其消费决策具有一定影响的有关个体或群

体^[4-5]。Park 和 Lessig (1977) 在比较研究参照群体对家庭妇女和在校学生的不同影响中, 基于 Drutsch 和 Kelman 的研究, 从信息、规范、价值观三种视角阐述了参照群体对消费决策的影响, 也称为信息性、功利性和价值性影响^[6]。而功利性与价值表现同属于规范性概念, 将参照群体影响分为信息性与规范性两个维度的研究取得了更好的测量效果^[4]。参照群体的信息性影响主要指参照群体传达消费某产品或服务过程中的有关消费信息, 丰富了消费者绿色消费知识, 利于明确自身需求; 参照群体的规范性影响主要表现为消费者在消费过程中因群体压力而隐藏自身态度、意愿, 做出符合群体规范的行为, 通过与群体成员行为保持一致维护自身形象, 从而避免惩罚或得到肯定与认可^[7]。

已有研究探讨了参照群体影响与消费行为之间的关系。不同类型、规模的参照群体会影响消费者的购买意愿, 亦会造成消费态度与行为差异, 如解芳等 (2019) 发现参照群体的信息性影响促进绿色购买意愿, 但由于当时绿色消费文化并不盛行, 未验证出功利性与价值表达性的影响作用^[3]; 陈凯和彭茜 (2014) 认为参照群体的功利性影响受群体结构的调节。参照群体规模越小, 人们之间关系更为紧密, 对购买行为有更大影响。但在传统消费方式占主导地位时, 持有绿色消费态度的个体会因群体规范而改变自身态度, 造成态度-行为缺口^[7]。然而, 在倡导绿色消费的时代背景下, 参照群体影响路径是怎样的, 参照群体对消费者决策时的心理状态产生了怎样的影响? 鲜有对信息性影响、规范性影响与绿色消费行为之间关系的作用机制研究。事实上, 从心理视角探讨参照群体对消费个体决策的影响有重要的理论与实际意义。本文结合中国消费情境, 将参照群体影响划分成信息性与规范性两个维度, 引入知识认知、感知行为控制、消费情感为中介变量, 构建多重中介模型, 探讨参照群体影响对绿色消费意愿的作用机理, 并据此提出适合本土化绿色消费的相关建议, 以期推动形成绿色消费风尚, 促进绿色消费的长远发展。

二、文献回顾与研究假设

1、参照群体影响与绿色消费意愿

参照群体指对个体决策行为有影响的有关个人或群体^[6]。在复杂多变的信息时代, 参照群体的影响愈加广泛。参照群体通常分为主要、次要与渴望群体^[3]。主要群体与消费者接触频繁, 产生更大的示范作用; 次要群体涉及一些正式组织, 接触较少; 渴望群体是消费者希望加入其中的群体, 从情感上影响着非群体成员的行为。根据参照群体理论, 群体的影响无处不在, 通过影响人们的社会心理状态进而作用于行为。参照群体的信息性影响与规范性影响会作用于个体消费行为^[8]。当消费者购买某种商品或服务时, 在不确定性影响下会搜索有关信息, 观察其信任人士的消费行为来判断品牌质量^[9], 获得充分信息后进行决策。消费者借由参照群体获得的更多信息在一定程度上降低了购买决策的不确定性。同时, 由于消费者身处于社会情境中, 更容易受周围群体影响而改变自身行为, 遵从群体规范以避免惩罚或赢得认同^[7]。当消费者在决策过程中为迎合群体而做出他人期望行为时, 参照群体就发挥了规范性作用。

已有研究发现, 参照群体影响对消费者购买意愿有促进作用。赵晓飞和高琪媛 (2016) 从参照效应视角探究了参照群体对农产品网购意愿的影响, 结果表明, 参照群体不仅有助于提高感知价值, 而且可以降低感知风险, 对农产品网购意愿有显著促进作用^[10]。宫秀双等 (2017) 采用多元回归法分析 1000 多个居民的消费数据后发现, 居民的消费意愿会因参照群体的信息性影响与规范性影响而显著提升。在绿色消费情境中, 参照群体也发挥了重要作用^[11]。如解芳等 (2019) 发现居民的绿色购买行为受参照群体信息性影响, 参照群体影响可以通过感知价值与绿色信任促进绿色消费。由此可知, 在绿色消费过程中, 消费者受到社会环境中的参照群体影响^[3]。一方面, 消费者通过观察参照群体的行为获得与产品、服务有关的更多信息, 在购买决策中降低不确定性感知, 促进购买意愿; 另一方面, 受周边群体的影响, 消费者会自觉遵从群体规范, 改变自身的态度、信念等, 做出符合群体期望的行

为。因此,本研究提出如下假设:

H1a: 参照群体的信息性影响正向促进绿色消费意愿;

H1b: 参照群体的规范性影响正向促进绿色消费意愿。

2、知识认知的中介作用

知识认知指消费者了解的绿色消费知识,是消费者对商品购买、处理等的有关信息认知^[12]。除了阅读、体验、试错等知识获取渠道外,观察他人的行为或听取他人的建议是重要的知识获取来源。绿色消费作为一种新颖的消费方式,消费者在购买决策中因对产品、服务等不了解的情况下,往往会积极收集有关信息,通过观察或参考“权威专家”、“形象代言人”等人言行的方式掌握产品有关知识^[9]。参照群体的信息性影响将有助于丰富知识储备,降低购买不确定性。同时,参照群体的看法或建议会影响消费者对产品、服务等感知态度,进而影响消费决策。同样,处于社会环境中的消费者会受到群体压力的影响。参照群体的规范性影响会向消费者传递期望信息,影响其消费行为。在绿色消费过程中,周围群体的绿色购买行为使其更为关注大众消费产品或服务的有关内容,在考虑群体行为的基础上做出迎合群体期望的行为。因此,本文提出如下假设:

