New Energy Supply Chain Configuration Diversified Development: The Role of the Digital Economy

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***Abstract*—The profound integration of the digital economy and supply chain (SC) is a crucial guarantee for enhancing the resilience and security of new energy SC. Existing research mainly focused on the impact of digital economy on enterprise internal characteristics, with relatively limited attention to the study of multiagent collaboration in the SC. Based on data from listed new energy enterprises from 2011 to 2021, this article employed a two-way fixed-effects model to explore the impact and mechanism of the digital economy on the new energy supply chain configuration (SCC). The research reveals that: 1) Digital economy can significantly promote the SCC diversified development. After some endogeneity tests, the research results remain robust. 2) Digital economy can significantly enhance the downstream customer sales diversification, with limited impact on upstream supplier procurement. Nonstate-owned enterprises in a disadvantaged position are more inclined to promote SC diversification through digitization. This impact is more pronounced in the eastern region. 3) Digital economy can promote the diversified development by improving the supply–demand matching accuracy, reducing external transaction costs, and promoting technological innovation. The research conclusion and policy suggestions can provide a theoretical basis for digital transformation and diversified development of new energy enterprises.**

***Index Terms*—Digital economy, digitization, diversified development, new energy, supply chain (SC) configuration.**

I. Introduction

IN THE current global landscape marked by political and economic turbulence, geopolitical tensions, trade frictions, extreme weather events, and other factors profoundly impact the stability of global supply chains (SCs). Persistent "bottlenecks," "breakpoints," and "weak links" at the level of industrial and SC operations have long been critical structural issues hindering the efficiency improvement of China's industrial development and the smooth circulation of the national economy [1]. The Chinese government has prioritized achieving self-control and autonomy in industrial and SCs, emphasizing the enhancement of domestic circular dynamics and reliability, the elevation of international circulation quality and standards, and the accelerated construction of a modern economic system. This involves a concerted effort to increase overall factor productivity, improve the resilience and security levels of industrial and SCs, and make substantial progress in energy transition towards building a clean, low-carbon, secure, and efficient energy system [2]. Against this backdrop, the rapid development of the new energy industry has emerged as a crucial initiative to address climate change and ensure energy security [3]. Consequently, the resilience and security of China's new energy industry chain and SC hold significant practical significance for accelerating the establishment of a new development paradigm.

Simultaneously, the rapid development of digital technologies, represented by artificial intelligence, blockchain, cloud computing, and Big Data, has become a crucial means for transforming and enhancing traditional momentum while cultivating new development forces [4]. The impact of digital economy (DE) on enterprises extends beyond their internal operations, it has the potential to alter their relationships with the external components of the SC [5]. Traditional SC operating models often suffer from pain points such as slow market responsiveness, low levels of information sharing between upstream and downstream entities, and high operational risks, severely constraining the efficient operation of enterprise SCs. There is an urgent need for deep integration with digital technologies to propel the SC into a new era of digitization. By endowing the SC with new features such as support from Big Data, networked sharing, and intelligent collaboration, digital technologies can enhance information transparency at various stages, increase the sensitivity of the SC to market demands, and facilitate the SC efficient operation [6].

In the dual context of the DE and the energy low-carbon transformation, new energy enterprises can leverage digital technologies to enhance information sharing and collaboration with upstream suppliers and downstream customers. This enables the redesign and planning of SC structures and activities, thereby driving the gradual transition of new energy enterprises' SC operations from traditional to digital modes [7]. Therefore, the DE can reconfigure the collaborative relationships between upstream and downstream stakeholders in the new energy industry chain through means such as data-driven approaches, information sharing, resource optimization, and organizational changes. This transformation alters SC governance structures and optimizes the SC configuration (SCC) of new energy enterprises [8]. Based on this, this article utilized data from Chinese A-share listed new energy enterprises from 2011 to 2021 to calculate the diversification degree of supplier procurement and customer sales. This metric serves as a crucial indicator to measure the new energy SCC. Simultaneously, this article constructed a

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comprehensive index for the DE development at the city level to investigate the impact of it on the new energy SCC. We further examined potential heterogeneity in this impact and explored its mechanisms from three aspects: supply–demand matching accuracy, external transaction costs, and technological innovation (TI). Based on the research findings, this article presented targeted policy recommendations, aiming to provide insights and references for China in enhancing the resilience of the new energy SC and achieving low-carbon energy transition.

This article's potential contributions are as follows.

1) Existing literature primarily examined the impact of digital technology on enterprise production efficiency, performance, innovation, and stock liquidity, focusing mainly on characteristics at the internal level of the enterprise. There is a relative lack of research transitioning from internal management collaboration to a broader study of multiagent collaboration within the SC. This article explored the impact of the DE on the new energy SCC, enriching and expanding the relevant research on the integration of digital technology with the SC. It provides new perspectives and insights for subsequent research.
2) Current studies often concentrated on factors influencing the overall SC structure. In contrast, this article focused on the new energy SC, examining the impact mechanisms of the DE on new energy SCC from aspects such as supply–demand matching, transaction costs, and TI. It systematically extended research on DE to the new energy SCC, serving as a reference for related studies.
3) The research results and corresponding policy recommendations in this article can provide a theoretical basis for the digital transformation (DT) and diversified development of new energy enterprises. This is advantageous for new energy enterprises in formulating adjustment strategies in the current highly uncertain economic environment, effectively optimizing the new energy SCC, enhancing SC resilience and security, and steadily advancing the low-carbon energy transition.

