RETHINKING GREEN ENERGY DEVELOPMENT: COGNITIVE BIASES

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RETHINKING GREEN ENERGY DEVELOPMENT: COGNITIVE BIASES

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EDITORIAL
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Editorial: Rethinking Green Energy Development: Cognitive Biases

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Keywords: cognitive bias, energy system, green energy, energy transition, energy policy

Editorial on the Research Topic

Rethinking Green Energy Development: Cognitive Biases

Green energy development is a key strategy during the energy transition which is a process of large-scale socio-technological change (Geels, 2014). Due to the technical complexity and social reflexivity of the energy system (Geels, 2002; Loorbach, 2010), cognitive biases towards the green energy system is inevitable. Cognitive biases pose great challenges to achieve consensus for contemporary policy making. One effective step for addressing this challenge, as the socio-technological theorists have suggested, is to explore and exhibit the multiplicity of value, the complexity of the socio-technological system, and the reflexivity of such system as well (Rip and Kemp, 1998; Coglianese et al., 1999; Rotmans et al., 2001; Kemp et al., 2007). Motivated by this, this special issue includes a collection of nine studies from researchers with distinctive backgrounds on the issue of green energy.

Four papers in this issue have shed important light on the multiplicity of values. Specifically, Hu et al. suggest how difficult it is to simultaneously account and balance the economic value and the environmental impacts of shale gas extraction. Shale gas has been recognized as a type of unconventional energy that somehow can enlarge the possibility of relying on fossil fuels. Similarly, Lin et al. address the challenges on integrating both economic value and green trust during the transition from an existing product to a disruptive green product. Fan et al. highlight that the public evaluation on China's energy storage projects have multiple dimensions. Li et al. have developed an acceptance model by capturing various aspects of an individual's belief. They used this model to reveal the public attitude toward the commercial fleet of methanol vehicles in China.

The energy system is complex that any analysis on the performance of a specific technical tool in the green energy domain could be. As such, researchers should expand the analytic scope when approaching problems related to green energy. However, it could also be in vain to conduct an analysis that covers the entire energy system. In other words, the analysis on energy system should find a "midway" between specificity and abstraction. In this regard, Xue et al., Zhang and Gu, Guo et al. and Chen et al. are good examples. The analytic scopes of these studies are energy consuming sectors, social capital, digital finance, and information technology investment, respectively. Those terms refer to either a manageable sub-sector (Xue et al.) or a controllable "fluid" that runs throughout the energy system (Zhang and Gu, Guo et al. and Chen et al.). To overcome cognitive biases also means to have more attention paid to the invisible depth. Social capital, digital finance and information technology investment are invisible relative to engineering projects. Each of these invisible elements, however, has profound impact on the landscape of the entire energy system. The above studies also have methodological implications on how to quantitatively approach a complex social-technological system. Xue et al. have applied a novel slack-based data envelopment analysis,

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which is insightful to other sub-systems of energy. Zhang and Gu have conducted a panel data regression model to account for environment governance efficiency. They also set an example for how to quantify social capital with official data.

The energy system is reflexive, with both top-down and bottom-up cognitive influences in the energy system. Reflexivity runs through the supply chains of the energy industry, through the decision loops of energy policy, and through the multiple levels of the entire energy system. As such, the consumer acceptance and the public attitude play a key role in green energy development. On one hand, consumer acceptance and public attitude are affected by the knowhow of experts and policy makers. One the other hand, experts' and policy makers' knowledge should be adjusted according to the feedbacks from consumers and the public. However, there exists a so called "knowledge deficit" which has too overwhelmingly emphasized on the knowledge of experts and policy makers. Now it is the time to increase the cumulation of consumer knowledge and public opinions. This is why five manuscripts (Fan et al., Hu et al., Li et al., Lin et al., and Jiang et al.) from this collection have focused on either the consumer cognition or the public attitude. Notably, Fan et al. find that the public attitude toward energy storage projects presents a cognitive bias: the public opinions of energy storage are usually not the same even for the same issue. Representation distortion could happen during a survey, as the survey hosts and the survey respondents are associated in reflexive chains. Fan et al. demonstrate on how to dig undistorted information from the corpus of natural language, which can provide more real and credible information than survey data.

The journal Frontiers in Energy Research has provided an international platform for green energy communications. This collection reveals how cognitive biases can arise from monotony of value, from oversimplification in the analysis of green energy development and from ignoring the voice of consumer and the public. Therefore, this special issue points out that the existence of cognitive bias could slow down the transition towards green energy. Future green investment and policy making shall address the cognitive bias to overcome the limits of consensus and regime resistance against green energy transition.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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ORIGINAL RESEARCH
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How Information Technology Investment Affects Green Innovation in Chinese Heavy Polluting Enterprises

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Promoting green innovation is an effective way to solve the increasingly serious environmental pollution problems in emerging economies. Information technology is constantly changing the operation mode of enterprises; however, whether information technology investment helps promote enterprises' green innovation is still an important issue to be studied. According to resource-based and knowledge integration theory, this study constructs data from Chinese A-share listed heavy polluting enterprises during 2010–2018, adopting the panel data Tobit model to investigate the nexus between information technology investment and green innovation. Our empirical results demonstrate that the amount of information technology investment is positively correlated with the emerging levels of green patents in Chinese heavy polluting enterprises, and this positive correlation only significantly exists in state-owned enterprises (SOEs) and enterprises with a strong sense of environmental responsibility and strict environmental regulation. The findings of this study help understand in depth how information technology investment affects enterprises' green innovation and its boundaries, which also have important policy implications for government departments and enterprises to make better use of information technology to deal with the challenge of environmental pollution.

Keywords: information technology investment, green innovation, resource-based, knowledge integration, heavy polluting enterprises

INTRODUCTION

Environmental pollution problems have been increasingly serious in emerging economics, which has received considerable attention from the academic community and policy makers. As an important participant in emerging markets, China has been facing this issue for a long time due to its rapid industrialization and urbanization (Wang et al., 2015; Du and Huang, 2017) and has been among the world's top polluters in recent years according to Numbeo's national pollution index ranking[1]. In recent years, green transformation has become China's national strategy. As one of the five development concepts (innovation, coordination, green development, opening up, and sharing), green development was formally written into China's "14th Five-Year Plan". Informatization, green

[1]https://www.numbeo.com/cost-of-living/

innovation, and green energy are important ways to achieve green development. However, due to cognitive bias (Pronin, 2007), most enterprises have not yet realized that information technology investment (hereafter IT investment) and green innovation can promote the development of green energy. Given the ambiguity effect, enterprises often avoid less informed options when making decisions. Few studies focus on combining IT investment, green innovation, and green energy; therefore, an enterprise ignores the role of information technology and green innovation. In addition, enterprises have status quo bias and omission bias. So, they tend to believe that the harm caused by active action is worse than that caused by passive omission and neglect to explore the way of developing green energy. As a result, it is necessary to explore more effective measures to advance the development of green energy. Informatization and green innovation are both crucial methods.

Scientific and technological innovation is the key to achieve green energy. Both efficient utilization of traditional energy and large-scale adoption of green energy rely on scientific and technological progress (Wurlod and Noailly, 2018). Green innovation refers to green technological innovation, which is a kind of technological innovation that can reduce pollution, avoid energy consumption, and improve the ecological environment (Braun and Wield, 1994). Therefore, the Chinese government regards green innovation as an important starting point for promoting green development. In 2019, the Ministry of Science and Technology of Chinese National Development and Reform Commission has issued *A Guideline on Building a Market-Oriented Green Technology Innovation System* to call for enterprises to solve deep-rooted environmental pollution problems through green innovation. Green innovation promotes green energy by adopting energy-saving technology to improve energy utilization efficiency and reduce energy consumption. Green innovation is able to promote the transformation of energy and also improve social productivity and production level. Heavy pollution industry is the main source of environmental pollution with the high energy consumption and high pollution in the production process. Therefore, promoting green innovation in heavily polluting industries is the key to improving China's environmental conditions and achieving sustainable development.

Real-time information sharing has become the basis of competition under the background of industry 4.0. Information technology is widely integrated in social production, economy, and life, making informatization, digitalization, and intelligentization become the driving force of enterprise innovation and transformation development. Informatization helps improve enterprises' search and discover ability, decision-making efficiency, process management (Ardito et al., 2019; Lin and Kunnathur, 2019), and learning and absorption capacity (Nambisan et al., 2019), which are crucial for technical knowledge accumulation and technological research development. Improving digital capabilities through IT investment is an important way to promote enterprise transformation and upgrading. Now Chinese heavy polluting industries need to carry out green innovation. There are a wide range of factors influencing enterprise green innovation. The premise of enterprise green innovation means having the awareness to carry out relevant activities and obtain innovating ability. For heavy polluting enterprises, information technology capabilities brought by IT investment benefit enterprises' production efficiency, pollution sources control, and pollutants utilization rate, which contribute to more competitive green products in the market. The development of information technology can promote the intelligent operation of green energy system and improve their safety, reliability, and sustainability (Dincer and Acar, 2017). With the rapid development of science and technology in China, IT investment has benefited green innovation in the context of information and digital economy and has affected the development of green energy systems. Now, research on the relationship between IT investment and product innovation stays in the initial stage. Traditional product innovation aims to improve enterprise's profits, while green innovation aims to improve enterprise's environmental performance such as energy saving, emissions, and pollution reduction. The influence of IT investment may differ between green innovation and traditional product innovation. However, the nexus of IT investment and green innovation still remains unclear.

Many factors may moderate the relationship between IT investment and green innovation. The factors include enterprise attribute, enterprise internal, and external factors. State ownership, environmental responsibility, and environmental regulation can stand by the three dimensions. Enterprises with different state ownership follow different business logics (Zhou et al., 2017) and react differently in face of environmental pollution. Enterprises' sense of environmental responsibility can influence the input of base resource and knowledge learning (Shahzad et al., 2020). Environmental regulation led to different green innovation condition (Zhang et al., 2018) and had a different influence on the relationship between IT investment and green innovation. According to resource-based and knowledge integration theory, we construct data from Chinese A-share listed heavy polluting enterprises during 2010–2018 and adopt the panel data Tobit model to empirically analyze the impact of IT investment on green innovation and its moderating factors.

Our contribution is mainly reflected in the following aspects. On the one hand, we provide empirical evidence that IT investment can help promote green innovation in Chinese A-share listed heavy polluting enterprises. Green innovation is different from innovation in goals and effectiveness (Peng et al., 2021). Most existing literature only focuses on IT investment and innovation (Wu et al., 2020), but neglects the combination of information technology and green development background. We find that promoting green innovation needs plenty of resources and abilities, and the capacity that comes with IT investment can match them. We take IT investment and green innovation of heavy polluting enterprises as research subjects, which are pioneering innovations in related fields. We finally find that IT investment can promote green innovation. Our research has filled the gap between IT investment and green innovation.

On the other hand, our findings help understand in depth how IT investment affects green innovation and its boundaries.

Existing literature lacks in-depth research on the heterogeneous influence of IT investment and green innovation. Exiting research shows that green innovation is influenced by the internal factors like corporate governance (Chen et al., 2016), external factors like institution factors (Sun et al., 2019), and so on. It is worthy to examine the role of these factors in the relationship between IT investment and green innovation. We clarify this influence varies for enterprises with different attributes in the nature of property rights, social responsibility, and environmental regulation. We find that IT investment only promotes green innovation in state-owned enterprises (hereinafter referred to as SOEs), enterprises with a strong sense of environmental responsibility, and enterprises in areas with strict environmental regulations.

The rest of this study is organized as follows: "Literature Review and Research Hypotheses" section reviews the related literature and proposes the research hypotheses. "Data" section describes the data and presents the model and variables. "Empirical Results and Analysis" section presents the empirical results. "Robust Test and Endogeneity Treatment" section presents further analysis, and "Concluding Remarks" section provides the conclusions and policy implications.

LITERATURE REVIEW AND RESEARCH HYPOTHESES

Literature Review

A stream of literatures has discussed whether IT investment can trigger innovation. Digital transformation is crucial for all economies to cope with the fierce competition under the background of industry 4.0 (Zhou et al., 2020). Some studies have provided evidence that digitalization along with IT investment can enhance the learning ability and improve the information transparency to promote enterprise innovation (Nambisan et al., 2020). Information technology supports innovative processes by making companies respond flexibly (Wu et al., 2020). Some literatures indicate that innovation is a comprehensive utilization of internal and external knowledge (Lv et al., 2017; Xiong and Sun, 2017). Internal IT capabilities provide high quality products and services to make enterprises minimize costs and improve management efficiency. External IT capabilities enable enterprises to perceive and understand changes in external markets like consumers and other stakeholders timely (Ding and Wu, 2020). The early researches on IT investment and enterprise innovation mainly adopt the method of questionnaire interview. Nowadays, existing literatures rarely involve the role of information technology and the formation of innovation ability in decision making (Dy et al., 2017; Wu et al., 2020).

At present, green innovation has been debated hotly, and the studies mainly focus on innovation, technology, green, sustainability, performance, and so on. There is a large volume of published studies describing the influencing factors of green innovation. For example, existing research results mainly spot on the inside of the organization (Xavier et al., 2017; Zhou et al., 2018) and corporate governance, such as company size, establishment time, shareholding ratio, R&D investment, internal benefits, comprehensive management system, and senior management cognition. (Chen et al., 2016). From the external perspective of enterprises, institutional factors (Sun et al., 2019), green social capital (Awan et al., 2019), pollution spillover (Luo et al., 2021), and upstream and downstream factors such as customers, suppliers, and markets (Bai et al., 2019) also have an impact on enterprises' green innovation. As for the research on the driving force of green innovation, existing results suggest that reputation mechanism (Zhang and Walton, 2017), government subsidies (Xie et al., 2015), and the pressure of environmental regulation (Cheng, 2020) are the driving force to promote enterprises' green innovation. In reality, fewer enterprises take the initiative to promote green innovation. The theoretical basis of green technology innovation mainly includes Porter hypothesis, regulation push and pull theory, science and technology push and market pull theory, and double externality theory.