H2a: 参照群体的信息性影响正向促进知识认知;

H2b: 参照群体的规范性影响正向促进知识认知。

绿色消费作为一种新颖的消费模式,在知识认知方面越完备的消费者将基于自身需求产生更为明确的购买意图。知识的积累有助于降低信息搜寻成本与感知风险程度^[13],进而提升购买意愿。*Schlegelmilch* 等(1996)认为消费者丰富的环境知识会促进绿色购买行为^[14]。*Stewart* 等(2015)认为参照群体提供的消费信息可以加深消费者对产品或品牌的印象,使其在购买过程更为高效,对后续消费行为产生正向影响^[15]。参照群体的信息性影响为消费者提供判断与选择的依据,丰富消费者的知

识认知和信息储备,转变消费者的意识观念^[16],从而促进产生绿色消费意愿。参照群体的规范性影响使消费者在社会环境中增强对参照群体偏好产品、品牌、服务或商家的了解,在群体压力下影响认知与选择^[17],从而做出从众行为。因此,本研究提出如下假设:

H3: 知识认知正向促进绿色购买意愿。

H4a: 知识认知在参照群体的信息性影响与绿色购买意愿之间起中介作用;

H4b: 知识认知在参照群体的规范性影响与绿色购买意愿之间起中介作用。

3、感知行为控制的中介作用

感知行为控制指对实际行动控制程度的认知,是对会影响特定行动目标实现控制方面的信念感知,感知到的行为障碍会阻碍行为发生,而预期的行为效果将增强消费意愿^[18]。例如,在绿色消费过程中受到风险感知、时间压力、低感知可获性等因素会削弱购买意愿^[19],对绿色消费提升生活健康品质、改善环境节约资源的效果认知会增强人们的绿色消费意愿^[20]。参照群体的信息性影响有助于节约认知努力,提供更多消费相关信息,从而降低感知风险,增强对绿色消费的控制程度认知。同样,参照群体的规范性影响使消费者在了解群体成员行为后与参照对象建立关联,基于群体成员的行为增强感知可获性与感知效果,提高行为的感知控制程度。因此,本文提出如下假设:

H5a: 参照群体的信息性影响正向促进感知行为控制;

H5b: 参照群体的规范性影响正向促进感知行为控制。

根据计划行为理论,感知行为控制对绿色消费意愿有正向促进作用^[21]。消费者的感知行为控制越高,对绿色消费行为的感知效果和行为控制认知越强,从而提升其绿色消费意愿。参照群体的信息性影响为消费决策提供更多信息,加深消费者对商品或服务属性的了解,降低不确定性因素,增强控制感知程度,进而提升绿色购买意愿

。参照群体的规范性影响使消费者为遵从群体规范获得价值性认同而做出群体一致性行为，提高绿色消费的感知效果^[10]，促进绿色消费意愿的形成。因此，本研究提出如下假设：

H6：知识认知正向促进绿色购买意愿。

H7a：知识认知在参照群体的信息性影响与绿色购买意愿之间起中介作用；

H7b：知识认知在参照群体的规范性影响与绿色购买意愿之间起中介作用。

4、消费情感的中介作用

消费情感指消费过程中对事物持有的情绪倾向，包含消费者的情感态度，如喜爱感、满足感、欣慰感等^[22]。根据社会互动理论，人们在社会环境中的相互交往与沟通联系，在心理与行为上会相互作用。参照群体的信息性影响与规范性影响使消费者获得更多绿色消费有关信息，在深化事物认知的基础上加深印象，迎合群体成员期望以获得他人认同与肯定。Bateman和Valentine（2015）通过观察消费者与销售人员的互动发现，与销售人员的接触增加了消费者对产品的购买信任^[23]。参照群体产生的社会性影响在社会互动过程中产生稳定的社会联

结^[24]，更多的信息储备与规范信息影响人们对绿色消费的情感态度。因此，本文提出如下假设：

H8a：参照群体的信息性影响正向促进消费情感；

H8b：参照群体的规范性影响正向促进消费情感。

Ritter等（2015）研究证实环境情感显著影响绿色购买意愿^[25]。前人研究发现，积极情绪会促使他人进行亲社会行为。当消费者将绿色产品与积极的情绪反应相联结，在消费过程中感受到的满足感会促进重复行为的发生，使人们对绿色购买产生积极主动的行为倾向。参照群体的信息性影响使消费者掌握更多绿色消费知识与相关技能，规范性影响使其遵从规范得到肯定，对绿色消费产生积极的情绪感受，在情感需求的影响下提升绿色消费意愿。因此，本研究提出如下假设：