II. Literature Review and Theoretical Mechanism

A. Digital Economy and Enterprise Characteristics

As a transformative technological and organizational change characterized by disruptive innovation, the DE has reshaped the underlying logic of enterprise value creation. The academic community has conducted in-depth research on the microeconomic effects of digital technology applications. Lin and Xie [9] pointed out that the DE has improved the operational efficiency of power companies by promoting innovation, increasing capital utilization, and alleviating capital constraints. Tang et al. [10] employed a multidimensional fixed-effects model to explore the impact of the DE on corporate green innovation based on microdata from Chinese A-share listed companies from 2011 to 2020. Cheng et al. [11] found that the total factor productivity of real economy enterprises initially declines during the early stages of DE, but improves beyond a critical threshold. They noted that this impact is primarily achieved through turnover rate of operating funds, human capital structure, and financing constraints. Building on these studies, scholars have further investigated how the DE influences corporate organizational structures to improve energy efficiency and environmental performance [12], [13], [14].

We can find that existing literature primarily focused on the impact of digital technology on enterprise production efficiency, performance, organizational structures, corporate innovation [15], stock liquidity, and other internal characteristics. However, these studies mainly focused on the internal characteristics of enterprises and did not capture the more fundamental features of the DE, namely the transition from internal management collaboration within enterprises to a broader study of multiagent collaboration within the SC. Overall, the current research on how DE influences collaborative relationships among various entities at different nodes of the SC is relatively limited.

B. Digital Economy and SC

With the widespread application of DE in the SC field, domestic and foreign scholars have explored the effects of it on the SC from different perspectives [16], [17], [18]. First, some studies have analyzed information sharing among different entities in the DE and SC. Wang et al. [19] found that blockchain technology, as a shared distributed database, can facilitate information sharing, reduce information asymmetry, and enhance the collaborative efficiency of all participants in the SC. Wang et al. [20] pointed out that Big Data technology helps improve the information visibility, making SC decisions more intuitively transparent and better predicting supply and demand uncertainties. Second, the DE enhances the traceability of SC information [21]. Behnke and Janssen [22] demonstrated that digital technology visualizes the entire process of food from raw material procurement to sales, contributing to the establishment of a comprehensive food quality safety traceability system and ensuring the food safety level. Third, the DE increases the trust level among different entities in the SC. The decentralized nature of digital technology enables supply and demand sides to break free from traditional models that rely on personality or third parties to establish trust relationships, achieving trust transactions without the need for trust. Korpela et al. [23] found that the information aggregation function of blockchain technology can reduce the occurrence of information distortion and opportunistic behavior. Song et al. [24] discovered that digital technology is an effective way to address trust issues in the SC finance network. Finally, some studies have discussed the impact of the DE on SC management and environmental performance [25], [26], [27]. Yuan and Pan [28] explored how the DE application to influence an enterprise's circular economy capability through SC management, considering aspects such as SC risk management, SC collaboration, and SC integration. Li et al. [29] empirically calculated and analyzed the carbon emissions and evolution of China's DE between 2007 to 2017 from the perspective of the entire industry chain.

The above-mentioned literature examined the effects of the DE on the SC from various perspectives. However, there is currently a relatively limited amount of research systematically investigating the relationship between the DE and SCC. The specific connections and causal mechanisms between the two still be unclear. In addition, existing studies mostly focused on the impact of the DE on the entire industry chain structure, with a significant lack of research on the new energy SC. Therefore, this article concentrated on the new energy SC, examining the impact mechanisms of the DE on its configuration from aspects such as supply–demand matching, transaction costs, and TI. This study systematically extended the research on DE to the new energy SCC. The research findings and corresponding policy recommendations can provide a theoretical basis for the DT and diversified development of the new energy SC.

C. Theoretical Mechanism Analysis

Digital technology is a key driving force for the SC innovative development, propelling SC management towards increased digitization, networking, and intelligence [30]. It can be inferred that the widespread application of digital technology will be advantageous in strengthening effective collaboration between upstream and downstream enterprises in the new energy SC, reducing operational and transaction costs for businesses, and fostering supply–demand matching accuracy as well as TI.

1) Supply–Demand Matching Accuracy: The SC constitutes a collaborative system involving different stakeholders, yet the independence of suppliers and demanders in terms of products or business activities forms the objective basis for the contradictions in supply and demand within the SC. Due to this separation of supply and demand, coordination between upstream and downstream in the SC involves reconciling differences in spatial locations, production quantities, timing of supply and demand, and commodity valuations. Throughout the collaborative process in the SC, partners both upstream and downstream need to engage in multiple communications and coordination efforts to address supply and demand differences and dynamic situations [31]. DE can effectively reduce information asymmetry between upstream and downstream enterprises in the new energy SC, enhancing the degree of information and resource sharing. This allows enterprises to better understand the dynamic changes of key upstream suppliers and downstream customers, eliminate coordination obstacles, reduce SC redundancy, and facilitate more efficient collaboration with upstream suppliers and downstream customers. Therefore, DE can effectively enhance the supply–demand matching accuracy in the management of the new energy SC, thereby encouraging new energy enterprises to lean towards diversification in SCC.