Based on the studies above, researches on the relationship between IT investment and green innovation are still in the blank stage. As green innovation plays a crucial role in innovation, how IT investment affects green innovation of heavy polluting enterprises is worthy of attention. We should take the following aspects into account: first, most of the researches adopt questionnaire interview and use small data sample. So far, however, there has been a lack of large-sample microdata application, which fails to provide more accurate quantitative analysis for evaluating IT investment effect and fails to be widely representative. Second, there is a shortage of in-depth research on heterogeneity factors influence between IT investment and green innovation. Most literatures only study whether IT investment promotes innovation activities but fail to explore the performance, motivation, and possible path in heterogeneous subjects.

Research Hypotheses

IT Investment and Green Innovation

Resource-based theory implies that enterprises improve operating and decision-making efficiency based on their own resources (Wernerfelt, 1984; Barney, 1991). To give priority to ecology and green development, enterprises should improve producing speed, optimize operating mode, and reduce costs. Nowadays, heavy polluting enterprises have been confronted with serious environmental problems, making green innovation become an urgent situation. In order to solve environmental pollution problems and realize green innovation, heavy polluting enterprises have to adopt a better control process and get corresponding support from hardware and software facilities. The introduction of advanced information technology, equipment, and talents has enhanced the foundation of green technology research and development. Computer-aided designing, manufacturing, diagnosing, testing, and other technologies can make green technology run through the whole process of production. Heavy polluting enterprises' informatization has broaden the financing channels, and the venture capital also has provided external capital to improve green innovation's source and stability. In addition, enterprises need to increase the information storage capability and enlarge the information search space. IT investment has brought much resource advantages (Ardito et al., 2021), enabling standardized information storage process and improvement of decision-making efficiency (Nambisan et al., 2020).

Knowledge integration theory refers to forming new knowledge by combining enterprises' inside and outside knowledge (Ruiz-Jiménez et al., 2016). IT investment mainly supports two capabilities: internal and external IT capabilities (Mao et al., 2016). Internal IT ability refers to internal knowledge that makes every enterprise process transparent and visualized. When faced with pollution problems, management decision making and green products innovation are advantageous to the flow of knowledge within the organization (Scuotto et al., 2017; Eller et al., 2020). Due to the increased external knowledge, enterprises can perceive the changes of external market and policy timely and make scientific response effectively (West and Bogers, 2014). Heavy polluting enterprises absorb internal and external knowledge acquired from IT investment by using their knowledge integration ability (Liu et al., 2013) and then affect the whole enterprise operation process (Qi et al., 2021). Green technology patents and related knowledge can help enterprises improve innovation level by overcoming technology transfer and spillover obstacles and obtaining vital information and knowledge from the external environment. Heavy polluting enterprise uses information search and discover ability to acquire external knowledge and improve green innovation ability to ease the pollution source. From the perspective of knowledge integration, heavy polluting enterprises systematize, socialize, and coordinate work by combining consciousness motivation with green innovation foundation (Kogut and Zander, 1992; de Boer et al., 1999; Van den Bosch et al., 1999).

Hypothesis H1. IT investment can promote green innovation of heavy polluting enterprises.

IT Investment, State Ownership, and Green Innovation

There are usually two kinds of institutional logics in Chinese market: political logic and market logic, which have different influence orientations on enterprises' decision making (Zhou et al., 2017), thus having different effect on the relationship between IT investment and green innovation. Due to the influence of political consciousness and resource advantages, SOEs usually follow political logic. As SOEs' controlling subjects are closely connected with government organizations, they tend to consider the willingness of the state when making decisions. With the government advocates alleviating environmental problems through green innovation and promoting transformation and upgrading by informatization, state-owned heavy polluting enterprises put more energy and resources to information construction and green innovation activities (Klemetsen et al., 2018). CEO's promotion in SOEs usually depends on their political achievements; thus, they would pay more attention in developing green strategies and trigger green innovation (Rong et al., 2017). Meanwhile, SOEs' cost of green innovation technology exploration is lower owing to the policy advantages and financial subsidies, so the innovation and environmental protection atmosphere inside can be stronger than non-SOEs (Sun et al., 2017). The advantages of capital and costs are usually helpful for SOEs to face the risk of green innovation (Bai et al., 2019). Non-SOEs follow the market logic in their decision making and pursue more profit in business activities. Enterprises cannot get great benefits in the short term since the cost of green innovation is high. Green innovation relies more on resource input; however, non-SOEs share few resources and are under heavy financial burden, thus crowding out the green innovation resource. Green innovation's positive impact on enterprises' performance improvement takes a long time to emerge. Managers are forced to give up green innovation with high input, high risk, and high uncertainty under the pressure of short-term performance and cash flow. Therefore, non-SOEs usually have less motivation in green innovation than SOEs (Květoň and Horák, 2018).

Hypothesis H2. IT investment plays a stronger role in promoting green innovation of state-owned heavy polluting enterprises.

IT Investment, Environmental Responsibility, and Green Innovation

With the improvement of enterprises' environmental responsibility, IT investment of heavy polluting enterprises has a stronger effect on green innovation. A large number of literatures show that all aspects of enterprise social responsibility are closely related to environmental development, especially environmental responsibility (Shahzad et al., 2020). Heavy polluting enterprises fulfill their social responsibility by adopting industrial transformation and technological innovation to reduce environmental pollution (Li and Wang, 2018; Kraus et al., 2020). Enterprises are able to gain first-mover advantage by adopting an ecofriendly market-driven strategy, which motivate them to undertake green innovation (Fudenberg and Levine, 2009). Enterprises with strong sense of environmental responsibility are more inclined to take environmental protection measures when making investment decisions under the same condition of IT investment amount, internal decision-making thresholds, and knowledge learning and integration costs. A strong sense of environmental responsibility can increase resource productivity and efficiency, drive industries rule making, and finally promote industrial process change and product innovation.

Hypothesis H3. IT investment has a stronger positive effect on the green innovation of heavily polluting enterprises with a strong sense of environmental responsibility.

IT Investment, Environment Regulation, and Green Innovation

As environmental pollution and environmental regulation exist in the production processes, heavy polluting enterprises are faced with system pressure (Zhang et al., 2018). Implying nongreen technologies has preliminary production advantages because of the scale effect. Many heavy polluting enterprises lack environmental protection awareness and willingness to carry out green innovation. In this case, the government needs to take guidance and supervision measures, such as increasing investment to solve environmental problems. Heavy polluting

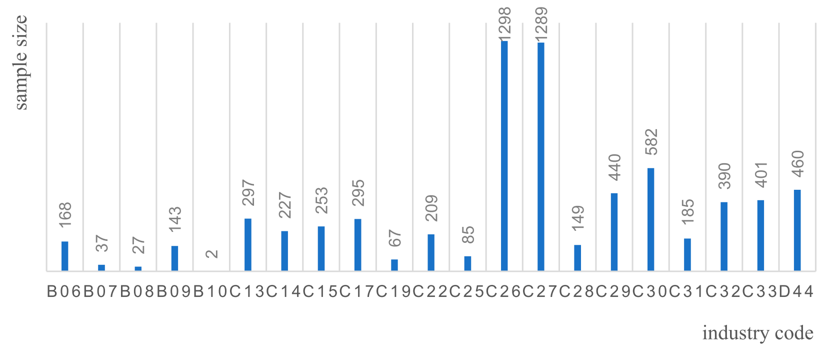

FIGURE 1 | Distribution of enterprises on detailed industries.

enterprises need to maximize stakeholder's benefit and meet the environmental protection requirements of suppliers, consumers, and other stakeholders. So, they should attach importance to environmental problems and take practical activities to achieve sustainable development. As the supervision focus of environmental authorities, heavy polluting enterprises tend to solve environmental problems by IT investment. Enterprises with stricter environmental regulation usually invest more resources related to environmental pollution government under a similar informationization condition and then increase their internal and external knowledge to deal with pollution. Meanwhile, government departments' supervision has enhanced enterprises' environmental awareness and impetus for green innovation when collecting local environmental information (Dowell and Muthulingam, 2017).

Hypothesis H4. IT investment has a stronger positive effect on the green innovation of heavily polluting enterprises in areas with strict environmental regulations.

DATA

Data and Samples

According to the *List of Classified Management of Environmental Protection Verification of Listed Companies (EIA Letter [2008] 373)* and Cai et al. (2020), the samples are composed of listed Chinese heavy polluting enterprises. The heavy polluting enterprises are contained from 2010 to 2018. The samples are finally refined into 21 categories as follows and the distribution is shown in **Figure 1**: B06 coal mining and washing; B07 oil and gas mining; B08 ferrous metal mining and dressing; B09 nonferrous metal mining and dressing; B10 nonmetallic mining and dressing; C13 agricultural food processing; C14 food manufacturing; C15 wine, beverage, and refined tea manufacturing; C17 textiles; C19 leather, fur, feather and its products, and shoes; C22 paper and paper products; C25 petroleum, coal, and other fuel processing; C26 chemical raw materials and chemicals manufacturing; C27 pharmaceutical manufacturing; C28 chemical fiber manufacturing; C29 rubber and plastic products; C30 nonmetallic mineral products; C31 ferrous metal smelting and calendering; C32 nonferrous metal processing; C33 metal products; and D44 electric power, thermal production, and supply. We can draw from the figure that C26 chemical raw materials and chemicals manufacturing and C27 pharmaceutical manufacturing industries are the main source of pollution, which would cause relevant authorities' attention.

We first download the listed enterprises' original IT investment data from Wind database. Then, we collect the Chinese listed companies' green patent data from CNRDS database. Next, we gather enterprise environmental responsibility index from Hexun database and get environmental regulation data from *China Statistical Yearbook*. Later, we derive all kinds of financial data and other industry index data from CSMAR database.

In addition, we perform basic processing on some outliers in the sample, such as deleting sample values that cannot be obtained. For the sake of alleviating the bias caused by particularly extreme values, we winsorized 1 and 99% to continuous variables. After excluding financial enterprises, ST and *ST enterprises, we finally collect 7004 observations in enterprise-year level.

Variables

Green Innovation

We measure green innovation based on the number of green invention patent applications of listed companies. Our main dependent variable is natural logarithm of one plus the patent application amount. Green patents are conducive to resource conservation, energy efficiency improvement, pollution prevention, and sustainable development. They are widely used as the main measure of green innovation (Fabrizi et al., 2018; Fang and Na, 2020). The number of patent applications reflects the instantaneous innovation ability of enterprises. Therefore, we choose the number of green patent applications as the measurement index of green innovation.

IT Investment

On the basis of previous relevant studies (Wang et al., 2020), we use the total amount of enterprise hardware and software investment to analyze IT investment, including IT hardware investment and IT software investment. We replace IT hardware investment with the year-end balance of electronic

TABLE 1 | Variable definitions.

Dependent variable	Description
GP	Natural logarithm of one plus the patent application amount
Independent variable	**Description**
ITI	Natural logarithm of one plus the IT software and hardware amount
Other variables	**Description**
Soe	State-owned dummy variable: it equals 1 if the actual controller of the enterprise is the central or local government, otherwise 0
Ers	Score from Hexun database
Reg	Ratio of government's environmental investment to GDP amount of each province
Rd	Natural logarithm of one plus the research and development amount
Sub	Natural logarithm of one plus the government subsidy amount
Cash	Ratio of monetary funds plus investment in securities to current liability
Roa	Ratio of enterprise's net profits to total average assets
Lev	Ratio of total liability to total assets
Size	Natural logarithm of one plus the total assets amount
Top	Ratio of the largest shareholders' holdings to the total shares of the enterprise

equipment, microcomputer, and other items in the company's fixed assets list. We use the year-end balance of the company's intangible assets related to computer software, systems, and information-related technologies. Our main independent variable is natural logarithm of one plus the IT software and hardware amount. Heavy polluting enterprises must better manage information to achieve transformation and upgrading. Exploring the impact of IT investment on green innovation of heavy polluting enterprises is significant, so we take IT investment of heavy polluting enterprises as an independent variable.

Moderating Variables

We focus on three types of moderating variables from the perspective of enterprise attributes, internal factors and external factors, including state ownership, environmental responsibility degree, and environmental regulation.

The state ownership represents the actual controller nature of the company, which is set as dummy variable (Hu et al., 2021; Zhao and Li, 2021). We define 1 to represent SOEs and 0 to represent non-SOEs. We use environmental responsibility scores from Hexun database to measure the sense of enterprise environmental responsibility (Kraus et al., 2020) according to previous relevant studies (Lin and Bao, 2021). In terms of the environmental regulation, we take the ratio of the government's environmental investment to GDP amount of each province as a measure index (Shen, 2012; Chen and Qian, 2019).

Control Variables

In this study, control variables include R&D investment (Rd), government subsidy (Sub), net profit margin on total assets (Roa), asset-liability ratio (Lev), company Size (Size), Cash ratio (Cash), and shareholding ratio of the largest shareholder (Top).

The R&D investment is measured by natural logarithm of one plus the research and development amount in the current year. The larger the amount of R&D investment is, the more special support for innovation and output of innovation will be (Huang et al., 2021).

TABLE 2 | Descriptive statistics.

Variable	Obs	Mean	SD	Min	Median	Max
GP	7,004	0.160	0.493	0	0	3.091
ITI	7,004	0.220	0.669	0	0.026	5.698
Rd	7,004	14.050	7.160	0	17.191	23.770
Sub	7,004	16.630	2.917	0	16.931	23.882
Cash	7,004	1.190	3.649	−4.359	0.388	167.544
Roa	7,004	0.050	0.063	−1.892	0.043	0.590
Lev	7,004	0.400	0.234	0.007	0.386	10.082
Size	7,004	22.120	1.317	16.117	21.897	28.520
Top	7,004	36.490	15.122	3.390	35	95.950

Government subsidy is measured by natural logarithm of one plus the government subsidy amount in the current year. The more government subsidies enterprises received, the more they are likely to innovate accordingly (Khan et al., 2020).

Cash ratio is measured by the ratio of monetary funds plus investment in securities to current liability. As innovation needs sufficient financial support, this index is chosen to measure the cash level of enterprises (Core and Guay, 2001; Huang et al., 2021; Lv et al., 2021).

The net interest rate on total assets is measured by the ratio of enterprise's net profits to total average assets. Enterprises with better business performance are more inclined to carry out innovative research and development activities (Huang et al., 2021; Lv et al., 2021).