H9：消费情感正向促进绿色购买意愿。

H10a：消费情感在参照群体的信息性影响与绿色购买意愿之间起中介作用；

H10b：消费情感在参照群体的规范性影响与绿色购买意愿之间起中介作用。

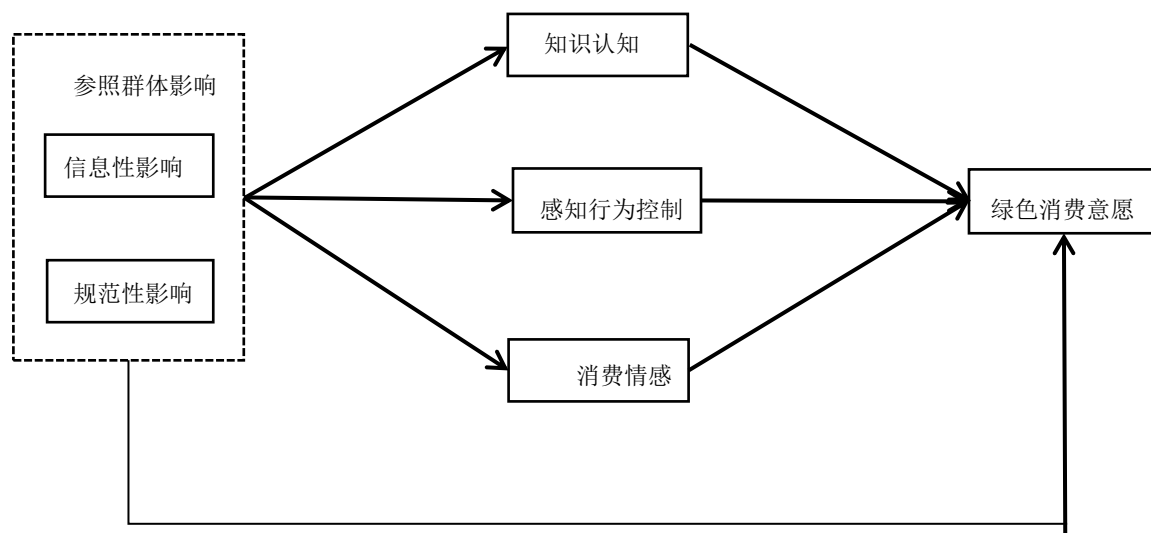


图1 研究模型

三、研究设计

1、变量测量

参照群体影响的量表是在借鉴Park和Lessig^[6]（

1977）提出的量表基础上，结合中国消费情境作简要修改，分为了信息性影响与规范性影响两大类，分别有4个题项、5个题项。知识认知与消费情感借

鉴了江元美^[20]（2011）和王建明^[26]（2015）开发的量表，知识认知有3个题项，消费情感有5个题项。感知行为控制参考了劳可夫^[18]（2013）开发的量表，共4个题项。绿色消费意愿参照了Gollwitzer^[27]（1999）开发的量表，共4个题项。同时，本研究将绿色消费行为具体化为对节能家电产品的购买行为，以获知具体绿色消费意愿。之所以选择节能家电产品是因为它具有一定的市场知晓度，消费者对节能家电产品的购买决策受客观环境及经济条件约束，属于理性消费行为^[18]。在问卷设计中，除人口统计

变量外，其他题项均采用Likert-7级量表测量。

2、数据获取与样本描述

本研究首先进行小样本预调研验证问卷的信效度。预调研共发放问卷115份，回收有效问卷98份，在预调研中各量表都通过了信效度检验。正式调研通过随机抽样的方式共发放问卷488份，在过滤掉填答随意或答案呈明显规律性的答卷后，回收有效问卷394份，有效回收率80.74%。正式调研中人口统计变量的描述性分析结果如表1所示。

表1 人口统计变量的描述性分析结果

特征变量	类别	频数	百分比 (%)
性别	男	179	45.4
	女	215	54.6
年龄	18-30 岁	259	65.7
	31-45 岁	94	23.9
	46 岁及以上	41	10.4
婚姻状况	未婚	224	56.9
	已婚	170	43.1
学历	初中及以下	30	7.6
	高中	69	17.5
	大学	204	51.8
	研究生及以上	91	23.1
职业	学生	131	33.2
	科研、教育和环境卫生领域的人员	21	5.3
	机关或事业单位工作人员	45	11.4
	企业管理人员	79	20.1
	一般工人或服务人员	61	15.5
	退休及其他	57	14.5
家庭可支配年收入	1-5 万元	74	18.8
	5-10 万元	143	36.3
	10-20 万元	115	29.2
	20-30 万元	45	11.4
	30 万元以上	17	4.3

四、假设检验与实证分析

1、信效度检验与同源偏差检验

本研究使用SPSS26.0软件检验问卷的信效度，问卷总体KMO值为0.929，Bartlett球形检验显著。各个潜在变量的KMO值均大于0.7，适合做因子分析。之后进行验证性因子分析，采用Cronbach'α系数法

检验信度，并计算各变量的组成信度（CR）与平均方差提取量（AVE）。结果如表2所示，所有观察变量的因子载荷均大于0.6，Cronbach'α与CR值均大于0.7，除感知行为控制的AVE为0.472，其他变量的AVE均大于0.5，说明问卷具有较好的信度与聚合效度。此外，本研究通过比较各变量两两之间的

Pearson系数与AVE平方根值，验证变量之间的区别效度。结果如表3所示，各个变量两两之间的Pearson相关系数均小于其自身的AVE平方根值，说明各潜在变量之间具有良好的区别效度。