2) External Transaction Costs: Drawing insights from the analysis of DE activities by Goldfarb and Tucker [32], the cost reduction effects of DE on the SC processes are primarily manifested in three aspects. First, DE enhances the transparency of SC information, reducing monitoring costs. Authorized individuals can now access information about the entire process from product origin to sale, significantly improving the transparency of the entire SC. This ensures that all involved parties can promptly identify issues in the operation of the SC system, thereby reducing the monitoring costs associated with SC operations. Second, DE drives the transformation and upgrading of logistics towards intelligence, greatly reducing logistics transportation and inventory costs. Smart logistics formed based on DE has significant advantages in warehouse location optimization and goods transportation. Utilizing technologies such as cloud computing and Big Data, it can optimize the layout of stored goods, seamlessly integrate warehousing networks and distribution networks, and greatly enhance logistics efficiency [33]. Finally, DE can enhance the trust between enterprises, reducing the cost escalation caused by the risk of default. Due to the permanent tracking feature of digital technology, the behavior of transaction participants will be permanently recorded, helping enterprises to more reasonably arrange production plans and reduce excessive inventory due to mutual distrust [34].

3) Technological Innovation: Numerous studies indicate that the DE can significantly drive TI in new energy enterprises [35], [36]. With the emergence of new products, services, and business models, this digital revolution has transformed the behavior of both enterprises and consumers, enhancing efficiency, reducing costs, and fostering the emergence of new industries and markets. This has diversified transactions between suppliers and customers in the new energy sector.

Based on the above-mentioned analysis, the DE primarily promotes SC diversification of new energy enterprises through three pathways: enhancing supply–demand matching accuracy, reducing external transaction costs, and fostering TI. This optimization contributes to the overall enhancement of the new energy SCC.

III. Methodology

A. Benchmark Model

This article employed a two-way fixed effects model to investigate the impact of the DE on the new energy SCC. The baseline model is as follows:

$$\mathrm{SCC}_{ijt} = \alpha_0 + \beta_1 DE_{jt} + \gamma X'_{ijt} + \theta X''_{jt} + u_i + \lambda_j + \delta_t + \varepsilon_{ijt} \quad (1)$$

where the explained variable is SCC_{ijt}, representing the SCC of new energy enterprise i in year t. DE_{jt} is the core explanatory variable, denoting the digital economy composite development index of the city j in year t. β_1 represents the marginal effect of the DE on the new energy SCC. X'_{ijt} denotes the individual-level control variables, and X''_{jt} represents the city-level control variables. u_i, λ_j, and δ_t represent the individual, city, and time fixed effects, respectively. ε_{ijt} is the random disturbance term.

B. Variable Selection

1) Explained Variable: The explained variable in this study is the SCC of new energy enterprises, measured by the diversification of supplier procurement and customer sales. The core distinction between centralization and diversification lies in whether an enterprise's procurement is concentrated among a few suppliers with high proportions and whether its sales are concentrated on a few customers with high proportions. Regarding suppliers, if a significant proportion of the purchase amount comes from a few top-ranked suppliers, meaning that the company primarily sources inputs from a limited number of upstream suppliers, it is considered to have a high level of supplier concentration. Conversely, if this proportion is low, indicating that the enterprise procures inputs more evenly from multiple suppliers, its supplier configuration is considered more diversified. The same principle applies to downstream customer sales. Following existing research [37], excluding the top five suppliers and customers, this article used the mean proportion of purchases from other suppliers and the mean proportion of sales to customers to measure the diversification degree. This can also be expressed as follows:

$$\begin{aligned}\text{Diversification}_{it} &= 1 - \text{Centralization}_{it} \\ &= 1 - \frac{\sum_1^5 \text{SPR}_{it} + \sum_1^5 \text{CSR}_{it}}{2}. \qquad (2)\end{aligned}$$

In this context, $\text{Diversification}_{it}$ represents the SC diversification degree of new energy enterprises, while $\text{Centralization}_{it}$ indicates the SC centralization level. $\sum_1^5 \text{SPR}_{it}$ represents the sum of the procurement proportions from the top five suppliers, $\sum_1^5 \text{CSR}_{it}$ represents the sum of the sales proportions to the top five customers.

2) Core Explanatory Variable: The core explanatory variable in this study is the urban-level DE. We measured the comprehensive development level of the DE by combining data availability from the perspectives of Internet development and digital financial inclusion. For the measurement of Internet development at the urban level, following the approach in the literature [38], we utilized four indicators: Internet penetration rate, relevant employment, related output, and mobile phone penetration rate. The actual content corresponding to these four indicators includes the number of broadband Internet access users per hundred people, the proportion of employees in the computer services and software industry to urban units' employees, per capita telecommunications service volume, and the number of mobile phone users per hundred people. The original data for these indicators can be obtained from the "China City Statistical Yearbook." For the development of digital finance, the China Digital Inclusive Finance Index is used. This index is jointly compiled by Peking University Digital Finance Research Center and Ant Group [39]. Through principal component analysis, the data for these five indicators are standardized to reduce dimensionality, and the obtained index represents the comprehensive development of the DE.

3) Control Variables: To more accurately explore the impact of DE on the new energy SCC, this study needs to include control variables that may affect SCC. At the individual enterprise level, we selected enterprise age (Lnage), enterprise size (Lnsize), capital intensity (CI), enterprise financing constraints (WW) [40], research and development (RD), the proportion of independent directors (IDP), and equity balance degree (EBD) as control variables [41]. At the city level, we choose the level of urban economic development (Lncgdp), industrial structure (CIS), urban population size (Lncpop), and urban technological level (CTL) as control variables [42].