The asset-liability ratio is measured by the ratio of total liability to total assets. Moderate operating liabilities enable enterprises to obtain more cash flow and thus have sufficient funds to carry out green innovation activities (Huang et al., 2021; Lv et al., 2021).

The size of enterprise is measured by the natural logarithm of one plus the total assets amount of the enterprise. When the enterprise is large, the asset size is large and the constraint is small. Moreover, large-scale enterprises choose to participate more in innovation activities (Bu et al., 2020; Huang et al., 2021; Lv et al., 2021).

TABLE 3 | Correlation coefficient analysis of major variables.

	GP	ITI	Rd	Sub	Cash	ROA	Lev	Size	Top
GP	1	0.050***	0.185***	0.195***	−0.123***	−0.035***	0.134***	0.222***	0.054***
ITI	0.128***	1	0.209***	0.212***	−0.075***	0.036***	0.122***	0.316***	0.057***
Rd	0.080***	0.056***	1	0.311***	−0.048***	0.102***	0.001	0.316***	0.004
Sub	0.132***	0.122***	0.130***	1	−0.286***	−0.056***	0.350***	0.590***	0.094***
Cash	−0.046***	−0.061***	0.014	−0.088***	1	0.465***	−0.766***	−0.410***	−0.020
Roa	−0.008	−0.007	0.067***	0.001	0.129***	1	−0.494***	−0.150***	0.074***
Lev	0.102***	0.154***	−0.166***	0.120***	−0.315***	−0.514***	1	0.537***	0.068***
Size	0.325***	0.361***	0.010	0.336***	−0.175***	−0.044***	0.415***	1	0.179***
Top	0.110***	0.104***	−0.033***	0.041***	0.004	0.082***	0.060***	0.256***	1

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

The shareholding ratio of the largest shareholder is measured by the ratio of the largest shareholders' holdings to the total shares of the enterprise. The large shareholding ratio is conducive to the rapid decision making of the company (Mudambi and Swift, 2014; Lv et al., 2021). Here, **Table 1** shows all of the variable definitions.

Summary Statistics

The statistical characteristics of our main variables are listed in **Table 2**. We collected 7004 observations. The average number of green patent applications of enterprises is 0.16, greater than the median, indicating that there are not many green invention patents applied by heavy polluting enterprises in China.

EMPIRICAL RESULTS AND ANALYSIS

Baseline Results

The value of green innovation is between 0 and 1, and a total of 6,093 observations of green innovation are 0 in 7,704 observations and green innovation number is centered above 0. It is not suitable to continue to use the least square method in traditional regression to estimate the parameters, and it meets the setting conditions of the Tobit regression model of the restricted dependent variable (Tobin, 1958). So first we construct a panel Tobit model to explore the direct impact of economic policy uncertainty on green innovation. Our baseline regression equation based on the Tobit model is as follows:

$$GP_{i,t} = \beta_0 + \beta_1 \times ITI_{i,t} + \gamma_K \times Control_{i,t} + \eta_j + \theta_i + \mu_i$$

Control represents the control variable, η and θ represent industry effect and year effect, and μ represents the random error term. GP is explanatory variable and represents the logarithm of green invention patent applications of enterprises in the current year. ITI is explanatory variable and represents the logarithm of total IT investment in the current period.

For preliminarily discussing the relationship between IT investment, green invention patent application, and other control variables, we perform a Pearson correlation analysis on the panel data, and the results are shown in **Table 3**. IT investment is positively correlated with enterprise green innovation.

For testing the relationship between IT investment and green innovation in heavily polluting enterprises, we perform a Tobit regression on the panel data and our basic empirical results are shown in **Table 4**. In column 1, the coefficient of the interaction term is positive and significant at the 1% level according to the results under the control of related variables. This means that when we do not consider the influence of other factors, heavy polluting enterprise green innovation ability will increase 0.029 units when an additional unit of IT investment increases.

TABLE 4 | Regression results of baseline model and robustness test: alternative estimation methods.

Variable	(1)	(2)	(3)
	Tobit	Fe	Re
	GP	GP	GP
ITI	0.029***	0.036***	0.029***
	(2.98)	(3.29)	(2.95)
Rd	0.004***	0.004***	0.004***
	(4.83)	(4.28)	(4.83)
Sub	0.001	0.000	0.001
	(0.34)	(0.11)	(0.35)
Cash	0.001	0.002	0.001
	(0.91)	(1.42)	(0.90)
Roa	0.177**	0.199**	0.176*
	(1.98)	(2.11)	(1.96)
Lev	0.022	0.022	0.022
	(0.75)	(0.70)	(0.73)
Size	0.066***	0.007	0.067***
	(7.97)	(0.56)	(8.22)
Top	0.001	−0.000	0.001
	(1.09)	(−0.12)	(1.11)
Year	Yes	Yes	Yes
Ind	Yes	Yes	Yes
_cons	−1.320***	0.040	−1.346***
	(−6.50)	(0.11)	(−6.74)
sigma_u	0.325***		
	(39.65)		
sigma_e	0.301***		
	(108.95)		
Observations	7,004	7,004	7,004

*Note: (1) t-statistics are reported in parentheses; (2) *, **, and *** indicate significance at the 10, 5, and 1% levels, respectively.*

According to the resource-based theory and knowledge integration theory, IT investment exerts positive effect on green innovation of heavy polluting enterprises. They achieve standardization of work content, specialization of knowledge transfer procedures, integration of working information, and knowledge from IT investment. The standardization of enterprise process system and decision-making efficiency of

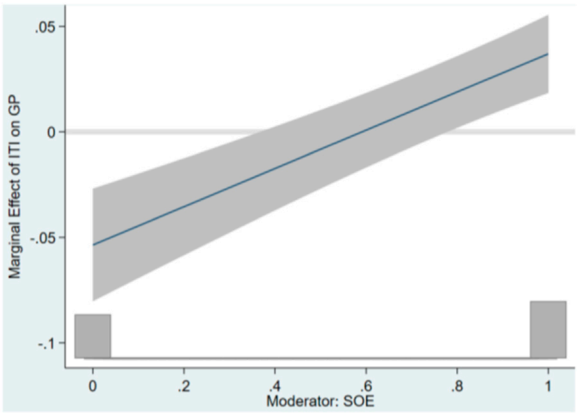

FIGURE 2 | Effects of state ownership.

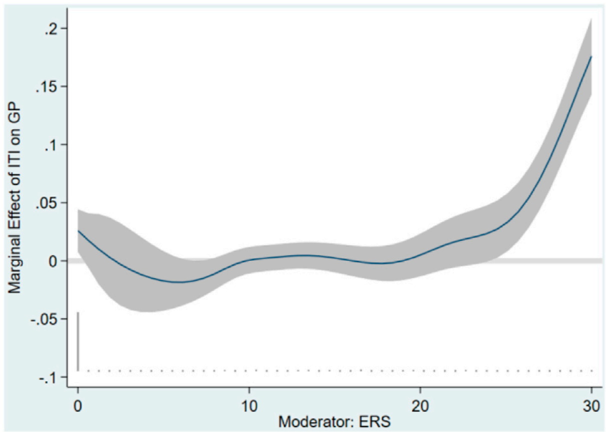

FIGURE 3 | Effects of environmental responsibility.

management are improved, thus contributing to the reduction of production costs and risk. IT investment's social advantages help employees recognize the business philosophy and organizational culture, uphold environmental protection beliefs and strengthen environmental protection skills learning, and then realize the organizational goals. Green innovation is the right way to promote transformation and upgrading. IT investment helps various departments coordinate and communicate with each other, which results in strong internal learning atmosphere. The manager is inclined to make environment-oriented decisions and combine the internal and external goals for the sake of solving the prominent environmental problems (Sinha and Akoorie, 2010). Heavy polluting enterprises need to explore green knowledge and technology to develop new business solutions and promote environmental products and innovation processes (Zhang and Walton, 2017). Therefore, the more IT investment the heavy polluting enterprises put in, the higher level will the green innovation be.

Heterogeneous Effects

After answering the question of whether IT investment is effective on enterprise green innovation, we further analyze the affecting factors of the two to provide a basis to improve the implementation effect of relevant policies. From the perspective of enterprise attributes, internal factors and external factors, we choose state ownership, sense of environmental responsibility, and environmental regulation to represent the three aspects. The marginal effects of the three factors are shown in the figure below, which is drawn by the Kernel test in the Interflex command (Hainmueller et al., 2019). This method visualizes the multiplicative interaction model, relaxes the linear interaction effect on hypothesis, and prevents excessive explanation. Traditional rendering methods only present the marginal effect on specific values; however, they fail to present it continuously. Interflex can make up for this limitation, and the kernel estimator can reduce the deviation raised from the lack of common support.

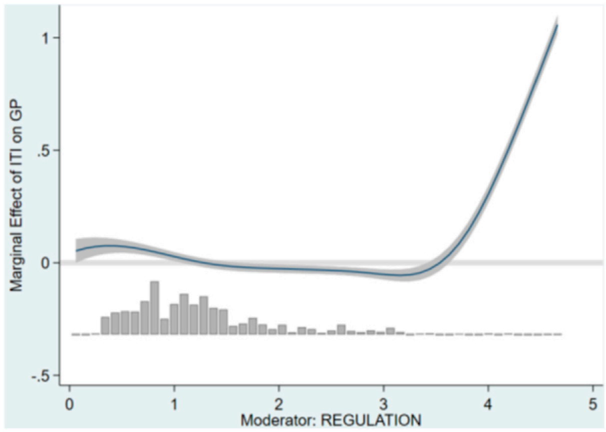

FIGURE 4 | Effects of environmental regulation.

Effects of State Ownership

Figure 2 shows the marginal effect of IT investment on green innovation of heavily polluting SOEs and non-SOEs. The blue line represents the size of the moderating effect, and the gray area represents the 95% confidence interval. When the Soe value is greater than 0.592, the marginal effect of IT investment on green innovation is positive. However, when the Soe value is less than 0.592, the marginal effect of IT investment on green innovation is negative. The marginal effect is negative in non-SOEs (non-SOEs = 0) and positive in SOEs (SOEs = 1). In addition, the marginal effect of SOEs (SOEs = 1) is stronger than that of non-SOEs (non-SOEs = 0). This is because the system logic, resource capacity, and other aspects between the two types of enterprises are different (Liu et al., 2016). The results indicate that IT investment plays a stronger role in promoting green innovation of state-owned heavy polluting enterprises.

Effects of Environmental Responsibility

Figure 3 shows the marginal effect of IT investment on green innovation of heavy polluting enterprises with different sense of

TABLE 5 | Robustness test: alternative proxies for green innovation and IT investment.

Variable	(1) GP2	(2) GP	(3) GP
ITI	0.015**		
	(2.19)		
ITI_{i-1}		0.053***	
		(4.03)	
ITI_{i-2}			0.039**
			(2.56)
Rd	0.002***	0.003***	0.001
	(3.69)	(2.91)	(0.93)
Sub	−0.002	0.000	0.000
	(−1.31)	(0.22)	(0.22)
Cash	0.001	−0.000	−0.002
	(0.97)	(−0.16)	(−0.70)
Roa	−0.009	0.190*	0.237**
	(−0.15)	(1.94)	(2.15)
Lev	0.008	−0.101**	−0.110**
	(0.39)	(−2.12)	(−1.96)
Size	0.045***	0.078***	0.084***
	(8.56)	(7.88)	(7.27)
Top	0.000	0.001	0.001
	(0.74)	(0.96)	(1.07)
Year	Yes	Yes	Yes
Ind	Yes	Yes	Yes
_cons	−0.961***	−1.509***	−1.693***
	(−7.50)	(−6.39)	(−6.22)
sigma_u	0.188***	0.338***	0.355***
	(37.82)	(38.29)	(35.53)
sigma_e	0.211***	0.305***	0.313***
	(109.29)	(99.15)	(89.32)
Observations	7,004	5,913	4,870

*Note: (1) t-statistics are reported in parentheses; (2) *, **, and *** indicate significance at the 10, 5 and 1% levels, respectively.*

environmental responsibility. When the value of environmental responsibility fulfillment degree is greater than 19.592, the marginal effect is positive. However, when the value of environmental responsibility fulfillment degree is less than 19.592, the marginal effect is negative. The marginal effect is negative with the weaker sense of environmental responsibility and positive with the stronger sense of environmental responsibility. In addition, the marginal effect of heavy polluting enterprises with strong sense of environmental responsibility is stronger than others. We can draw the conclusion that IT investment has a stronger positive effect on the green innovation of heavily polluting enterprises with a strong sense of environmental responsibility.

Effects of Environmental Regulation

Figure 4 shows the marginal effect of IT investment on green innovation of heavy polluting enterprises under different environmental regulation. The diagram shows that when the environmental regulation degree is greater than 3.627, the marginal effect is positive. However, when the environmental regulation degree is less than 3.627, the marginal effect is negative. The marginal effect is negative under the loose environmental regulation and positive under the strict environmental regulation. In addition, the marginal effect of heavy polluting enterprises with strict environmental regulation is stronger than others. We can draw the conclusion that IT investment has a stronger positive effect on the green innovation of heavily polluting enterprises in areas with strict environmental regulations.

ROBUST TEST AND ENDOGENEITY TREATMENT

Alternative Estimation Methods

In order to further test the reliability of the research results, the random effect model and the fixed effect model were used in this study to conduct surrogate tests respectively. The result is shown in the second and third columns in **Table 4**. In the random effect model, the regression coefficient of IT investment on the green innovation ability of heavy polluting enterprises is 0.036, which passes the t-statistical test of 1% significance level. In the fixed effect model, the regression coefficient of IT investment on green innovation ability of heavy polluting enterprises is 0.029, which passes the t-statistical test of 1% significance level. This indicates that IT investment still plays a promoting role in green innovation of heavy polluting enterprises after changing the model, which is consistent with the original conclusion.