本研究采用Harman单因子法检验同源偏差，结果表明，共有四个因子的特征根大于1，其中第一个因子的方差解释率为25.143%，小于40%，说明同源偏差不严重。

表 2 验证性因子分析及信度分析结果

潜在变量	观察变量	因子载荷量	Cronbach's α	组成信度（CR）	平均方差提取量（AVE）
信息性影响	II1	0.790	0.850	0.884	0.656
	II2	0.838			
	II3	0.810			
	II4	0.800			
规范性影响	NI1	0.773	0.869	0.892	0.625
	NI2	0.668			
	NI3	0.823			
	NI4	0.860			
	NI5	0.814			
知识认知	KC1	0.849	0.849	0.861	0.675
	KC2	0.826			
	KC3	0.788			
感知行为控制	PBC1	0.705	0.744	0.781	0.472
	PBC2	0.733			
	PBC3	0.655			
	PBC4	0.651			
消费情感	CE1	0.716	0.908	0.900	0.644
	CE2	0.779			
	CE3	0.877			
	CE4	0.820			
	CE5	0.812			
绿色消费意愿	GCW1	0.785	0.882	0.919	0.740
	GCW2	0.899			
	GCW3	0.909			
	GCW4	0.842			

注：II 为信息性影响（Information Influence），NI 为规范性影响（Normative Influence），KC 为知识认知（Knowledge Cognition），PBC 为感知行为控制（Perceived Behavioral Control），CE 为消费情感（Consumption Emotion），GCW 为绿色消费意愿（Green Consumption Willingness）。

表 3 区别效度分析结果

	1	2	3	4	5	6
1 信息性影响	0.810					
2 规范性影响	0.442**	0.791				
3 知识认知	0.450**	0.294**	0.822			
4 感知行为控制	0.419**	0.316**	0.534**	0.687		
5 消费情感	0.651**	0.330**	0.460**	0.593**	0.802	
6 绿色消费意愿	0.726**	0.441**	0.462**	0.433**	0.702**	0.860

注：N=394，对角线粗体字为 AVE 平方根，下三角数值为变量间 Pearson 相关系数，**表示在 1%水平（双侧）显著相关。

2、结构模型检验

首先，本研究运用MPLUS8.3软件验证模型的拟合情况，结果显示，Chi-square/Freedom degree=2.494，小于临界值3；CFI=0.911，达到0.9的临界值；TLI=0.898，接近0.9；RMSEA=0.062，SRMR=0.073，均小于临界值0.08，模型拟合情况良好。其次，验证变量之间的直接关系，将人口统计变量作为控制变量，对变量进行回归分析，分析结果如表4所示，验证了本文部分假设。再次，本研究验证参照群体影响与绿色消费意愿之间的中介效应，采用Bootstrap法进行5000次重复抽样，设置95%

的置信区间。若置信区间中不包含0，则表明中介效应存在。研究结果如表5所示，信息性影响与绿色消费意愿之间的三条中介路径影响显著，规范性影响与绿色消费意愿之间的三条中介路径影响显著。具体而言，参照群体的信息性影响与规范性影响可以通过知识认知影响绿色消费意愿，H4a、H4b成立；参照群体的信息性影响与规范性影响可以通过感知行为控制影响绿色消费意愿，H7a、H7b成立；参照群体的信息性影响与规范性影响可以通过消费情感影响绿色消费意愿，H10a、H10b成立。

表4 变量间回归分析结果

Hypotheses	Estimate	S.E.	Std. Estimate	Est./S.E.	P	Results
H1a: 信息性影响→绿色消费意愿	0.642	0.038	0.658	16.929	***	支持
H1b: 规范性影响→绿色消费意愿	0.139	0.035	0.154	3.979	***	支持
H2a: 信息性影响→知识认知	0.433	0.056	0.391	7.760	***	支持
H2b: 规范性影响→知识认知	0.116	0.051	0.113	2.250	0.025*	支持
H3: 知识认知→绿色消费意愿	0.403	0.040	0.456	9.997	***	支持
H5a: 信息性影响→感知行为控制	0.345	0.049	0.357	6.987	***	支持
H5b: 规范性影响→感知行为控制	0.136	0.046	0.151	2.981	0.003**	支持
H6: 感知行为控制→绿色消费意愿	0.434	0.046	0.430	9.376	***	支持
H8a: 信息性影响→消费情感	0.675	0.040	0.663	16.822	***	支持
H8b: 规范性影响→消费情感	0.309	0.046	0.326	6.684	***	支持
H9: 消费情感→绿色消费意愿	0.668	0.034	0.697	19.470	***	支持

注：*、**、***分别表示在 5%、1%、1%的显著性水平。

表5 中介效应结果

Path	Estimate	S.E.	LLCI	ULCI
直接效应				
信息性影响→绿色消费意愿	0.631	0.038	0.556	0.706
间接效应				
信息性影响→知识认知→绿色消费意愿	0.075	0.021	0.037	0.121
信息性影响→感知行为控制→绿色消费意愿	0.066	0.023	0.026	0.116
信息性影响→消费情感→绿色消费意愿	0.265	0.038	0.197	0.346
总效应	0.706	0.035	0.637	0.775
直接效应				
规范性影响→绿色消费意愿	0.298	0.040	0.219	0.378
间接效应				
规范性影响→知识认知→绿色消费意愿	0.092	0.020	0.057	0.136
规范性影响→感知行为控制→绿色消费意愿	0.091	0.024	0.051	0.143
规范性影响→消费情感→绿色消费意愿	0.185	0.033	0.140	0.270
总效应	0.390	0.042	0.308	0.473