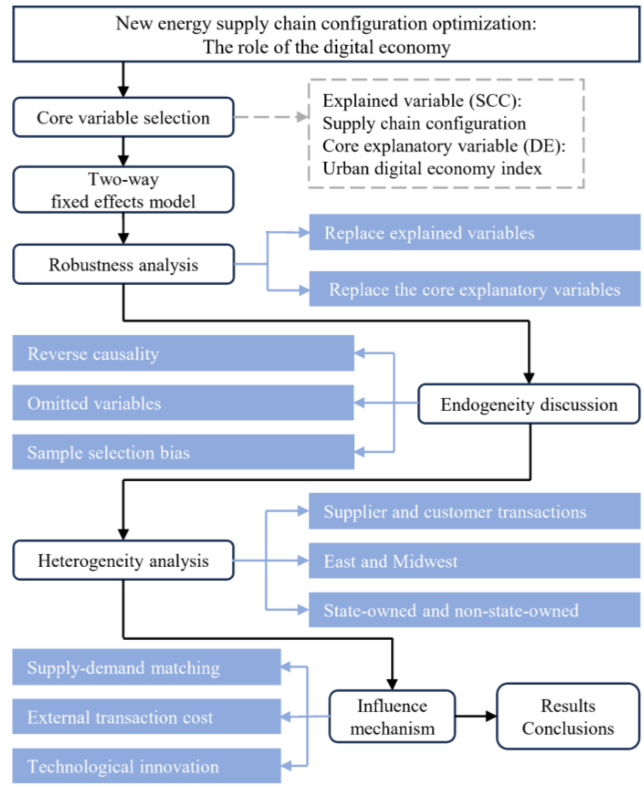

Fig. 1. Flow chart of the study.

C. Research Framework

This article primarily examined the role of the DE in optimizing the new energy SCC, as illustrated in Fig. 1. The research process can be divided into five steps. First, we constructed panel data and employed a two-way fixed-effects model to investigate the direct impact of the DE on the SCC of new energy enterprises. Second, to ensure the reliability of empirical results, we conducted robustness analyses by substituting both the explained and core explanatory variables. Third, to address potential endogeneity issues, we adopted methods involving a lagged one-period core explanatory variable and instrumental variables (IV) to alleviate reverse causality. In addition, we employed a combination of fixed effects and excluded pilot policy impacts to prevent omitted variable bias. Finally, we employed the Heckman two-step method to address potential sample selection bias. Fourth, building on the robustness of empirical results, we conducted heterogeneity analyses based on SC types (suppliers and customers), regions (eastern and central/western), and enterprise ownership (state-owned and non-state-owned). Fifth, we further explored the mechanisms through which the DE influences the new energy SCC, including supply-demand matching (SDM) accuracy, external transaction costs, and TI. Based on the empirical findings, this article presented research conclusions and proposed targeted policy recommendations.

D. Data Sources and Statistical Description

Given the availability of data for calculating the urban-level DE index, this study set the research period from 2011 to 2021.

TABLE I
DESCRIPTIVE STATISTICS

Variable	Description	N	Mean	SD	Min	Max
SCC	Supply chain configuration	966	0.6282	0.1948	0.0530	0.9608
DE	Digital economy	966	1.1466	1.1686	-1.4451	3.9671
Lnage	Enterprise age	966	2.9091	0.3261	1.7918	3.6376
Lnsize	Enterprise size	966	7.9840	1.1258	4.8903	12.1387
CI	Capital intensity	966	1.2616	0.4127	0.2662	2.8379
RD	Research and development	966	0.0322	0.0232	0.0000	0.1626
WW	Financing constraint	966	-1.0435	0.0752	-1.8041	-0.8318
IDP	Independent director proportion	966	0.3655	0.0502	0.2500	0.6250
EBD	Equity balance degree	966	0.6684	0.5655	0.0234	2.9695
Lncgdp	Economic development of the city	966	8.6870	1.1762	5.6330	10.6448
CIS	Industrial structure of the city	966	0.4047	0.1033	0.1583	0.6681
Lncpop	Population size of the city	966	6.3970	0.5653	4.7212	8.1365
CTL	Technology level of the city	966	13.0069	1.5076	8.4848	15.5568
SCCt3	Top three suppliers and customers	637	0.7022	0.1819	0.0717	0.9744
HHI	Herfindahl-Hirschman Index	664	0.1598	0.2454	0.0008	1.5404
DE_ewm	The entropy weight method	966	0.4642	0.2073	0.0043	0.9628
DE_ta	Text analysis	966	0.9941	1.0623	0	4.2627
IV	Instrumental variable	951	10.1364	9.2813	0.2339	44.8716
EDB	Executive digital background	686	0.1691	0.3751	0	1
SCCD	Supply chain customer diversification	966	0.5996	0.2582	0	0.9980
SCSD	Supply chain supplier diversification	966	0.6568	0.1930	0.0818	0.9841
SDM	Supply-demand matching	772	0.4270	1.1778	-0.8510	11.4452
Intangible	Proportion of intangible assets	949	0.0473	0.0603	0.0013	0.6409
Sell	Proportion of selling expense	887	0.0363	0.0335	0.0000	0.2820
TI	Technological innovation	950	8.1272	1.6825	2.3026	11.2797

Simultaneously, the research sample consists of Chinese A-share listed enterprises in the new energy sector. Data on corporate supplier procurement, customer sales, finance, and other enterprise-level information are obtained from the CSMAR and CNRDS databases. DE calculations and related data at the urban level are sourced from the China Urban Statistical Yearbook and Peking University's Digital Finance Research Center. In addition, to enhance data validity, the study applied sample selection criteria, including the exclusion of financial companies listed on the stock exchange, companies classified as special treatment or potential treatment in the current year, and samples with missing key variables. Table I provides a description and statistical results for all variables in this study.