Alternative Proxies for Green Innovation

In order to further test the reliability of the research results, we select alternative variables and put them into the model for regression analysis again. We test the robustness of the conclusion by changing the green innovation measurement index of enterprises. The number of successful applications of green invention patents (GP2) is a common indicator of green innovation, so it is introduced as the substitution variable. We can find in the first column of **Table 5** that the coefficient of IT investment is positive and statistically significant at the 5% level, indicating that IT investment positively impacts the green innovation of heavy polluting enterprises. This finding provides evidence of the hypothesis.

Alternative Proxies for IT Investment

The increasing number of green invention patent applications has a negative effect on the increase of IT investment. The higher the level of the green innovation is, the stronger the internal and external capabilities of enterprises will be, which tend to improve the enterprises' informatization. Therefore, the endogenous problem of mutual causality between IT investment and green invention patent applications occurs in the analysis. We lagged the total IT investment of enterprises by one and two periods to solve the problem, which are represented by ITI_{i-1} and ITI_{i-2} (Bi and Zhai, 2017). We control the endogeneity and explore the relationship between IT investment and green innovation of heavy polluting enterprises. As is shown in the second and third columns of **Table 5**, the coefficients of the lagging IT investment of the first and second phases are positive and statistically significant at the 1% level and 5% level, respectively. This indicates that there is still a significant positive correlation between IT investment and enterprise green innovation after one and two lagged periods. This finding provides evidence that increased IT investment can help promote green innovation in heavy polluting enterprises.

TABLE 6 | Endogenous treatment: regression results after PSM.

	(1)	(2)	(3)
	Radius (caliper match)	Nuclear match	Markov match
ITI	0.031***	0.031***	0.022**
	(3.20)	(3.20)	(2.02)
Rd	0.004***	0.004***	0.005***
	(4.78)	(4.78)	(4.87)
Sub	−0.000	−0.000	−0.001
	(−0.14)	(−0.14)	(−0.30)
Cash	0.001	0.001	0.001
	(0.57)	(0.62)	(0.61)
Roa	0.220**	0.220**	0.195*
	(2.43)	(2.44)	(1.92)
Lev	−0.036	−0.036	−0.020
	(−0.86)	(−0.86)	(−0.43)
Size	0.069***	0.069***	0.076***
	(7.88)	(7.89)	(8.05)
Top	0.000	0.000	0.000
	(0.66)	(0.66)	(0.20)
Year	Yes	Yes	Yes
Ind	Yes	Yes	Yes
_cons	−1.330***	−1.330***	−1.486***
	(−6.42)	(−6.42)	(−6.67)
sigma_u	0.314***	0.314***	0.316***
	(38.92)	(38.93)	(38.18)
sigma_e	0.301***	0.301***	0.304***
	(108.58)	(108.61)	(99.95)
Observations	6,976	6,979	6,026

*Note: (1) t-statistics are reported in parentheses; (2) *, **, and *** indicate significance at the 10, 5 and 1% levels, respectively.*

TABLE 7 | Test results based on IV Tobit model.

	(1)	(2)
	First stage	Second stage
Variable	ITI	GP
IT-AVE	1.854***	
	(5.23)	
IV-IT		1.854**
		(2.07)
Rd	0.006***	0.038***
	(4.65)	(3.86)
Sub	−0.000	0.043***
	(−0.12)	(2.65)
Cash	−0.000	−0.005
	(−0.01)	(−0.35)
Roa	0.072	1.226
	(0.50)	(1.47)
Lev	0.038	−0.322
	(0.87)	(−1.14)
Size	0.188***	0.195
	(24.11)	(1.13)
Top	0.001	−0.003
	(1.21)	(−1.19)
Year	Yes	Yes
Ind	Yes	Yes
_constant	−4.089***	−8.443**
	(−24.72)	(−2.31)
Observations	7,004	7,004

*Note: (1) t-statistics are reported in parentheses; (2) *, **, and *** indicate significance at the 10, 5 and 1% levels, respectively.*

Endogenous Treatment

Regression After PSM

We use propensity score matching to solve the inverse causality caused by sample selection bias. The enterprise's choice of IT investment decision is often not a random behavior, but a choice made by the enterprise according to its own operating conditions. Enterprises with a higher level of green innovation tend to have abilities including stronger learning ability, higher decision-making efficiency, and stronger process management ability. In this situation, they may be more inclined to invest in IT and thus result in sample self-selection bias. Therefore, in order to control selection bias, we use PSM method before regression analysis. This method is a nonparametric estimation tool that does not require a specific function form and requires the setting of treatment group and control group (Tian and Meng, 2018; Huang et al., 2021). We divided the total samples into two groups and calculated the average value of IT investment by industry and year. The sample enterprises higher than the average value are regarded as the treatment group, and the lower are treated as the control group. We use radius matching, nuclear matching, and Markov matching to remove the unmatched results and regress the observed values after matching. The results shown in **Table 6** suggest that IT investment is positively correlated with green innovation of enterprises, indicating that the results are still robust.

Test Results Based on IV Tobit Model of Basic Results

We test the instrumental variable (IV) to exclude the effect of endogeneity. IV is a popular technique of estimation that is widely used when the correlation between the explanatory variables and the regression error term is suspected. The IT investment of other enterprises in the whole industry affects the IT investment of a single enterprise. Therefore, we select IT-AVE, the average of IT investment in other sample companies in the same industry and year as the instrument (Zhang et al., 2020), which satisfies the correlation requirements of instrumental variables. At the same time, individual companies are unlikely to influence overall IT investment by industry and year. Therefore, the instrumental variables selected in this study have met the exogenous requirements of instrumental variables.

In the first column of **Table 7**, we select IT investment as the explained variable and calculate IT-AVE as the explanatory variable to carry out multiple regression. The empirical test results show that the regression coefficient of IT-AVE is significantly positive, which is consistent with the expectation of this study. In the second column of **Table 7**, we regress the IV-IT obtained in the first stage with the number of green patent applications, i.e., green innovation of enterprises, as the explained variable. The regression results show that the regression coefficient of IV-IT is significantly positive at the level of 5%. These results indicate that the results obtained from the previous tests are less affected by endogeneity problems.

Based on the above studies, robustness test and endogeneity discussion were conducted. We can draw the conclusion that IT investment can promote green innovation of heavy polluting enterprises, which is consistent with the original conclusion.

CONCLUDING REMARKS

Exploring how IT investment affects green innovation of heavy polluting enterprises is of great research value under the social background of rapid development in information technology, sustainable development in environment, and innovation atmosphere. The industrial digitization, green transformation, and traditional industry upgrading goals mentioned in the 14th Five-Year Plan of the Chinese government have provided an opportunity and paved the way for our study. We established a Tobit model with relevant data of heavy polluting industries in listed companies from 2010 to 2018 to explore the impact of IT investment on green innovation. The empirical results are shown as follows. First, IT investment promotes green innovation of heavy polluting enterprises. Second, IT investment plays a stronger role in promoting green innovation of state-owned heavy polluting enterprises. Third, IT investment has a stronger positive effect on the green innovation of heavily polluting enterprises with a strong sense of environmental responsibility. Fourth, IT investment has a stronger positive effect on the green innovation of heavily polluting enterprises in areas with strict environmental regulations. Our conclusion is a supplement to the related research on IT investment and enterprise innovation.

This study provides a reference for designing green innovation policies of heavily polluting industries in China and other developing countries, which is conducive to solve the pollution problems and promote industrial transformation and upgrading. First, we can predict that heavy polluting enterprises should increase their IT investment to positively accelerate green innovation. Second, state-owned heavy polluting enterprises should take the initiative to undertake greater responsibility for information upgrading and environmental protection construction and actively promote green innovation through IT investment. Third, enterprises must have an active environmental awareness and should take the responsibility to solve pollution problems. Fourth, the government should formulate appropriate policies to give correct and positive guidance and urge heavy polluting enterprises to carry out environmental protection activities.

The conclusions of the relationship between IT investment and green innovation can be transferred to other relevant areas, such as the energy field, whose environmental protection problem is also prominent. Informatization is helpful to build intelligent energy system and promote green development level in this field. Comprehensive informatization of energy systems plays an important role in processing large amounts of data, discovering causal relationships between different data sources, extracting knowledge, and predicting valuable information based on related data sources. Combining information technology with energy system planning, operation, management, policy, and trade can promote the planning and operation of energy system. Adopting information technology to collect information from the electric power, the customer, the energy investment, and other bodies is able to deepen people's understanding of the energy system and ultimately be beneficial to the blooming of green innovative products and services. China's sustainable development can be accelerated by the green energy industry.

This research has several limitations that suggest future research opportunities. First, we test a single-industry hypothesis and the generality of our findings may be limited in other industry settings. Future research is encouraged to examine our claims in other industries, particularly those with a high potential risk of environmental pollution. Second, our research samples are from a single country and may be affected by some backgrounds and policies when placed in different countries. In the future, these studies can be put into different enterprises in different countries to improve the external validity of the theory.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

XC, WM, and YP carried out conceptualization, writing the original manuscript, and revising. YT and ML did methodology development, model design, and data collection. GZ participated in conceptualization and manuscript revision. SY did results discussion and language polish.

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frontiers in Energy Research

REVIEW
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Cognitive Biases in Understanding the Influence of Shale Gas Exploitation: From Environmental and Economic Perspectives

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People have higher expectations for shale gas exploitation. However, the promotion of large-scale shale gas exploitation does not seem to be as good as it seems, since the extraction technology - hydraulic fracturing - harms the environment, which causes cognitive biases. This paper reviews studies that estimate the environmental and economic influence of the fracturing process in the U.S. and China to help people better understand the shale gas exploitation. It summarizes the methodological issues and results of main projections. There are shared problems in evaluating the influence of shale gas development due to limited identification methods, data sources and advancing exploitation technologies. Little research values the environmental influence of shale gas development in social benefit or economic benefit. Though varies significantly across various plays and parameter compared with conventional gases, previous researches indicate that water use for shale gas development will not affect the local water supply vastly, and the ultimate influence relies on the water management method. Moreover, compared with conventional natural gas and other energy resources, freshwater consumption about shale gas exploration is decreasing with the progress of exploration technology, while its life-cycle GHG emissions are greater in the long term.

Keywords: shale gas exploitation, environmental influence, estimation, energy production, economic influence

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INTRODUCTION

Compared to conventional energy sources like coal, natural gas is expected to be cheaper and have less greenhouse gas (GHG) emissions (Jacoby et al., 2011). As the unconventional natural gas distributed in shale, burning shale gas does not produce much GHG (Liss, 2014; Weijermars, 2014). Because of the improvement of exploitation technologies, which is also known as hydraulic fracturing or "fracking", energy companies can extract shale gas under the ground at a depth that was impossible in the past. The U.S. remains the largest explorer and producer of shale gas (EIA, 2013).

The work that the U.S. has carried out in shale gas and shale oil leads other countries to find its possibility for energy supply. According to the U.S. Energy Information Administration, China is the single largest depository of natural gas all over the world (EIA, 2013) and China started its shale gas production in 2012. However, less than 2% of the total production of the natural gas reserve has been explored till 2019, which seems that the exploration is in a slow progress.

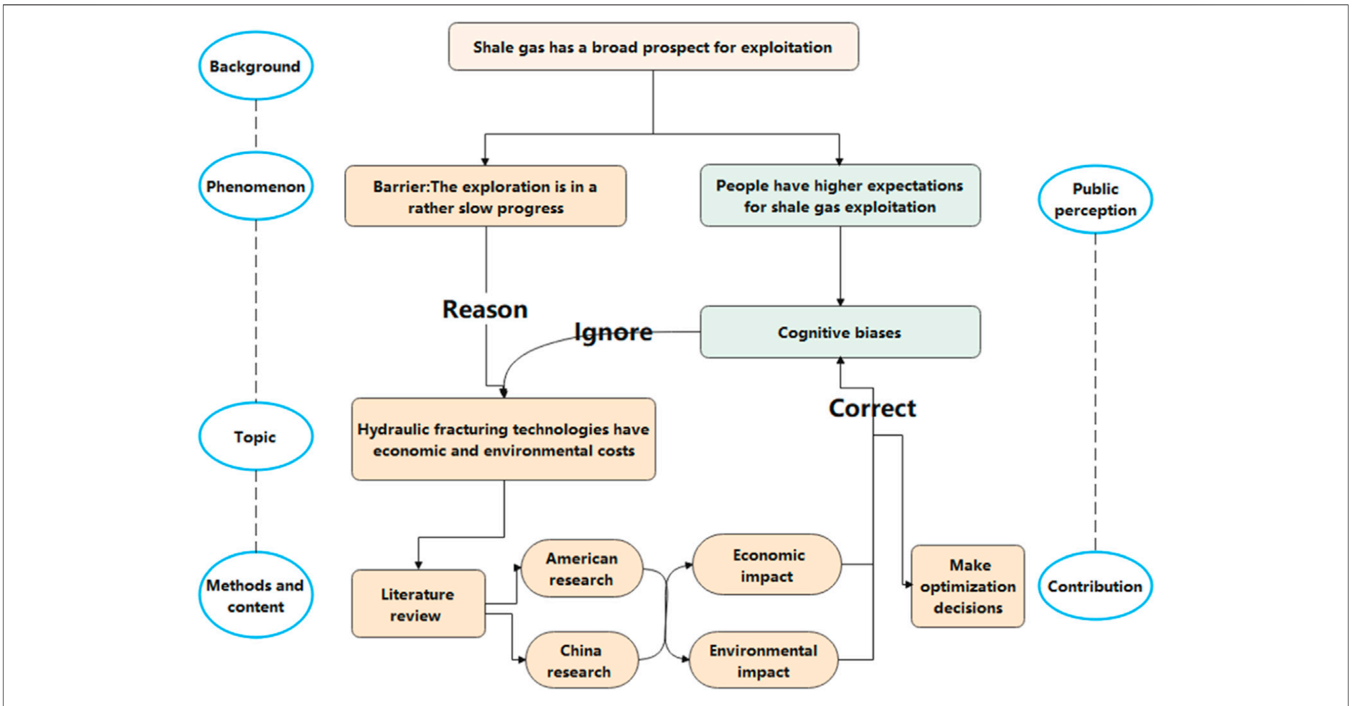

FIGURE 1 | General research frame.