五、研究结论与讨论

1、研究结论

本研究讨论了参照群体的信息性与规范性影响对居民绿色消费意愿的影响机理,构建多重中介模型分析了知识认知、感知行为控制与消费情感的中介效应。研究表明:参照群体的信息性影响与规范性影响有助于促进绿色消费意愿的形成;知识认知、感知行为控制、消费情感在参照群体影响与绿色消费意愿之间存在中介效应。具体而言,在绿色消费决策过程中,参照群体的信息性影响促进消费者了解产品或服务的属性特征,降低不确定性风险的情况下促进购买意愿;参照群体的规范性影响作用于消费观念,在群体压力下影响消费行为。绿色消费观念日渐被民众接受,规范性影响逐渐发挥重要作用,但目前的消费决策更依赖于信息性影响。参照群体的影响主要通过改变消费者的心理状态而发生作用,具体表现为参照群体丰富知识认知、提高感知效力,通过从事与他人一致性的行为满足自身被认同感,从而促进形成绿色消费意愿,有助于居民集体践行绿色消费行为。

2、管理启示

(1) 消费者频繁互动的对象同质性程度较高,容易形成消费圈子,共享消费相关知识、信息。同时,参照群体可以满足个人认同需要,使人们自觉遵守群体规范。参照群体的信息性影响便于消费个体知识获取,减少认知努力;规范性影响主要影响个体的价值认可等情感。在绿色消费观念日趋加强的背景下,政府可以组建专门的绿色消费社区,加强参照群体内部沟通,积极发挥参照群体的正向作用。企业也可以利用参照群体产生的口碑效应,组建网络社区,以社会化营销的方式促进绿色消费。一方面通过群体内的信息沟通,可以降低信息的获取障碍,营造浓厚的绿色消费氛围,利用现有的绿色消费个体去影响和挖掘更多的潜在绿色消费者,树立绿色消费典型,逐步形成全民参与绿色生活方式的新气象;另一方面绿色消费社区中的社会认同感将促进群体绿色消费,群体消费风向将进一步指引企业进行绿色生产创新,进而推动绿色消费的发

展。

(2) 消费者知识认知的缺乏会阻碍消费者绿色消费实践,通过多种传播渠道进行知识的广泛宣传,将环境行动知识、绿色消费理念渗透至生活各个方面,有助于提升社会大众对绿色消费的整体知识认知,推动绿色消费践行。同时,个体对绿色消费行为的感知效果和群体成员合作行为期望间的相互作用会调节态度和行为意向之间的关系。因此,政府需要着手打造更加安全、可信赖的购物消费环境,降低个体感知风险。通过广泛的宣传教育活动,强化个人对绿色发展的重要性认知,提升个体感知效力的同时提供更多产品可获性的信息,进一步激发消费者的行为意向及相应行为。另外,政府不仅可以从绿色生产方面为企业提提供经济利益刺激,还可以从绿色消费方面重视消费者补偿性绿色消费研究,将积极的情绪与绿色消费关联,在潜移默化中塑造更多真正的环保主义者。

3、局限与未来展望

本研究通过问卷调查的方式了解参照群体对居民绿色消费意愿的影响,横断面的研究难以获知变量间的动态关系,未来的研究可以进一步扩大样本范围与规模,采用纵向追踪的方式考察参照群体影响与绿色消费意愿的关系。此外,绿色消费的意愿与行为之间可能存在一定差别,未来的研究可以深入分析参照群体对实际绿色消费行为的影响,并探索参照群体影响的边界条件。

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企业绿色文化与企业节能行为：领导者支持、成员环境认知的影响

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摘要：本研究以企业文化理论、刺激-机体-反映理论和计划行为理论为基础，探讨企业绿色文化如何通过成员环境认知的中介作用影响节能行为。本研究共选取 859 名企业管理者和一般职工作为研究样本，采用 PLS-SEM 模型考察环境认知在绿色环境氛围、绿色制度文化、绿色理念文化与企业节能行为之间的中介作用，以及领导者支持、行业污染水平的调节作用。研究结果表明，（1）企业绿色文化对企业节能行为和成员环境认知具有正向影响；（2）环境认知在绿色文化与节能投资行为、节能管理行为之间起中介作用，而在绿色文化与社会交际行为的中介影响不显著；（3）领导者支持在绿色制度文化与环境认知的关系中起正向调节作用；（4）不同污染水平下的文化与行为关系存在一定差异。最后，基于实证结果提出了促进节能行为的相关建议。

关键词：绿色文化；节能行为；领导者支持；环境认知

Corporate green culture and corporate energy-saving behaviour: the impact of leader support and member environmental cognition

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Abstract: This study proposed a framework to explore how corporate green culture influences energy-saving behaviour through the mediating role of members' environmental cognition based on corporate culture theory, stimulus-organism-response theory and theory of planned behaviour. A total of 859 corporate managers and general workers were selected as the research sample, and the PLS-SEM was used to examine the mediating role of environmental cognition between green environmental climate, green institutional culture, green philosophy culture and energy-saving behaviour, as well as the moderating role of leader support and industry pollution levels. The results showed that (1) corporate green culture has a positive influence on corporate energy-saving behaviour and members' environmental cognition; (2) environmental cognition mediates between green culture, energy-saving investment behaviour and energy-saving management behaviour, while the mediating effect between green culture and social-communicative behaviour is not significant; (3) leader support plays a positive moderating role in the relationship between green institutional culture and environmental cognition; (4) there are certain differences in the relationship between culture and behaviour at different pollution levels. Finally, relevant recommendations to promote energy-saving behaviour are proposed based on the empirical results.