IV. Results and Discussion

To avoid multicollinearity issues, this study examined the variance inflation factor (VIF) for each explanatory variable, as presented in Table II. The results indicate that the maximum VIF is 7.66, and the mean VIF is 2.43, both below the threshold of 10. Consequently, this study does not suffer from a severe multicollinearity problem.

A. Baseline Regression

Table III presents the baseline regression results of this study. Column (1) does not include control variables and fixed effects, and the regression result is significantly positive at the 1% level. Columns (2) and (3) include control variables at the enterprise and city levels, respectively. The regression results remain significantly positive. In column (4), with the inclusion of clustered robust standard errors on the basis of controlling for enterprise, year, and city fixed effects, the estimated coefficient for the DE is 0.0357 and significantly positive at the 1% level. The regression results convincingly indicate that the development of the city's DE can effectively promote the SC diversification of new energy enterprises. Therefore, the development of the city's DE is a crucial driving factor for optimizing the new energy SCC.

TABLE II
VARIANCE INFLATION FACTOR

Variable	VIF	1/VIF
DE	1.70	0.5894
Lnage	1.08	0.9226
Lnsize	1.85	0.5419
CI	1.21	0.8285
RD	1.12	0.8952
WW	1.83	0.5465
IDP	1.05	0.9558
EBD	1.04	0.9603
Lncgdp	7.66	0.1306
CIS	1.75	0.5730
Lncpop	1.64	0.6100
CTL	7.20	0.1389
Mean VIF	2.43	

B. Robustness Test

To enhance the reliability of the empirical results, this study conducted a series of robustness tests, and Table IV presents the regression results. First, the measurement method for the explained variable was replaced. We substituted the proportion of transactions with the top three suppliers and customers for the top five, and the results in column (1) show that the estimated coefficient remains significantly positive. In addition, following the construction method of the Herfindahl index as per [43], we recalculated the explained variable using the Herfindahl index instead of the original mean algorithm. Column (2) displays the regression results, and the estimated coefficient remains significantly positive at the 1% level.

Second, the measurement method for the core explanatory variable was replaced. We employed the entropy weight method to reconstruct the comprehensive development index of the DE, and the coefficient in column (3) remains significantly positive. Furthermore, as this study used a city-level DE index and lacked data for measuring enterprise-level digitalization, we captured the enterprise-level DT process using text analysis. The frequency of occurrence of key terms related to enterprise DT in annual reports was used as a proxy, and after logarithmic transformation, the coefficient in column (4) remains significantly positive. Even after replacing the indicators for SCC and the DE, the estimated coefficients in the regression results remain positive and are significant at least at the 5% level. This strongly indicates that the DE can significantly promote the new energy SCC diversified development, promoting the diversification of both suppliers and customers.

C. Endogeneity Discussion

1) Reverse Causality: The mutual causation between explanatory and explained variables is a significant potential source of endogeneity in this study. Therefore, this article conducted tests using lagged processing and IV methods, and the regression results are presented in Table V. First, we select the lagged one-period DE as the core explanatory variable for the reregression. Since the SC decisions of enterprises in the current period cannot feasibly influence the development of the DE in the preceding period, this can partially alleviate the endogeneity issues arising from reverse causality. The estimated coefficient in column (1) is significantly positive, indicating that the DE can still promote the SCC diversified development. Second, we regressed the lagged explained variable as a control variable. The regression results in column (2) show that although SCC is influenced by the previous period, the estimated coefficient for the DE remains significantly positive. This strongly suggests that the DE development is a crucial driving factor for promoting SC diversification.

Finally, we employed the IV method to further address the potential issue of reverse causality. Drawing on the approach of [44], we used historical postal and telecommunications data for each city in 1984 as IV. In addition, the original data for the IV used in this study is in cross-sectional form. Following the methods suggested in existing literature to address this issue [45], [46], we created an interaction term using the fixed telephone lines per hundred people for each city in 1984 and the year as IV for the DE index of that city. We conducted a two-stage least squares regression using this IV, and the regression results are presented in columns (3) and (4). The first-stage regression results demonstrate a high correlation between the IV and the DE index, passing the LM unrecognizable test and weak IV test. The estimated coefficient in the second stage remains significantly positive at the 5% significance level, suggesting to some extent that the empirical results of this study are reliable.

2) Sample Selection Bias: Considering the potential impact of sample selection bias in new energy enterprises on the estimation results, this study employed the Heckman two-step procedure to correct for potential bias issues. The estimation results are presented in columns (1) and (2) of Table VI. In the first stage, this study took the DT of enterprises as the explained variable and introduced the exogenous variable of executive digital background (EDB). Drawing on the literature [47], we used personal characteristics data of executives from listed enterprises to measure the EDB. The estimated coefficient is significantly positive, indicating that listed companies with executives having a digital background are more likely to develop the DE, validating the rationality of the selection of exogenous variables. In the second stage, we further incorporated the inverse Mills ratio (IMR) to re-examine the impact of the DE on enterprise SCC. The regression results show that, even after controlling for sample selection bias, the coefficient of the DE remains significantly positive.