A potential barrier of this slow process is the environmental and economic costs for hydraulic fracturing process (Healy, 2012; Wan et al., 2014). The exploitation techniques and the environmental and economic impact raise important questions about the shale gas exploitation opportunity (Boudet et al., 2014; Cotton et al., 2014; Davis and Fisk, 2014; Andersson-Hudson et al., 2016). Initial studies on this topic address the qualitative analysis of shale gas extraction, exhibiting a series of factors that should be considered when applying hydraulic fracturing, without measuring those impacts in figures (Sovacool, 2014). Then with the progress of fracturing practice, there are a growing number of studies to analyze its impacts in a quantitative method, estimating the level of influence.

In particular, based on the existence of cognitive biases, this article believes that people tend to amplify the benefits of shale gas exploitation due to less GHG emissions, while ignoring the environmental and economic costs caused by technologies (Li et al., 2020).

This review aims to summarize studies that indicated the environmental or economic influence of fracturing technologies for drilling shale gas. Specifically, this review focused on the studies in the U.S. and China, to see the numeric conclusions and trends of environmental and economic impact in shale gas development, despite methodological and regional variations in references.

To give a systematic summary of estimating environmental impacts, this study first introduces how hydraulic fracturing work does and the most influenced aspect in every phase during the working process. After that, this review introduces the environmental elements instead of the drilling step, in order that the specific impact on each environmental element could be understood more clearly (**Figure 1**).

Summaries draw from previous estimations indicate that though varies significantly across various scenarios compared with conventional natural gas resources, water use for shale gas development can be better controlled through efficient water management (Barbot et al., 2013). Freshwater consumption of shale gas exploration is smaller than that of conventional fuels, with a dwindling trend due to the advancing exploration technology, while its lifetime GHG emissions may be greater due to the lasting greenhouse effect of methane. Few researchers have tried to quantify the potential earthquake threats brought by shale gas drilling so far (Sun et al., 2021b). The paper helps people have a better understanding of the shale gas exploitation process in reality. This study would be helpful not only to researchers and operators of gas exploitation companies working to incorporate environmental and economic impacts into decision-making processes but to some public sectors.

MATERIALS AND METHODOLOGY

Hydraulic Fracturing Technology

Shale gas is a gas generated by the remains of sea animals. For millions of years, due to the movement of the earth's crust, layers of organic matter sink to depths of several kilometers. Under this anaerobic environment and high pressure, layers of organic matter are converted into natural gas and trapped in rocks. Shale gas is contained in natural gas in the holes of shale gas formations.

Every continent in the world reserves a large amount of shale gas, but only North America produces large-scale shale gas because the gas burying shale is too deep down in the ground. The shale gas mining methods has not been economic and attractive until the prices of natural gas and other fuels were raised (EIA, 2013). Horizontal drilling and hydraulic fracturing are non-commercial until new techniques are applied in the U.S. They enable extracting shale gas at depths of several kilometers.

Hydraulic fracturing allows companies to extract shale gas and shale oil that are previously inaccessible under the ground, which is of crucial importance since the demand for energy rises rapidly after the Industrial Revolution. Currently, hydraulic fracturing has been used over a million times in the U.S. While breaking the shale and releasing the gas, hydraulic fracturing has risks and receives controversial remarks (Geny, 2010; Spellman, 2012; Ahmadi and John, 2015; Milt and Armsworth, 2017).

The first step of exploitation is to set up a rig and vertical drilling. When the drill bit reaches the shale formations, it turns 90° and continues to drill horizontally. Then the steel tube is laid in the borehole dilled, which is called the casing. Concrete holds the casing in place to prevent material from leaking into or out of the borehole. To allow gas flowing to the surface, a performing gun is put down into the casing to perforate on the steel casing, causing holes connected in the casing and cracks in shale.

To produce shale gas, the crack in the shale must be expanded and this step is known as hydraulic fracturing. This involves injecting pressurized liquids into boreholes and shale fractures. Fracturing fluid consists of water, sands and various chemical agents which are used to increase the density of water, sterilize and dissolve minerals in the shale. Pressurized liquid increases pressure inside the casing, causing a rupture in cracks and forming new breaches (Brasch, 2012). In this step, the large amount of water and sands are undoubtedly burdens of local natural resources (Brantley et al., 2013; Eaton, 2013) and the liquid full of chemicals may pollute underground water through cracks and its branches (Vengosh et al., 2014; Darrah et al., 2014). Fracturing fluid may also change the pressure of the ground and loosen the soils, posing a potential hazard of the earthquake (Hitzman, 2013; Zoback, 2015).

Once hydraulic fracturing is performed, pressurized liquids are removed from the borehole. When the water pressure is removed from the drilling well, the small sand grains keep the fracture open. Then the pressure of the casing will be restored and shale gas flows through the hole and high to the ground. However, a small amount of transporting shale gas will escape into the atmosphere during the extracting and transfer to carbon dioxide in the end (Howarth et al., 2011; Huangfu et al., 2020).

Moreover, though it will be extracted from the ground first to collect shale gas, once a gas well dries up, fracturing fluid will be pumped back into the casing and locked in the deep. The major risk of this step is environmental problems (He et al., 2013; Vengosh et al., 2013). Hydraulic fracturing does not only use lots of water but also turning them into toxic liquid with the chemical component, which is irreversible and incapable to purify at present. Innumerable underground water sources have suffered from fracturing fluid in the U.S. and so far no investigation to show what is the long-term presentation of those locked up liquid. It is also inevitable to pollute the soil and plants around the drilling area (Yuan et al., 2015).

Methodology

The existing literature on this topic can be divided into categories as follows. Most studies investigate hydraulic fracturing's impact on the environment, with some specific section on public welfare. Their conclusions are based on the technical theory and materials used in the drilling process. These studies focus on identifying and analyzing the categories of influence more than on their specific level.

Many studies focus on one section of the whole drilling process and provide the measurement of potential influence due to the resources or generation. The main contents of these papers can be focused on one shale gas oilfield, a specific extraction plan or even an imputation model. Every well is the only one in the field of the productivity and consumption of hydraulic fracturing fluid, injected freshwater and wastewater. Most studies provide a sensitivity analysis, indicating indigenous climate or geographic impacts to variations in water and carbon influence.

Within studies that calculate the exact amount of GHG emission generated or water body impact, the life-cycle environmental influence of shale gas is compared with that of conventional resources or local energy supply. In this comparative way, these studies started to emphasize the influence of shale gas exploration from an economic perspective, rather than a single number.

Only a few references provide economic and monetary evaluations for the expected environmental influence due to hydraulic fracturing technology. The results of these references rely heavily on the resources of the dataset and the local geographic condition, and the impact of added earthquake risks is scarcely considered.

To keep the point in focus, this study will only introduce those studies with at least a quantitative analysis in economical detail, or those with valuable insights or innovations. In the meantime, more specific and recent papers have been prioritized in the paper.

MAIN PROJECTIONS IN LITERATURE

Water Consumption and Contamination in the Exploitation of Shale Gas

Complexity in Estimation and Decreasing Trends

The potential effects of shale gas operation on water resources triggered an intense public debate on hydraulic fracturing, since they may lead to environmental and public health threats (Soeder and Kappel, 2009; Kargbo et al., 2010; Gregory et al., 2011; Vidic et al., 2013; Brittingham et al., 2014; Mauter et al., 2014). Freshwater influence and accessibility are affected by local climate and water supply and demand. Conditions can be severe in places that are susceptible to drought. (Brittingham et al., 2014). Evaluation and estimation of the water impact from hydraulic fracturing are therefore essential considering the overall benefit of shale gas development.

TABLE 1 | Most relevant studies on water usage and wastewater on shale gas development.

References	Boundaries	Scenarios	Geographic area	Projection period	Projected influence
Nicot and Scanlon (2012)	Water flooding, and fracking, drilling, injection of water into an oil reservoir	Water use for fracking for shale-gas production obtained indirectly from the Railroad Commission (RRC) through a vendor (IHS) database	Barnett Shale, TX Haynesville Shale, TX Eagle Ford, TX	The year 2012	Barnett Shale, TX 10600 water use per well (cubic meters) Haynesville Shale, TX 21500 water use per well (cubic meters) Eagle Ford, TX 16100 water use per well (cubic meters)
Kargbo et al. (2010)			Marcellus Shale, PA	The year 2010	7700-38 000cubic meters water use per well
Dale et al. (2013)	life-cycle stage water consumption	Self-reported data from two operators in the Marcellus play	Marcellus Shale, PA	The year 2011–2012	2011–2012 well has mean impacts of 2.2 × 10^6 kg CO_2 -eq, 2.2 × 10^7 MJ of primary energy, and consumption of 8.2 × 10^4 barrels of water

Greenhouse gases emission in exploitation of shale gas

What adds to the complexity of the estimation of water body impact is that water varies due to multiple reasons, such as geographic conditions, the type of shale gas bed, the assumed efficiency of power plants, the water management, the tracking method of baseline water chemistry data and even the environmental oversight policy (Elbel and Britt, 2000; Holditch, 2007). Moreover, local water availability and competing demands also affect water use for shale gas (Nicot and Scanlon, 2012). Most references explain their core assumptions used in estimation, and some important element of them is stressed out in the following part.

As water-intensive energy technologies become more widespread, there are also water treatment or reuse plans intended to reduce the strain on water resources. The advancing water management leads to changing results of estimations, which presents a continually decreasing trend in water usage by 2014. However, better handling and treating water may be at the cost of burdening carbon impact.

Significantly Various Results in Water Consumption

In the literature (**Table 1**), water usage in shale gas exploitation across various geologic basins is complex. . The estimated water demand ranges from 1,400 to 33,900 cubic meters per shale-gas well (Nicot and Scanlon, 2012; Clark et al., 2013; Goodwin et al., 2014; Scanlon et al., 2014) and 8,177–9,009 cubic meters (Scanlon et al., 2014; Horner et al., 2016).

Historical data in references indicates the significance of drilling date, well borehole orientation, and target hydrocarbon on hydraulic fracturing water volumes, also, it accounts for the wide range of estimates (Nicot and Scanlon, 2012; Gallegos and Varela, 2014). The environmental effects are different with the change of target oil, gas reservoirs, the amount of water use, geologic and hydrologic settings. (Mauter et al., 2014; Gallegos et al., 2015). Though there are findings that state the reuse of hydraulic fracturing wastewater may alleviate the negative impact, however, this solution is difficult to implement in some areas since local regulatory structures in water treatment are rather complicated (Romo and Janoe, 2012).

Suggested Greater Actual Emission From Shale Gas Drilling

Although natural gas contributes to alleviating global warming for less GHG emissions, most people know little about the emission of shale gas extraction. The GHG emission of shale gas may contain two patterns. One is the direct emissions of CO_2, which is from end-use consumption, another is the indirect emissions of CO_2, which is from materials and fuels. It is well recognized in the references that the indirect emissions of CO_2 are smaller than those from the direct ones (Hayhoe et al., 2002; Santoro et al., 2011). Therefore, for shale gas, the GHG emission is mostly made up of direct CO_2 emissions and fugitive methane emissions.

The carbon footprint of shale gas is estimated to be lower than coal (Laurenzi and Jersey, 2013). However, the U.S. National Research Council warned that emissions from shale gas drilling can be larger than from conventional ones (Kling, 2010). Methane can make greater global warming effect on atmospheric aerosols than previously assumed according to the modeling (Shindell et al., 2009), even small leakages lead to considerable influence. Since methane is a strong GHG (Hultman et al., 2011), the carbon footprint (GHG emissions per low heating value of fuel) for shale gas is larger than that for conventional ones (Xie et al., 2021).

To see the trade-off of using shale gas as unconventional natural gas and the strong global warming effect of leaked methane, estimating the influence of GHG emission for the hydraulic fracturing process is therefore interesting.

The Greater Long-Term Carbon Footprint of Shale Gas Exploration

Apart from time range and projection methods, the estimation of GHG also relies particularly on the technical background document issued by the government and the location where the study takes place.

The technical report on GHG emissions was first drawn up in 1996 by the EPA (Harrison et al., 1996), which served as the basis for the national GHG inventory for the following decade. Nevertheless, the report only analyzed the facilities offered by

TABLE 2 | Most relevant studies on GHG emission on shale gas development.

References	Boundaries	Scenarios	Projected influence
Karion et al. (2013)	the Uintah Basin (4,800 gas wells and nearly 1,000 oil wells are concentrated)	Mass balance approach in atmospheric measurements	Methane emissions of 55 ± 15 × 10̇3 kg/h from a natural gas and oil production field
Heath et al. (2014)	GHG emissions of shale gas for electricity generation		Range from around 440–760 kg CO_2e/MWh
Laurenzi and Jersey (2013)	life cycle assessment (LCA) of GHG emission from Marcellus shale gas	Exxon Mobil field data and IHS Energy Well Production database	Marcellus shale gas life cycle yields 466 kg CO_2eq/MWh on average; The total emission amount associated with extraction phases shall be therefore 5.45 kg CO_2eq/MWh on average. The power plant is where most of the gas is burned
Li et al. (2019)	Conventional dehydration process and Stripping gas dehydration process	The hybrid life cycle inventory (LCI) model consists of process-based methods to evaluate the environmental impacts associated with shale gas dehydration	Increasing impacts from shale gas loss negate the gains from the savings in utility and electricity. A case with more trays and lower solvent purity is preferred in the environment

voluntarily participated companies, not on random sampling or a comprehensive evaluation of the actual extraction process (Kirchgessner et al., 1997). The distribution of emissions may be very different according to the region (Rusco, 2011).

In 2010, the first update EPA report on emission factors was launched, noting that some emission factors had potentially been understated in the 1996 report. Howarth et al. (2011) used the 2010 version reported emission factors and data from two shale gas formations and three tight-sand gas formations in the U.S. to estimate the GHG footprints accumulated of shale gas extraction. They were the first to publish a study calculating the emissions from well completion, liquid unloading, gas processing, transport, storage, and distribution losses and routine venting and equipment leaks.