Key words: Corporate green culture, Corporate energy-saving behaviour, Leader support, Environmental cognition

企业环境行为是否有利于企业内在价值？工作意义、个人-组织价值观匹配的影响

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摘要：企业通常将其环境行为视为利他性举措，对其是否能够提升自身内部价值仍持有怀疑。因此，基于社会认同理论，本研究深入探究感知到的企业环境行为与其内部价值之间的关系。鉴于组织公民行为是提升组织绩效，为企业创造价值的重要途径，因此，本文将组织公民行为作为企业内部价值的直接代理，构建了企业环境行为与组织公民行为的理论模型。通过对收集的249份有效问卷数据测试假设模型，我们发现一定程度上，感知到的企业环境行为可以通过促进工作意义进而正向影响组织公民行为的提升，更进一步的，较高的person-organization value fit会强化该正向效应。这表明，企业可以通过实施环境行为来促进组织公民行为，并重视员工工作意义在激发员工组织公民行为中所起的内在驱动作用，person-organization value fit在这个过程中的边界作用，以此帮助企业实现自身价值的提升，进而纠正企业对环境行为能够实现的价值认知偏差。

关键词：企业环境行为，组织公民行为，工作意义，人与组织价值观匹配，内在价值

Is corporate environmental behavior beneficial to corporate internal value? Corporate environmental behavior, organizational citizenship behavior and the mediating role of work meaning

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Abstract: Corporate environmental behavior is often viewed as an altruistic initiative, yet companies remain skeptical of its ability to enhance their internal value. Therefore, based on social identity theory, this study delves into the relationship between corporate environmental behavior and its internal value. Research has shown that organizational citizenship behavior can be a significant way to enhance organizational performance and create value for companies. This research considers organizational citizenship behavior as a direct agent for internal corporate value and constructs a theoretical model of corporate environmental behavior and organizational citizenship behavior. By testing the hypothesized model with a sample of 249 responses collected through a questionnaire survey, we found that perceived corporate environmental behavior positively influences organizational citizenship behavior by promoting work meaning, and this positive effect is strengthened with a higher person-organization value fit. These findings indicate that firms can promote organizational citizenship behavior through implementing corporate environmental behavior. Findings indicate that in the process of motivating employees to implement organizational citizenship behavior, firms shall attach importance to the internal driving power of employees' work meaning and the boundary-spanning roles of person-organization value fit, to enhance corporate value and correct corporate cognition deviation on the value of corporate environmental behavior.

Key Words: corporate environmental behavior; organizational citizenship behavior; work meaning; person-organization value fit; internal value

群体共情视角下的绿色消费行为 ——自我-他人重叠的调节效应

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摘要：绿色消费行为中消费者态度和行为之间常常存在一定的缺口。考虑到 Z 世代消费者特殊的消费群体性和社交网络性特征，本研究基于共情理论，构建了消费者环境关切对绿色消费行为的影响过程模型，同时探讨了自我-他人重叠的调节驱动效应。研究结果显示：环境关切对绿色消费行为具有显著的正向影响，共情在环境关切与绿色消费行为之间起到中介作用。此外，群体社交背景下，自我-他人重叠在环境关切与群体共情之间起到调节作用，提升消费者的自我-他人重叠，能够显著改善群体性消费者的绿色消费意愿。

关键词：绿色消费，群体共情，自我-他人重叠，Z 世代

Understanding Green Consumer Behavior from the Perspective of Group Empathy—— the Moderating Effect of Self-other Overlap

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Abstract: There is often a gap between consumer attitude and behavior in green consumer behavior. Considering the special consumer group and social network characteristics of Generation Z consumers, this study builds a process model of the impact of consumer environmental concerns on green consumption behavior based on the theory of empathy, and explores the moderating driving effect of self-other overlap. The results show that environmental concern has a significant positive impact on green consumption behavior, and empathy plays a mediating role between environmental concern and green consumption behavior. In addition, in the context of group social interaction, self-other overlap plays a moderating role between environmental concern and group empathy, and improving consumers' self-other overlap can significantly improve consumers' green consumption intentions.

Key words: green consumption, group empathy, self-other overlap, Z generation

敬畏感对绿色消费的影响：家庭生命周期的调节作用

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摘要：基于敬畏原型理论和家庭生命周期理论，本文通过三个实验研究了敬畏对绿色消费意愿的积极作用以及家庭生命周期的调节作用。研究 1 研究了敬畏感对消费者绿色消费意愿的积极影响。研究 2 发现上述积极影响由渺小感中介。研究 3 发现处于满巢 1 阶段和满巢 2 阶段（相较于其他生命周期阶段）的被试在敬畏情绪影响下绿色消费意愿得到显著提升。

关键词：敬畏感，渺小感，家庭生命周期，绿色消费意愿

The effect of awe on green consumption: The moderating role of family life cycle

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Abstract: Based on the prototype theory of awe and family life cycle theory, this paper studies the positive effect of awe on green consumption intention and the moderating effect of family life cycle through three experiments. Study 1 studied the positive impact of awe on consumers' green consumption intention. Study 2 found that these positive effects were mediated by feelings of smallness. In study 3, it was found that participants in full nest stage 1 and full nest stage 2 (compared with other life cycle stages) were significantly more willing to consume green under the influence of awe.