3) Omitted Variables: Despite addressing issues related to reverse causality and sample selection bias in the above endogeneity tests, there remains the possibility of endogeneity problems arising from omitted variables in the empirical model. First, we introduced joint fixed effects at the provincial-year, industry-year, and provincial-industry levels. The estimated coefficient in column (3) of Table VI remains significantly positive. Second, this study further considered the influence of

TABLE III
BASELINE REGRESSION

Variable	(1) SCC	(2) SCC	(3) SCC	(4) SCC
DE	0.0163***	0.0155***	0.0195***	0.0357***
	(0.0053)	(0.0045)	(0.0056)	(0.0124)
Lnage		0.0265	0.0306*	0.1327***
		(0.0164)	(0.0160)	(0.0365)
Lnsize		0.0631***	0.0674***	0.0467***
		(0.0062)	(0.0060)	(0.0112)
CI		-0.1105***	-0.0949***	-0.0293
		(0.0133)	(0.0133)	(0.0337)
RD		2.8381***	2.8464***	2.0355***
		(0.2311)	(0.2283)	(0.5317)
WW		0.5803***	0.4749***	0.0758
		(0.0893)	(0.0901)	(0.1549)
IDP		0.0851	0.0125	0.0035
		(0.1039)	(0.1021)	(0.1607)
EBD		0.0181**	0.0116	0.0234
		(0.0092)	(0.0090)	(0.0215)
Lncgdp			0.0158	0.0257
			(0.0118)	(0.0235)
CIS			0.3470***	0.3960***
			(0.0640)	(0.1392)
Lncpop			-0.0377***	-0.0007
			(0.0113)	(0.0385)
CTL			0.0001	0.0012
			(0.0089)	(0.0211)
Constant	0.6095***	0.6404***	0.4514***	-0.5334
	(0.0087)	(0.0970)	(0.1313)	(0.3829)
Year FE	No	No	No	Yes
Enterprise FE	No	No	No	Yes
City FE	No	No	No	Yes
N	966	966	966	964
R^2	0.0096	0.3345	0.3699	0.6248

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

SC policies. China initiated a pilot project for SC innovation and application in 2018, aiming to promote the development of an industry SC system characterized by innovation, coordinated development, integration of industry and finance, supply–demand matching, high-quality and efficiency, green and low-carbon, and global layout. Therefore, the trend toward diversification of enterprise may be influenced by the above-mentioned national SC policies. We re-estimated the model by excluding cities involved in the SC pilot program from the sample. The regression results in column (4) indicate that the coefficient remains significantly positive at the 1% level. This implies that even after removing the impact of the national SC innovation and application pilot policy, the DE still significantly enhances the diversification of new energy enterprises' procurement and sales, driving the diversification of SCC, providing further support for the core findings of this article.

TABLE IV
ROBUSTNESS TESTS

Variable	(1) SCCt3	(2) HHI	(3) SCC	(4) SCC
DE	0.0282**	0.0676***		
	(0.0135)	(0.0153)		
DE_ewm			0.1990***	
			(0.0693)	
DE_ta				0.0122**
				(0.0046)
Constant	0.0586	-0.0365	-0.5848	-0.5773
	(0.4287)	(0.4671)	(0.3767)	(0.3761)
Control	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
N	635	664	964	964
R^2	0.6341	0.6219	0.6247	0.6233

TABLE V
ENDOGENEITY DISCUSSION (REVERSE CAUSALITY)

Variable	(1) SCC	(2) SCC	(3) DE	(4) SCC
DE		0.0269**		0.1887**
		(0.0111)		(0.0952)
L.DE	0.0801***			
	(0.0147)			
L.SCC		0.7891***		
		(0.0283)		
IV			0.0314***	
			(0.0111)	
Constant	-0.9935**	-0.4005**	-0.0777	0.3970
	(0.4206)	(0.1701)	(1.0638)	(0.5224)
Control	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Underidentification test				4.645**
Cragg-Donald Wald F				23.773
N	744	744	942	942

TABLE VI
ENDOGENEITY DISCUSSION (SAMPLE SELECTION BIAS AND OMITTED VARIABLES)

Variable	(1) DE	(2) SCC	(3) SCC	(4) SCC
DE		0.0282**	0.0337**	0.0379***
		(0.0102)	(0.0146)	(0.0136)
EDB	0.4602**			
	(0.2265)			
IMR		-0.1475**		
		(0.0651)		
Constant	0.0182	-0.4028	-0.2416	-0.3938
	(0.1202)	(0.4431)	(0.4559)	(0.4200)
Control	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Province-Year			Yes	
Industry-Year			Yes	
Province- Industry			Yes	
N	682	682	733	706
R^2	0.0138	0.6253	0.7844	0.6393

TABLE VII
HETEROGENEITY ANALYSIS

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Customer	Supplier	East	Midwest	State-owned	Non-state-owned
	SCCD	SCSD	SCC	SCC	SCC	SCC
DE	0.0596***	0.0119	0.0778***	0.0058	0.0338	0.0729***
	(0.0169)	(0.0136)	(0.0157)	(0.0370)	(0.0250)	(0.0123)
Constant	-0.9335**	-0.1334	-0.6631	-0.1545	0.1161	-0.7112
	(0.3836)	(0.4810)	(0.5465)	(0.4304)	(0.7350)	(0.7288)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
N	964	964	700	262	439	520
R^2	0.6381	0.5151	0.5906	0.8551	0.8424	0.5671