In 2013 the EPA's emissions factors for calculating methane emissions from liquid unloading, unconventional completions with hydraulic fracturing, and re-fracturing of natural gas wells were raised down (EPA, 2013). It is driven by a report prepared by the oil and gas industry which stated that methane emissions from these three extraction steps were at least half less than the EPA's 2011 estimation (Shires and Lev-On, 2012). However, Karion, et al. (2013) found that results from the top-down approach of oil and gas production regions were estimates too low (Karion et al., 2013). The average leak rate they calculate is at least 1.8 times greater than the bottom-up estimate. It was very likely that the methodology that the public sectors used to account for fugitive methane emissions has some problems and this result in the lack of accurate and reliable estimates of associated emissions. **Table 2** shows the most relevant studies evaluating the GHG on shale gas development.

There are also studies trying to better monitor and control the global warming influence of shale gas extraction. Having a balance between the contradictory objectives is crucial for process optimization (Karion et al., 2013). Gao and You, (2015) propose a mixed-integer linear fraction programming (MILFP) model to address the optimal design and operations of water supply chain networks for shale gas production, reaching economic optimization and less GHG emission. It states that reverse osmosis (RO) technology is the best way to onsite treatment wastewater with outstanding economic and environmental performance. Li et al. (2019) offered a framework to assess the economic and environmental impact of shale gas dehydration. Especially, they discovered cases about optimal economic performance is suboptimal in environmental aspects and vice versa under different process parameters (Li et al., 2019).

Other references look into GHG emission as the water management cost from the gas extraction process. Clark et al. (2012) reported that a single fracturing job needs about 18,000 L (4,771 gallons) of diesel (Clark et al., 2012). And roughly 11,000 L (3,000 gallons) of diesel (Clark et al., 2012) and about 186,000 kWh of electric energy is needed for transportation and municipal wastewater treatment (Goldstein and Smith, 2002; EPA, 2010; EPA, 2013). It seems that wastewater management needs considerable energy and therefore contributes most to the total GHG emission. Absar et al. (2018) pointed out a trade-off between water and carbon impacts on the simple basis that energy is required for the treatment of water. The overall footprint of the shale gas production process are determined by the choice of wastewater management scenario. They calculated that a reduction of 49 percent in total water consumption or a 28 percent reduction in the water scarcity footprint in the production process can be achieved at a cost of a 38 percent increase in global warming potential (Absar et al., 2018).

Major Estimation in Literature

Less Feasibility and More Risk for Shale Gas Development

As the largest energy consumer in the world, China faces enormous energy needs under its efforts to make far-flung economic growth, while the government intends to reduce coal dependence and adopt an energy strategy that is responsible for society and economy (Wan et al., 2014). Replacing with natural gas therefore will make long-term advantages in reducing energy production costs and limit the extent where China relies on exported oil supplies.

Most studies in China in this field use economic features to evaluate the influence of shale gas exploitation. Primary researches concentrates on China's geological conditions and exploitation technologies (Hua et al., 2009; Wang et al., 2009; Chen et al., 2011; Wei et al., 2012). Some discussed the promotional policy of the China shale gas exploitation (Zhao et al., 2011; Farah and Tremolada, 2013; Zhang and Jiang, 2013), mainly focusing on analyzing the strategy based on the successful experience of the U.S.

Many references stated the key elements resulting in the difference of estimated environmental impact between the two countries. The geological conditions in China are much more complicated (Teng and Liu, 2013; Chen et al., 2017; Ma et al., 2021). China's shale basins are different from the ones in the United States, which located in harsh terrains and mountainous (Yu et al., 2013). China has the more complicated geological conditions and lacks environmental management laws and regulations, which will face more environmental risks caused by shale gas exploration compared to U.S. (Liu et al., 2021).

Moreover, even though the shale gas resources in China are abundant, water availability could limit shale gas commercialization successfully. The production sites of shale gas usually lack water resources (Ministry of Water Resources, 2011), making it hard to reach the economic scale of shale gas exploration on the condition of not wasting local water in some reserves-rich areas.

Yu concluded the socioeconomic impacts and risks encountered in the process of shale gas exploration in China, including the risk of uncertain estimated shale gas resources potential, limited technological experience and researches, exploration plan without long-term vision, and lack of water availability for exploration (Yu, 2015). However, as The Shale Gas Development Plan (2011–2015) said, to select suitable areas for shale gas exploration, the main criteria are the depth, resources, surface, and storage conditions of shale gas formations. The impacts studies conducted from the environmental perspective on China's shale gas exploitation are therefore very important.

Limited Data Resources and Optimal Trial

Results of existing studies in the U.S. are not readily suitable to China, because shale gas production in China and the U.S. is different in many aspects, such as geographical features, water accessibility, materials quantities, drilling equipment use, energy supplies, and drilling technology.

Basing on the first horizontal well in Sichuan China, Chang et al. (2014a) built a hybrid LCI model to measure the energy use, water use and emissions of the shale gas exploitation process. Combining average fugitive and flaring data from U.S. plays and the methane content data of shale gas in China, the estimated shale-to-well GHG emissions were 5,500 metric tons of carbon dioxide equivalents (CO_2e) (Zhao and Yang, 2015). Chang et al. (2014b) concluded that by 2020, the total consumption of direct water from 2013 to 2020 could reach 20–720 million cubic meters for 20–100 billion cubic meters shale gas exploitation in China. Furthermore, Chang et al. (2014a) and Wang et al. (2018) provided the basic data about energy use and direct water consumption of well drilling, hydraulic fracturing, well cementing, and well completion for later researches to look on. There was a need, however, to develop and consider in more developed technologies, for example,

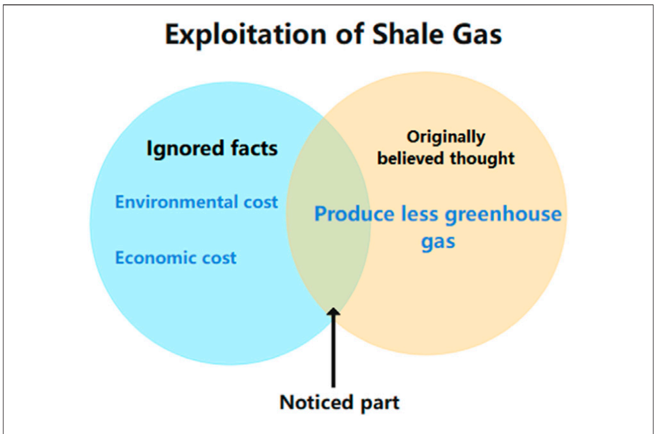

FIGURE 2 | Cognitive biases——Confirmation biases.

fracturing flow-back management, and the evaluation of water impact did not include groundwater contamination (Mohan et al., 2013).

Along with the development of Chinese shale gas industry, references later had more sufficient data and were able to consider impacts in a wider range of aspects. In Sichuan Basin, one of China's most promising shale gas basins, freshwater withdrawal per well in the surface for the hydraulic fracturing ranged between 20,000 and 30,000 cubic meters (Yang et al., 2015; Yu, 2015). Unlike most of the published results, Xiao et al. employed water footprint (WF) methodology to evaluate the impact of regional shale gas development on local water resources. The water intensity (WI) of shale gas extraction is in the range of 0.3–9.9 kg per cubic meters shale gas produced. They also found that although shale gas production needed a large amount of water, it would not affect the local water supply significantly.

Ren et al. built up a bi-objective programming model to work out the balance between economic and environmental goals. Results showed that the proportion of freshwater usage increases when decision maker wants to decrease the economic costs and fix the satisfaction degree for uncertain constraints. As a result, the environmental costs increase (Ren et al., 2019).

DISCUSSION

Cognitive Biases on Understanding the Influence of Shale Gas Exploitation

In the understanding of shale gas Exploitation, people often have some cognitive biases. Cognitive biases are systematic patterns of deviation from norm or rationality in judgment, which affect us in many areas of life, such as social situations, memory recall, what we believe, and our behaviors (Korteling and Toet, 2020; Schumm, 2021). Confirmation bias is a bias of belief that people tend to seek out or interpret information in a way that confirms their preconceived notions and ideas. In other words, people attempt to preserve their existing beliefs by focus on information that confirms those beliefs and discounting information that could challenge them. In terms of energy exploitation (Cafferata et al., 2021), people often believe that natural gas can produce less GHG compared with traditional energy and can better prevent environmental pollution (Wang et al., 2021). As a result, people tend to have better expectations for the exploitation of shale gas. Such preconceived belief reinforces the advantages of shale gas exploitation but ignores the environmental and economic costs of hydraulic fracturing, which is often a reflection of cognitive bias (see **Figure 2**).

By studying the current situation of natural gas exploitation technology in the United States and China, this paper concludes the economic and environmental challenges encountered in shale gas exploitation, which can better understand the impact of shale gas exploitation and correct people's original understanding deviation.

Variation Between Different Studies on Shale Gas Exploration

Estimation differs in data and modelling; fundamentally relies on the geographical characters in a specific area.

First, the estimation boundaries and therefore the most contributing phrases of the fracturing process are different. In the U.S., most shale gas well is developed nearby the conventional gas and oil wells. Therefore, well site investigation and preparation were assumed to have negligible water impacts and GHG emissions and they were excluded from the analysis. In China, on the contrary, well sites preparation takes up a large amount of additional energy consumption. Specifically, several standards documents give different data on drilling pad area, water impoundment capacity, and onsite road width and thickness. So it might not be suggested to simply compare the estimated results of different regions, but to look into the most influential and influenced factors in each case.

Second, researchers in China rely on open data and industrial background instructions to conduct researches. There are different sources, from volunteer collection and official regulations, in American practice, since the shale gas exploration has been mature for a longer time. We can see that early Chinese researcher had to use data from foreign cases to estimate the volume of indigenous water use. Moreover, the estimation mythology applied in the estimation in North America shows greater variety and flexibility in time frames and scenarios. There is a gap in the boundaries of database and evaluation mythology in Chinese shale gas exploitation practice.

However, Chinese researchers seem to start translating the results on an economic and monetary basis sooner. There have been a few attempts to transform the influence of GHG emission and water footprint into actual economic cost, and discussions on the trade-off between environmental and economic benefits in Chinese studies.

More mature technologies in the U.S. should be applied to China as the emergence of large-scale shale gas exploitation, such as water-based drilling, multi-stage fracturing, fracturing flow back management, drilling mud treatment. Governmental authorities should draft some industrial standards and regulations to guide drilling practices, and also, the full technological-economic-environmental effects of the process should be assessed completely.

Shared Problems in Evaluating the Exact Influence of Shale Gas Development

There are also shared problems in evaluating the exact influence of shale gas development.

First, the contamination from shale gas exploration cannot be precisely assessed since it is difficult to identify the effect of pure shale gas exploration on water pollution. For example, the presence of naturally occurring saline groundwater in areas of shale gas development poses challenges for quantifying contamination from active shale gas development, including the ability to distinguish naturally occurring groundwater salinization from anthropogenic sources of groundwater pollution.

There is a debate about the possibility of water contamination, and the extent to which it exists depends on the availability of baseline water chemistry data in aquifers. One method to fill the data gap is to build novel geochemical and isotopic tracers for confirming or refuting evidence for contamination. Therefore, studies should focus more on water contamination mechanisms for further investigation.

Another question is the uncertainty of estimation due to changing gas development technology. For example, by improving engineering controls, many of the risks mentioned in the literature are more likely to mitigate. Therefore, new primary data are needed to better understand the water consumption from shale gas transport and processing. To ensure the estimation of possible influence up to date and serves to policymaking, it is important to keep up with the changes brought by advanced solutions. In future studies, a more detailed comparative analysis of system boundaries, multiple uncertain factors and data set of different case studies should be provided. Additionally, better recognize the influence of technological progress on the water management of shale gas exploration could help us make the water management process more efficient.

CONCLUSIONS AND FUTURE STUDIES

The environmental influence of shale gas development and fracturing technologies make up a growing area of research (Sun et al., 2021a). However, there is still little research that can interpret the emission and pollution volume into social benefit or economic benefit accounting, to give more specific answers when considering the implementation of shale gas exploration in a certain area. In the past few years, many studies have been conducted in this attempt especially on the trade-off between carbon emission and water treatment the optimization of water management. Some researchers are trying to measure the environmental influence of shale gas development from per well unit to energy return unit and make a comparison with results of conventional gas resources.

In this case, the influence of shale gas development on the local environment is small and is dwindling with the progress of the water treatment method. Yet the impact on possible wastewater injection-induced earthquakes is too complex to be taken into account.

The long-term impact estimation of shale gas development also lacks investigation and discussion. Scientists have long known methane has greater global warming potential than carbon dioxide. The footprint for shale gas is larger than that for oil or conventional gas when viewed on any time horizon but particularly for over 20 years. The environmental effects for shale gas production are worth researching in the long run.

Overall, due to the existence of cognitive biases, people tend to amplify the advantages of shale gas exploitation because of less GHG emissions, while ignoring the environmental and economic costs in the process. To analyze the comprehensive economic-environmental impact of shale gas development further in time shall be important for decision-making and should be improved by further research.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

HH and YW finish the research and paper writing. LL and JL are responsible for data collection and analysis. JL works with the other authors for the Empirical Results Section.

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Evaluating Consumer Acceptance of the Commercial Fleet of Methanol Vehicles in China

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To enhance domestic energy security and reduce air pollution, China has accelerated the deployment of alternative fuel vehicles including methanol vehicles since the 2010s. Already completed pilot projects have demonstrated that methanol vehicles (commercial fleet) are economical, environmentally friendly, and technically mature. Therefore, the Chinese government aims to continually deploy methanol vehicles in coal-rich provinces. There are more than 20,000 methanol taxis in operation in China, it is important to evaluate the existing consumer acceptance of such commercial fleet before commercialization in a wider range. This paper proposes a conceptual model to identify consumer acceptance of methanol taxis. The model generates hypotheses that have been tested using surveys completed by taxi drivers of methanol vehicles in the cities of Xi'an (Shaanxi province) and Guiyang (Guizhou province). Results demonstrate that market, economic, and technological concerns strongly determine the consumer acceptance of the commercial fleet of methanol vehicles in China.

Keywords: methanol, methanol vehicle, structural equation model, consumer acceptance, China

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INTRODUCTION

With economic growth and the development of the automobile industry, the number of vehicles in China is constantly increasing. However, as the largest automobile market, China faces energy security and environmental challenges (Ji et al., 2019). From an energy security perspective, China imported 507-million-tons of crude oil and 132-billion-cubic meters of natural gas in 2019 to meet its massive energy demand (BP, 2020). From an environmental perspective, over 240 million conventional vehicles using gasoline or diesel contributed more than 36-million-tons of the total vehicle pollutants (Ministry of Ecology and Environment of China, 2019).