Key Words: Awe, Small Self, Family Life Cycle, Green Purchase Intention

自利型领导会阻碍员工绿色行为吗？环境责任感、自利动机和组织伦理氛围的影响作用

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摘要：本研究立足酒店行业，聚焦员工绿色行为中“对他人有利却需自身付出成本”的逻辑矛盾特征，探讨了消极领导风格——自利型领导是否以及如何阻碍了员工实施绿色行为。为了进一步探讨这一问题，本文从社会信息加工理论的视角，构建了一个多层次被调节的中介模型。我们通过问卷调查了我国多个酒店行业107个工作团队及其369个下属及其主管，实证结果支持了我们的假设，表明员工的环境责任感、自利动机在自利型领导和员工绿色行为之间起中介作用。研究还表明，组织伦理氛围对自利型领导与员工的环境责任感（自利动机）之间的关系有负向调节作用，这种伦理氛围也通过员工的环境责任感（自利动机）对自利型领导与员工绿色行为的间接影响有负向调节作用。这些结果告诉实践界，培养酒店员工的环境责任感，降低其自利动机，营造符合酒店绿色规范的伦理氛围，抑制领导者在组织中的自利型领导风格，是提高员工绿色行为的关键。

关键词：自利型领导，环境责任感，自利动机，员工绿色行为，组织伦理氛围

Does Self-interested Leadership Enhance Employee Green behavior? The Effect of Environmental responsibility, Self-interest motivation, and Organizational ethical climate

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Abstract: Based on the hospitality, this research focuses on the logical contradictory characteristics of employee green behavior of “benefiting others but at one's own cost”, and explores whether and how self-interested leadership, a negative leadership style, hinders employees from implementing green behaviors. In order to explore it further, this article tries to build a multilevel moderated mediation model from the perspective of social information processing theory. We investigated 107 work teams and 369 subordinates and their supervisors in several hotel enterprises in China through questionnaires, and the empirical results supported our hypothesis. It shows that environmental responsibility, self-interest motivation mediated the relationship between self-interested leadership and employee green behavior. It also indicates that organizational ethical climate negatively moderated the relationship between self-interested leadership and employees' environmental responsibility (self-interest motivation), and this ethical climate also negatively moderates the indirect effect of self-interested leadership on employee green behavior through employees' environmental responsibility (self-interest motivation). These results inform the practical circles that strengthening hotel employees' sense of environmental responsibility, weakening his or her self-interest motivation, creating an ethical climate in line with hotel green norms, and restraining leader's self-interested leadership style in organization should be effective ways of enhancing employee green behavior.

Key Words: Self-interested leadership, environmental responsibility, self-interest motivation, employee green

绿色游戏化设计对年轻一代亲环境行为的影响研究

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摘要：当前全球对环境问题的重视提升到了前所未有的高度，兴起的游戏化概念已经吸引了教育和市场营销等领域学者和专业人士的关注，游戏化能否应用以及高效运作到亲环境行为的领域已成为当前亟需深入探究的重要问题。本文基于文献背景和实践营销运用，建立了游戏化设计对年轻一代亲环境行为影响的理论模型，以在线游戏化互动平台（蚂蚁森林）为研究对象，从游戏化设计的角度出发，探索享乐型和功利型两类绿色游戏化设计机制对年轻一代（18 至 30 岁）的亲环境行为的影响，并引入游戏化呈现方式的高低解释水平作为调节，对亲环境情境下游戏化的应用进行深入探究。通过问卷调查获得的 974 份有效的问卷，通过回归分析得出：（1）绿色游戏化设计对年轻一代亲环境行为有显著正向影响，并且情感共情和认知共情在两者之间起中介作用；（2）游戏化呈现方式对游戏化设计和共情之间关系有显著的正向调节作用。由此可知，通过游戏化机制设计和游戏化呈现方式的改变提高个体的情感共情和认知共情，来提高亲环境行为是有效的方式。研究结果有助于为企业管理者提出政策建议，通过对游戏化呈现方式高低解释水平和游戏化机制的设计，进一步影响游戏化的有效性，改善环境问题，建立人与自然和谐共处的环境友好行为模式。

关键词：绿色游戏化设计；共情；亲环境行为；解释水平

Research on the Influence of Green Gamification on the Pro-environmental Behavior of the Young Generation