D. Heterogeneity Analysis

1) Supplier and Customer: This article further examined the heterogeneity of this impact, and the results are presented in Table VII. We divided the SC diversification into downstream customer sales (SCCD) and upstream supplier procurement (SCSD). The grouping regression results in columns (1) and (2) show that the DE significantly enhances the diversification of downstream customer sales. Its impact on the diversification of upstream supplier procurement is positive but not statistically significant. The potential reason for this might be that the SC upstream for new energy enterprises mainly consists of raw material suppliers. They are typically more associated with material supply and production processes and have less interaction with the end customers of new energy enterprises. In contrast, the DE is more involved in information and data processes, primarily catering to end users. Therefore, for new energy enterprises, the DE can play a positive role in attracting and satisfying customers, but its impact on upstream suppliers may be limited. However, the application of digital technology is continuously evolving, and it may have a more extensive impact on the entire energy SC in the future.

2) Eastern and Midwest Regions: This study examined the regional variations in this impact. We categorized the sample into the eastern and central-western regions for grouped regression, and the results are presented in columns (3) and (4) of Table VII. Significant heterogeneity is observed between the two regions, with the DE significantly enhancing SC diversification in the eastern region but not significantly in the central-western region. Possible reasons for this disparity include, on the one hand, the eastern region having a clear advantage in both digital technology and digital infrastructure compared to the central-western region. On the other hand, the eastern region experiences more intense market competition, with larger supplier and customer scales, motivating new energy enterprises to adopt digital technologies to pursue SCC diversification, thereby achieving maximum stability in the SC and business profitability. In contrast, the central-western region relies more on specific types of energy resources. While DE can improve the efficiency of extracting these resources, its impact on SC diversification is limited.

3) Enterprise Ownership: We further examined the impact of corporate dominance on this effect. Considering the significance of state-owned enterprises in the economic system and national economic operation, they have advantages in obtaining financing, tax benefits, and policy support. Therefore, state-owned enterprises are often given more attention by their partners in SC collaborations. Compared to nonstate-owned enterprises, they also face lower opportunistic risks. Thus, this article reflected the level of corporate dominance based on whether the enterprise is state-owned or not. The sample is divided into high and low corporate dominance groups, and a grouped test is conducted. The results in columns (5) and (6) indicate that the driving role of the DE in promoting upstream and downstream diversification is more prominent in enterprises with low dominance. The possible reason is that if an enterprise holds a dominant position in competition, both upstream and downstream entities will consider it a crucial resource. To maintain a strong and long-term cooperative relationship with the dominant enterprise, partners will make maximal efforts to ensure the raw material supplies or the product sales, reducing the likelihood of opportunistic behavior. When the enterprise has a lower dominant position, it is more inclined to use digital means to promote SC diversification, addressing the higher opportunistic behavior risk it faces. Therefore, the role of the DE becomes more pronounced in this context.

E. Influence Mechanism Analysis

In accordance with the theoretical analysis presented earlier, this article examined the impact mechanism of the DE on the new energy SCC from three perspectives: supply–demand matching accuracy, external transaction costs, and TI.

1) Supply–Demand Matching Accuracy: As the supply–demand matching accuracy is challenging to measure directly, this article referred to existing research [48] and indirectly characterized accuracy by deviations of enterprise supply elasticity from demand elasticity (production fluctuations from demand fluctuations). The specific definition is as follows:

$$\mathrm{SDM} = \frac{\sigma\left(\mathrm{Production}_{it}\right)}{\sigma\left(\mathrm{Demand}_{it}\right)} - 1 \tag{3}$$

$$\mathrm{Production}_{it} = \mathrm{Cost}_{it} - \mathrm{Inventory}_{it} - \mathrm{Inventory}_{it-1}. \tag{4}$$

Here, $\sigma(\cdot)$ represents the standard deviation of the variable, $\mathrm{Production}_{it}$ denotes the enterprise production, and Demand_{it} represents the enterprise demand. Enterprise production is calculated through (4), where Cost_{it} stands for the operating cost of the enterprise, and $\mathrm{Inventory}_{it}$ represents the net value of the enterprise's inventory. Enterprise demand is proxied by the operating cost Cost_{it}. The greater the deviation between supply and demand on the SC, the lower the supply-demand matching (SDM) accuracy. As this indicator pertains to enterprise-level data, this article regressed the lagged 1-period supply-demand deviation to avoid endogeneity. The estimated coefficient of column (1) in Table VIII is significantly negative at the 5% level, indicating that the DE can significantly reduce the degree of supply–demand deviation and enhance matching accuracy, and thus promote the new energy SCC diversified development.

2) External Transaction Costs: Considering the diverse nature of external transaction costs, which makes it challenging to comprehensively encompass them. This study employed two indicators for indirect measurement. First, this article used the specificity of enterprise assets to reflect external transaction costs. Enterprises with higher asset specificity face relatively greater risks of being locked in and are more likely to be threatened by the opportunistic behavior of trading partners, hence incurring higher external transaction costs. Drawing from existing literature [49], the study used the ratio of intangible assets to total assets (Intangible) to measure the specificity of enterprise assets. A higher value of this indicator indicates higher external transaction costs. The estimation results of column (2) show that the DE can significantly reduce external transaction costs for enterprises.