To strengthen domestic energy security and protect the atmospheric environment, the Chinese government has issued a series of policies for the development of alternative fuel vehicles (AFVs) (Zhang and Qin, 2018; Li et al., 2019a). Although China has already promoted electric vehicles (EVs) nationwide, other types of AFVs, and such as methanol vehicles, have also been deployed considering the adaption of regional natural resources (Li et al., 2020).

Methanol is mainly produced globally based on coal and natural gas (Hao et al., 2017). Since China's coal production accounts for 47.6% of the world's total, about 78% of China's methanol is made from coal through gasification and synthesis processes (BP, 2020). Methanol vehicles refer to vehicles that use pure methanol or blended with gasoline in different proportions based on minor modifications to internal combustion engines (Olah, 2005; Dolan, 2008). Compared with vehicles that use gasoline or diesel, methanol vehicles have fewer exhaust emissions (Wang et al., 2015). Also, the low price of methanol fuel and the low cost of "methanolized" conventional vehicles make methanol vehicles competitive from an economic perspective (Su et al., 2013; Li et al., 2020). Therefore, deploying methanol vehicles in coal-rich regions not only reduces energy imports and urban pollution but also achieves socio-economic benefits (Li et al., 2017). Considering that methanol vehicles are particularly competitive in coal-rich regions, their deployment can further diversify the AFV market (Shih et al., 2018; Yao et al., 2018).

In 2012, the Ministry of Industry and Information Technology (MIIT) launched ten pilot projects to comprehensively test the implementation of methanol vehicles (MIIT, 2012). The completed pilot projects demonstrated that methanol vehicles are technically mature, economic, and environmentally friendly (MIIT, 2019). With the success of pilot projects, the Chinese government aims to expand the deployment of methanol vehicles in coal-rich regions (MIIT, 2019). By 2019, more than 20,000 methanol passenger vehicles operate on the road, and all of them are taxi fleets (Li et al., 2020). Before issuing policies to expand the scope of methanol vehicles, it is important to evaluate the current user acceptance of such methanol vehicles from a consumer's perspective. This paper investigates consumer acceptance of the commercial fleet of methanol vehicles and considers policy implications for the further deployment of methanol vehicles in China. The rest of this paper is structured as follows: *Review of Consumer Acceptance Models* reviews consumer acceptance models; *Proposed Conceptual Model and Hypotheses* demonstrates the proposed conceptual model and hypotheses; *Methodology* details methodology for testing hypotheses; *Results and Discussion* provides results and discussion; the last section is conclusions and policy implications.

REVIEW OF CONSUMER ACCEPTANCE MODELS

As an AFV that has not been commercialized in China, methanol vehicles are regarded as new technology from the consumer's perspective. The Technology Acceptance Model (TAM) was developed to explore the public acceptance of new technologies (Davis, 1989). TAM explains how perceived usefulness (relative advantage) and ease of use subsequently influence adoption decisions and personal behavioral intentions (Davis, 1989; Petschnig et al., 2014; Wu et al., 2019). Based on TAM, TAM2 is proposed, which includes more constructs such as social influence processes (subjective norm, voluntariness, and image) and cognitive instrumental processes (job relevance, output quality, and result demonstrability) (Venkatesh and Davis, 2000). Both TAM and TAM2 have been widely applied to assess the acceptance of various new technologies, including AFVs (Dudenhöffer, 2013; Pfoser et al., 2018; Wu et al., 2019). In addition, Venkatesh and Bala (2008) introduced new constructs such as computer self-efficacy and computer anxiety, and thereby improving TAM2 (Lai, 2017). As another theoretic framework for analyzing user behavior and acceptance, TAM3 was developed (Hameed et al., 2012; Chen, 2018). Although TAM3 has been mainly applied in IT implementation, its constructs, and such as objective usability and perception of external control, and were also introduced to evaluate the acceptance of AFVs (Globisch et al., 2018).

Although TAM and its extended models are useful, numerous efforts have been made to improve their explanatory power. The Unified Theory of Acceptance and Use of Technology (UTAUT) was developed as an integrated model to enhance the understanding of technology adoption based on traditional TAM models (Venkatesh et al., 2003). Its constructs, including facilitation conditions, efforts expectancy, performance expectancy, and social influence, enable UTAUT to directly address the intent to use technology (Sovacool, 2017). To improve the original UTAUT, UTAUT2 which includes additional variables such as hedonic motivation, price value, and habit was formulated (Venkatesh et al., 2012). In addition to mobile and computer technology industries, UTAUT and its extended models have also been used to examine the adoption of AFVs (Khazaei and Khazaei, 2016; Sovacool, 2017). The constructs of TAM and its extended models including TAM2, TAM3, UTAUT, and UTAUT2 are illustrated in **Figure 1**.

The Theory of Planned Behavior (TPB) has been developed to predict the user's intentions. According to TPB, this intention is determined by constructs including attitude toward behavior, subjective norm, and perceived behavior control to predict the intention of various behaviors (Ajzen, 1991; Leonard et al., 2004). As an effective model for explaining behavioral intention, TPB has been used to analyze AFV's acceptance and purchase intentions (Mohamed et al., 2016; Afroz et al., 2015; Barbarossa et al., 2015; Wang et al., 2018; Xu et al., 2019). By comparing TAM and TPB in predicting the user's intention, Mathieson (1991) concluded that both theories are appropriate. The former model is easy to implement, while the latter can capture most aspects of an individual's belief through more variables (Chuttur, 2009).

Although TPB and TAM-related models are indeed popular when predicting the acceptance of new technology, they have limitations in terms of construct consideration. According to Will and Schuller (2016), it is difficult to develop conceptual models solely based on TPB or TAM-related models since consumers maybe lack hands-on experience in operating AFVs. Therefore, apart from existing normative variables, domain-specific constructs such as environmental or economic factors that also influence an individual intention should be considered (Burton-Jones and Hubona, 2006; Donald et al., 2014). To increase the comprehensiveness, many studies regarding AEV acceptance improved the original TAM or TPB models by introducing new constructs such as environmental concern (Barbarossa et al., 2015; Mohamed et al., 2016; Wu et al., 2019) and policy support (Zhang et al., 2018; Xu et al., 2019). In addition, other conceptual models which are independent of TPB or TAM-related models have been proposed for assessing the acceptance of AFVs (Kang and Park, 2011; Lai et al., 2015; Degirmenci and Breitner, 2017; Han et al., 2017; She et al., 2017;

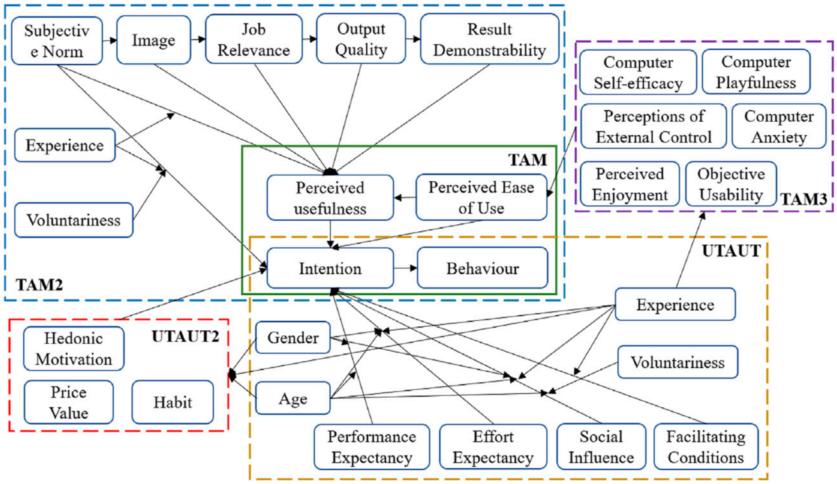

FIGURE 1 | Technology acceptance model-based models and their constructs.

TABLE 1 | Constructs and models used for investigating AFV's acceptance.

Reference	Type	Constructs	Model
Wu et al. (2019)	EVs	Green perceived usefulness, environmental concern, behavior intention, and perceived ease of use	TAM
Xu et al. (2019)	BEV	Attitude, perceived behavioral control, subject norm, environmental performance, price value, and incentive policy	TPB
Globisch et al. (2018)	EVs	Subjective norms, image and tasks, objective usability, perceived usefulness, ease of use, external control, and involvement	TAM3
Park et al. (2018)	EVs	Perceived usefulness, ease of use and enjoyment, satisfaction, public attitude, and perceived cost	TAM
Pfoser et al. (2018)	GVs	Accessibility, attitude, safety, usability, and usefulness	TAM
Wang et al. (2018)	EVs	Technical level, performance, cost of ownership, charging services, marketing, perceived values and risks, and innovative personality	Independent
Zhang et al. (2018)	EVs	Policy support, attitude, subjective norm, and perceived behavioral control	TPB
Degirmenci & Breitner (2017)	EVs	Environmental performance, price value, range confidence, and attitude	Independent
Han et al. (2017)	EVs	Emotional value, social value, epistemic value, monetary value, performance value, convenience value, functional value, and attitude	Independent
She et al. (2017)	EVs	Vehicle performance barrier, infrastructure barrier, and the financial barrier	Independent
Khazaei & Khazaei (2016)	EVs	Social influence, facilitating conditions, the anxiety of use, perceived enjoyment, and environmental concern	UTAUT2
Mohamed et al. (2016)	EVs	Environmental concern, attitude, subjective norm, perceived behavioral control, and personal moral norm	TPB
Wang et al. (2016)	HEV	Environmental concern, attitude, subjective norm, perceived behavioral control, and personal moral norm	TPB
Will & Schuller (2016)	EVs	Monetary incentives, system effects, user-friendliness, data security, and the general attitude	Independent
Afroz et al. (2015)	EVs	Perceived behavioral control, subjective norms, attitudes, purchase intention, individual and environmental consequences	TPB
Barbarossa et al. (2015)	EVs	Green self-identity, environmental consequences of using cars, green moral obligation, and attitude	TPB
Penerbit (2015)	NGV	Refueling station availability, initial modification cost, petrol price, and refueling time for NGV	Independent
Zhou et al. (2015)	EVs	Technological readiness, market readiness, institutional readiness, testing and showing,	Independent
Lai et al. (2015)	EVs	Environmental concern, perception of environmental policy and EVs, and reception of economic benefit	Independent
Petschnig et al. (2014)	AFVs	Perceived innovation characteristics, personal norm, attitude formation, and subjective norm	TPB
Dudenhöffer (2013)	EVs	Perceived ease of use, usefulness, subjective norm, affect, objective usability, experience,and price sensitivity	TAM
Kang & Park (2011)	FCEV	Acceptance, psychological needs, perceptions, and values, experiences	Independent

Wang et al., 2018). Previous studies regarding AFVs acceptance using TPB, TAM-related, or independent conceptual models are summarized as shown in **Table 1**.

As can be seen from **Table 1**, previous studies engaged different constructs to develop models for assessing the acceptance or purchase intention of AFVs. However, no study exists to date which is explicitly dedicated to the acceptance of methanol vehicles. Therefore, to address this gap, this paper proposed a conceptual model to investigate methanol vehicle's acceptance in China.

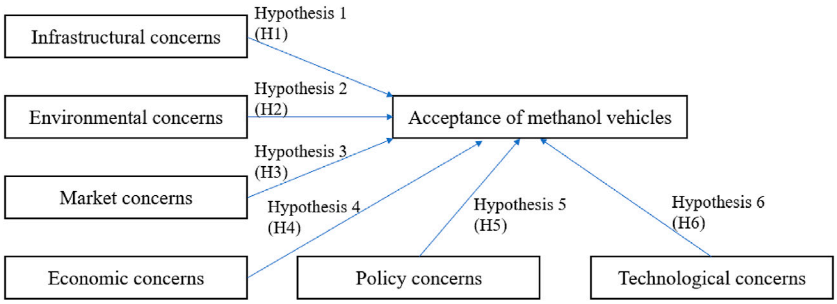

FIGURE 2 | The proposed conceptual model for assessing methanol vehicle acceptance in China.

PROPOSED CONCEPTUAL MODEL AND HYPOTHESES

The proposed conceptual model is developed to investigate the acceptance of methanol vehicles in China (**Figure 2**). This model includes the following constructs: environmental, economic, technological, market, infrastructural, and policy concerns. It not only considers constructs from the TPB and TAM-related models (i.e., environmental concerns) but also includes construct from independent models that may affect consumer acceptance of methanol vehicles (i.e., market concerns). The purpose of enhancing the original models is to provide policy implications for further adoption of methanol vehicles in China. The rest of this section explains the selection of constructs for the development of hypotheses.

Provision of sufficient infrastructure such as refueling stations or charging services directly affects consumer acceptance of AFVs. Facilitating conditions and services were considered when developing models for evaluating the adoption of EVs (Khazaei and Khazaei, 2016; She et al., 2017; Wang et al., 2018). Also, the availability of refueling stations was included as the main construct in the models for testing an individual's intention to use gas vehicles (Penerbit 2015; Pfoser et al., 2018). As the number of methanol vehicles increases in pilot cities, the distribution of refueling stations will influence the adoption of methanol vehicles (Li et al., 2019b). Therefore, the first hypothesis of this study is proposed from the perspective of infrastructure:

Hypothesis 1 Infrastructural concerns positively determine consumer acceptance of methanol vehicles.

Due to the serve pollution caused by conventional vehicles, Chinese people's awareness of environmental protection is increasing (Xu, et al., 2019). Therefore, the environmental concern is directly relevant to the acceptance of AFVs by the consumer (Wu et al., 2019). Previous studies have shown that environmental awareness is important in terms of the willingness to purchase EVs (Barbarossa et al., 2015; Lai et al., 2015; Wang et al., 2016). Considering that the main purpose of promoting methanol vehicles is to reduce air pollution, environmental performance should be included as a construct when determining consumer acceptance of methanol vehicles. Therefore, the second hypothesis is proposed from the environmental point of view:

Hypothesis 2 Environmental concerns positively determine consumer acceptance of methanol vehicles.