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Abstract: At present, the global attention to environmental issues has been raised to an unprecedented height. The rising concept of Gamification has attracted the attention of scholars and professionals in the fields of education and marketing. Whether Gamification can be applied and operated efficiently to the field of pro-environmental behavior has become an important issue that needs to be deeply explored. Based on the literature background and practical marketing application, this paper establishes a theoretical model of the impact of game design on the pro environmental behavior of the young generation. Taking the online game interactive platform (ant forest) as the research object, from the perspective of game design, this paper explores the impact of hedonic and utilitarian green game design mechanisms on the pro environmental behavior of the young generation (18-30 years old). It also introduces the high and low interpretation level of Gamification presentation as the adjustment to deeply explore the application of Gamification in the context of Pro environment. Through the regression analysis of 974 valid questionnaires obtained from the questionnaire survey: (1) green game design has a significant positive impact on the pro environmental behavior of the young generation, and emotional empathy and cognitive empathy play an intermediary role between them; (2) Playful presentation has a significant positive regulatory effect on the relationship between playful design and empathy. Therefore, it is an effective way to improve the pro environmental behavior by improving individual emotional empathy and cognitive empathy through the design of game mechanism and the change of game presentation. The research results are helpful to put forward policy suggestions for enterprise managers, further affect the effectiveness of Gamification, improve environmental problems, and establish an environment-friendly behavior model of harmonious coexistence between man and nature through the high and low

interpretation level of Gamification presentation and the design of Gamification mechanism.

Key Words: green gamification; empathy; pro-environmental behavior; interpretation level

个体情感对居民自愿减碳行为的影响机理——基于印象管理动机视角

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摘要：在可持续发展理念的指导下，促进居民自愿减碳对于节能减排目标的实现具有重要影响。本文基于动机理论，以印象管理动机作为中介变量构建个体情感对居民自愿减碳行为的影响机制模型，运用 535 份江苏省城市居民样本数据进行实证分析，探析个体情感对于居民自愿减碳行为的影响机理，并检验印象管理动机的中介作用。结果显示：个体情感的三个维度，即行为共情、自然共情、代际共情对自愿减碳人际行为和自愿减碳公民行为均具有显著正向影响；自然共情对自愿减碳素养行为起负向影响作用；印象管理动机在个体情感三个维度与自愿减碳人际行为的关系中分别起着部分中介作用。基于研究结果，本文提出引导居民自愿减碳行为的相关政策建议。

关键词：居民自愿减碳，印象管理动机，个体情感

Influence mechanism of individual emotions on residents' voluntary carbon reduction behavior: Based on the perspective of impression management motivation

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Abstract: Under the guidance of the concept of sustainable development, promoting residents' voluntary carbon reduction has an important impact on the realization of energy conservation and emission reduction goals. Based on motivation theory, this paper uses impression management motivation as an intermediary variable to construct a model of the influence mechanism of individual emotional factors on residents' voluntary carbon reduction behavior. The study uses 535 sample data of urban residents in Jiangsu Province to conduct an empirical analysis to explore the impact of individual emotional factors on residents' voluntary carbon reduction behavior and examine the mediating role of impression management motivation. The results show that: the three dimensions of individual emotional factors, namely behavioral empathy, natural empathy, and intergenerational empathy, have a significant positive impact on voluntary carbon reduction interpersonal behavior and voluntary carbon reduction citizen behavior; natural empathy has a significant positive impact on voluntary carbon reduction literacy behavior; impression management motivation played a negative role; impression management motivation played a partial mediating role in the relationship between the three dimensions of individual emotional factors and voluntary carbon reduction interpersonal behavior. Based on the research results, this paper puts forward relevant policy recommendations to guide residents' voluntary carbon reduction behavior.

Key Words: residents' voluntary carbon reduction, impression management motivation, individual emotion

形象建设视角下个体食物浪费行为形成机制研究

顾笑

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摘要：个体对外在容貌及社会认同感的重视为揭示其行为起因提供了独特视角。本研究从外表形象建设和社交形象建设需求出发探讨中国个体食物浪费行为的形成机制，特别考虑了情绪、文化程度和 BMI 指数在关系传导中所扮演的角色。通过问卷调研数据（N=749），采用因子分析、相关分析和层次回归分析方法，发现对外表形象及社交形象建设需求高的个体均更倾向于发生食物浪费行为。在传导机制方面，激动、兴奋等积极情绪和焦虑、厌恶等消极情绪是形象建设影响食物浪费行为的中介因素，情绪波动会加剧个体产生食物浪费。在交互效应方面，BMI 指数显著地正向调节形象建设对食物浪费行为的预测作用，文化程度则缓冲了这种预测作用。最后，为减少食物浪费提出相关政策建议。

关键词：外表形象；社交形象；食物浪费行为；传导机制

Research on the formation mechanism of individual food waste behavior from the perspective of image construction

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Abstract: The attention regarding individuals' external appearance and social identity provides a unique perspective to reveal the cause of their behavior. This study explored the formation mechanism of individual food waste behavior in China from the needs of appearance image construction and social image construction, especially considering the role of emotion, education level, and Body Mass Index (BMI) in relationship transmission. This study collected data by questionnaire in 133 cities in 32 provinces of China. By using the methods of factor analysis, correlation analysis, and hierarchical regression analysis, this study found that individuals with high need for external appearance image and social image construction are more likely to waste food. In terms of transmission mechanisms, positive emotions (such as excitement) and negative emotions (such as anxiety and disgust) are the intermediary factors of image construction affecting food waste behavior, and emotional fluctuations can aggravate individual's food waste behavior. In terms of interaction effects, BMI index significantly positively regulates the predictive effect of image construction on food waste behavior, while the level of education buffers this predictive effect. Finally, relevant policy suggestions are put forward to guide individuals to reduce food waste.

Keywords: appearance image; social image; food waste behavior; formation mechanism