Second, this article used the ratio of selling expenses to operating income (Sell) to gauge external transaction costs for enterprises. A higher value of this indicator suggests higher external transaction costs in the sales process for new energy enterprises [50]. To distinguish from the empirical process of the previous indicator, we constructed the interaction term of Sell and DE, adding it to the regression model. In column (3), the coefficient of the interaction term is significantly positive at the 1% level. This indicates that the higher the external transaction costs faced by new energy enterprises in the sales process, the more pronounced the effect of the DE in optimizing SCC. This further validates the results presented earlier.

3) Technological Innovation: Referring to existing literature [51], [52], this study measured TI by the number of invention

TABLE VIII
MECHANISM ANALYSIS

Variable	(1) SDM	(2) Intangible	(3) Sell	(4) TI
DE	-0.1622**	-0.0145***	0.0500***	0.3218***
	(0.0704)	(0.0039)	(0.0157)	(0.1075)
DE×Sell			2.1518***	
			(0.5044)	
Constant	-2.0473*	-0.0310	-0.7685*	-3.4309**
	(1.1771)	(0.1262)	(0.3841)	(1.6025)
Control	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
N	772	947	884	948
R^2	0.1615	0.6206	0.6275	0.8955

patents obtained by new energy enterprises in the current year, and took the logarithm for processing. The regression results of column (4) show that the estimated coefficient is significantly positive at the 1% level. This strongly indicates that the development of the DE can significantly promote TI in new energy enterprises, giving rise to new industries and markets. This has diversified the SC of new energy enterprises, optimizing their SCC.

V. CONCLUSION AND POLICY IMPLICATIONS

A. Conclusion

In the context of the low-carbon energy transformation, the deep integration of the DE with the new energy SC is not only a crucial driving force for China to build a clean, low-carbon, safe, and efficient energy system but also a significant guarantee for enhancing the resilience and security of the new energy SC. Based on data from listed new energy enterprises and the comprehensive development index of the DE at the city level, this article employed econometric models to explore the impact and mechanism of the DE on the SCC of new energy enterprises, leading to the following research conclusions.

First, the DE can significantly promote the new energy SCC diversified development. After a series of endogeneity tests, the research results remain robust. The DE is identified as a crucial factor in restructuring the collaborative relationships between upstream and downstream in the SC of new energy enterprises, optimizing their SCC.

Second, the effect of the DE on the new energy SCC exhibits heterogeneity. First, the DE significantly enhances the downstream customer sales diversification in the SC of new energy enterprises, with limited impact on the upstream supplier procurement diversification. Second, the promoting effect of the DE on the diversified development of the new energy SC is more pronounced in the eastern region. Finally, nonstate-owned enterprises in a low-advantageous position tend to promote SCC diversification through digital means.

Finally, the results of the mechanism analysis indicate that the DE can achieve new energy enterprises SCC diversification development by enhancing the SDM accuracy, reducing external transaction costs, and promoting TI.

B. Policy Implications

In the dual context of the DE and low-carbon transformation of energy, digital technology can drive the SC operations of new energy enterprises to gradually transition from traditional modes to digital operational models. The research findings of this article provide important policy implications for accelerating the DT of new energy enterprises and enhancing SC resilience.

First, the DE can effectively promote the SCC diversification for new energy enterprises. Government departments should use the industrial chain SC as a focal point, encouraging collaboration between upstream and downstream enterprises in seizing the opportunities for DT, and improving the efficiency of data flow and sharing on the SC. In addition, government departments can promote the overall SC digital construction based on leading enterprises, enhancing the resilience of China's new energy SC and steadily achieving low-carbon energy transformation while ensuring energy security.

Second, diversification of upstream suppliers serves as a robust safeguard for new energy enterprises to cope with external sanctions or unforeseen supply disruptions. Government departments should actively establish digital collaborative management platforms, encouraging upstream suppliers to integrate with information management systems and using digital means to strengthen the overall management of new energy suppliers. Simultaneously, governments at all levels should strengthen risk warning and alerts for upstream new energy suppliers, enhancing the resilience and security of the new energy SC.

Finally, during the process of DT, new energy enterprises should facilitate the flow of information and logistics within the SC. Focusing on enhancing SDM accuracy and reducing external transaction costs, new energy enterprises should provide ample guarantees for the SCC diversification. In addition, local governments should vigorously promote the construction of new infrastructure, particularly by increasing digital investments in the central and western regions. This includes attracting enterprises related to the DE to establish businesses and research centers in these regions, collectively driving TI and the new energy SC diversified development.

C. Research Limitations

This study examined the impact of the DE on the SCC of new energy enterprises. Due to the unavailability of direct DE data at the enterprise-level and the inability of the word frequency obtained through text analysis to intuitively reflect DE development. This article is constrained to use the city-level comprehensive DE development index as the core explanatory variable. Furthermore, due to data availability constraints, the sample in this study only covers the top five customers and suppliers in the SC of new energy enterprises. This makes it challenging to comprehensively depict the overall distribution characteristics of the SCC. As indicators for the DE and SC of new energy enterprises continue to improve, future research can delve deeper into exploring the impact of DT on SCC, providing more profound policy recommendations for China's achievement of low-carbon energy transformation.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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