Market concerns are related to the participation of methanol vehicle manufacturers in the vehicle market. One of the main goals of deploying methanol vehicles in China is to reduce its dependence on oil and diversify the AFV market (Li et al., 2020). Previous studies included market-related constructs when assessing the acceptance of EVs (Zhou et al., 2015; Wang et al., 2018). Considering that methanol vehicles may become an important type of AFV in coal-rich provinces, it is necessary to evaluate consumer's concerns about the methanol vehicle market. Therefore, the third hypothesis is proposed from the market perspective.

Hypothesis 3 Market concerns positively determine consumer acceptance of methanol vehicles.

When assessing consumer acceptance of AFVs, constructs related to economic concerns were commonly included in previous theoretical models. Specifically, price value was regarded as a construct in TPB-based models to identify the user's intention to purchase EVs (Degirmenci and Breitner, 2017; Xu et al., 2019). Similarly, cost-related constructs such as perceived cost and price sensitivity were included in TAM or independent models to understand the public attitudes towards different types of AFVs (Kang and Park, 2011; Dudenhöffer, 2013; Penerbit 2015; Park et al., 2018). Because methanol vehicles have price advantages in both vehicle and fuel, consumer's economic concerns will affect the acceptance of methanol vehicles. Therefore, the fourth hypothesis is developed from an economic perspective:

Hypothesis 4 Economic concerns positively determine consumer acceptance of methanol vehicles.

Because policy support plays an important role in accelerating the deployment of AFVs in China, previous studies included this construct when establishing theoretical models. For example, policy incentives and policy support were selected as key constructs affecting the adoption of EVs (Langbroek et al., 2016; Zhang et al., 2018; Xu et al., 2019). Although there are currently not enough financial incentives to develop methanol vehicles in China, other policy support such as no license plate restriction will determine consumer's intentions to use methanol vehicles (Li et al., 2019b). Therefore, the fifth hypothesis is proposed from the perspective of policy:

Hypothesis 5 Policy concerns positively determine consumer acceptance of methanol vehicles.

As the basic construct of TAM and its extended models, technology-related constructs such as usability, usefulness, and accessibility were often selected in previous studies investigating AFVs acceptance (Dudenhöffer, 2013; Globsich et al., 2018; Wu et al., 2019). Other technology-related constructs (such as technical level and readiness) were also included in the independent models used to test the adoption of EVs (Zhou et al., 2015; Wang et al., 2018). Although the pilot projects demonstrated that methanol vehicles are technically mature, consumer's technological concerns, including driving range and the safety of using methanol as fuel, and still need to be considered. Therefore, the last hypothesis is proposed from a technical perspective:

Hypothesis 6 Technological concerns positively determine consumer acceptance of methanol vehicles.

METHODOLOGY

Survey Design: Study Area, Sample, and Data Collection

A questionnaire survey method was applied to test the proposed hypotheses. The survey was conducted in Xi'an (the capital city of Shaanxi province) and Guiyang (the capital city of Guizhou province) from June to July 2020. Xi'an and Guiyang were selected for the following reasons: 1) Xi'an and Guiyang are two major methanol vehicle pilot cities, with the greatest number of methanol vehicles and methanol refueling stations in operation. Each city has approximately 10,000 methanol taxis which is far more than other pilot cities. 2) Both Xi'an and Guiyang municipal governments implement a list of policies to deploy methanol vehicles and planned to commercialize methanol vehicles in 2021 (Li et al., 2019a). 3) Both cities also deploy gas and electric vehicles, which diversifies their AFVs market. Therefore, the respondents in Xi'an and Guiyang could have a comprehensive and objective idea when evaluating methanol vehicles.

Considering that our research objective is to examine methanol vehicle's acceptance, it is necessary to include the respondents who have already used methanol vehicles. The total number of methanol passenger vehicles has already exceeded 20,000 in China. However, all of them are used as taxis. Therefore, taxi drivers of methanol vehicles from Xi'an and Guiyang were selected as respondents.

A small study with 50 responses was conducted to verify the validity of the questionnaire. After this study, the questionnaire was modified accordingly, and 600 finalized questionnaires were distributed to two target groups of respondents through online surveys. Specifically, 300 questionnaires were distributed to taxi drivers of methanol vehicles in Xi'an, and the rest were given out to taxi drivers in Guiyang.

Procedure and Measures

The questionnaire designed based on the proposed conceptual model includes three sections (**Supplementary Table SA1**). The first section explains the research aim and the guidelines of the questionnaire. The second section includes the socio-demographic information of the respondents. The third section demonstrates the measurement for scale items of conceptual model constructs. The construction of the scale items is based on TPB and TAM-related models using the scale development procedures suggested in (Sweeney and Soutar, 2001; Rossiter, 2002).

In total, 23 measurement items were applied to measure seven constructs including six different aspects and methanol vehicle acceptance. The respondents were invited to indicate their level of agreement for the items based on a 7-Likert scale ranging from 1 to 7, where 1 represents strong disagreement and 7 represents strong agreement (Barbarossa et al., 2015; Wu et al., 2019).

Structural Equation Model

The structural equation model (SEM) is developed to analyze the relationships among unobserved constructs (latent variables) from observed indicators (She et al., 2017). In general, SEM contains two sub-models: a measurement model that describes the relationships of constructs (latent variables) and their corresponding observed variables; a structural model that illustrates the causal relationship among the constructs (Bollen et al., 2014; Zhang et al., 2018). SEM is a technique for reducing errors when measuring subjective latent constructs and incorporating them into hypothesis testing (Hair et al., 2010; Mohamed et al., 2016). Therefore, SEM has been widely used in social science including the examination of AFVs acceptance (Han et al., 2017; Wu et al., 2019; Xu et al., 2019). Since methanol vehicles have not yet found wide application in China, many features of consumer acceptance of methanol vehicles cannot be described directly. Because SEM represents a tool for testing the relationship between variables, it is used for assessing the acceptance of methanol vehicles in China. Partial Least Squares (PLS) is selected to estimate the parameters of SEM. According to Degirmenci and Breitner (2017), the PLS approach requires a relatively small size of samples and is appropriate for the early stages of research such as the adoption of methanol vehicles. Based on the formula for sample size calculation (Afroz et al., 2015), the number of valid questionnaires in this study is acceptable for the application of structural equation modeling.

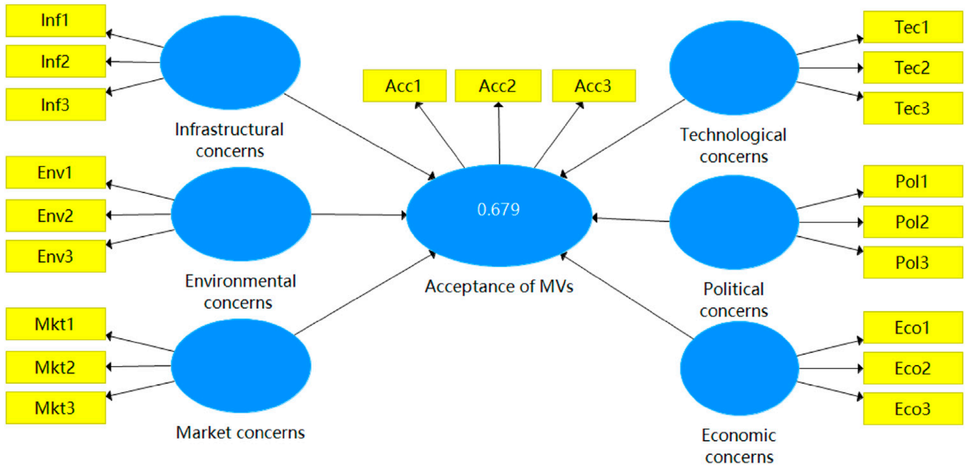

FIGURE 3 | The proposed structural equation model of methanol vehicles acceptance.

TABLE 2 | Results of the measurement model.

Construct	Items	Loading	Cronbach's α	Composite reliability (CR)	Average variance extracted (AVE)
Infrastructural concerns	Inf1	0.770	0.613	0.753	0.507
	Inf2	0.614			
	Inf3	0.742			
Environmental concerns	Env1	0.896	0.667	0.803	0.581
	Env2	0.691			
	Env3	0.679			
Market concerns	Mkt1	0.899	0.880	0.926	0.806
	Mkt2	0.924			
	Mkt3	0.871			
Economic concerns	Eco1	0.887	0.738	0.851	0.657
	Eco2	0.847			
	Eco3	0.684			
Policy concerns	Pol1	0.842	0.684	0.824	0.611
	Pol2	0.810			
	Pol3	0.683			
Technological concerns	Tec1	0.870	0.832	0.898	0.748
	Tec2	0.871			
	Tec3	0.855			
Acceptance	Acc1	0.821	0.833	0.899	0.749
	Acc2	0.893			
	Acc3	0.881			

RESULTS AND DISCUSSION

A total number of 354 validated questionnaires have been collected, based on the statistics provided by an online survey machine. The collected data is used as the input to the proposed SEM model (**Figure 3**). The results are obtained using the PLS algorithm.

According to the value of determination coefficient R^2 shown in **Figure 3**, the examined constructs explained a total of 67.9% of the variance, indicating that the proposed model is a well-fitted regression model (Kristal et al., 2010). **Table 2** shows the measurement results, including loading, Cronbach's α, composite reliability, and average variance extracted values. The loading of each item is deemed to be acceptable because its value exceeds the threshold of 0.6 (Anderson and Gerbing, 1988; Han et al., 2017; Pfoser et al., 2018). Similarly, Cronbach's α for infrastructural, environmental and policy concerns are acceptable (>0.6). The values of the remaining constructs are excellent (>0.7). The results of composite reliability (>0.7) and average variance extracted (>0.5) also meet the recommended thresholds (Anderson and Gerbing, 1988; Han et al., 2017; Pfoser et al., 2018). In order to test the validity of data collection, the discriminant validity is calculated (**Table 3**).

It can be seen from **Table 3** that the values on the diagonal are the largest in each column. Therefore, the results also demonstrate the validity of data collection. The proposed

TABLE 3 | Discriminant Validity.

	Acceptance	Economic concerns	Environmental concerns	Market concerns	Infrastructural concerns	Policy concerns	Technological concerns
Acceptance	0.866						
Economic concerns	0.721	0.811					
Environmental concerns	0.630	0.591	0.762				
Market concerns	0.756	0.678	0.716	0.898			
Infrastructural concerns	0.486	0.492	0.422	0.555	0.712		
Policy concerns	0.483	0.361	0.595	0.537	0.287	0.781	
Technological concerns	0.749	0.740	0.631	0.761	0.563	0.547	0.865

TABLE 4 | Results of hypothesis testing.

Hypothesis	Path coefficient	T-value (bootstrap)	*p*-value	Result
H1	0.001	0.009	0.993	Rejected
H2	0.061	0.638	0.524	Rejected
H3	0.319	2.855	0.004	Supported
H4	0.274	2.475	0.013	Supported
H5	0.044	0.705	0.481	Rejected
H6	0.241	2.251	0.024	Supported

TABLE 5 | Group comparison of hypothesis testing.

Group in	Hypothesis	Path coefficient	T-value (bootstrap)	*p*-value	Result
Xi'an	H1	0.046	0.570	0.568	Rejected
	H2	0.028	0.290	0.772	Rejected
	H3	0.324	2.652	0.008	Supported
	H4	0.309	3.075	0.002	Supported
	H5	0.020	0.257	0.797	Rejected
	H6	0.229	2.022	0.043	Supported
Guiyang	H1	0.004	0.044	0.965	Rejected
	H2	0.099	0.898	0.369	Rejected
	H3	0.286	2.482	0.013	Supported
	H4	0.277	2.262	0.024	Supported
	H5	0.035	0.508	0.612	Rejected
	H6	0.238	2.050	0.040	Supported

conceptual model is in line with the acceptable levels of reliability and is well-supported by the collected data.

The results of hypothesis testing with all data input are presented in **Table 4**. According to previous studies, *p*-value has been widely used to test hypotheses (Pfoser et al., 2018; She et al., 2017). Based on *p*-value (>0.05), hypotheses 1, 2, and 5 are rejected, which means that infrastructural, environmental, and policy concerns have a negligible impact on the acceptance of methanol vehicles. In contrast, hypotheses 3, 4, and 6 are supported, meaning that market, economic, and technological concerns strongly determine the consumer acceptance of methanol vehicles. Specifically, the path coefficient of market concerns is the highest, indicating that market-related items have the greatest impact on the consumer acceptance of the commercial fleet of methanol vehicles in China. Due to the lack of participation of manufacturers and the current immature methanol vehicle industry chain, this result is quite reasonable. Moreover, economic and technological concerns which also have high path coefficient values, greatly influence the adoption of methanol vehicles. Considering that all respondents were taxi drivers, it was reasonable to expect that they gave priority to items related to economic and technical perspectives, and such as fuel price and driving range.

Since the survey was conducted in two cities, this study used different data to compare the acceptance of methanol vehicles between two groups of taxi drivers (**Table 5**).

According to the results shown in **Table 5**, consumers (taxi drivers) in two cities had a very similar rate of acceptance of methanol vehicles. Consumers in both Xi'an and Guiyang are more concerned about items of market, economic, and technological aspects than that of environmental, infrastructural, and policy aspects. However, there are some minor differences based on the comparison of *p*-values. Specifically, economic concerns have a much greater impact on taxi drivers of methanol vehicles in Xi'an (0.002) than that of Guiyang (0.024). Since the diversification of the AFV market in Xi'an (gas vehicles), the price advantage of methanol fuel in Xi'an is not as good as in Guiyang. Also, based on the comparison of *p*-values for hypothesis 1, taxi drivers in Xi'an have more concerns from an infrastructural perspective than drivers in Guiyang. This is because the city of Xi'an is larger than Guiyang, but the density of refueling stations is lower. In general, there is no significant difference in terms of the acceptance of methanol vehicles between the two cities.

CONCLUSION AND POLICY IMPLICATIONS

Evaluating consumer acceptance of the commercial fleet of methanol vehicles is essential for the further deployment of methanol vehicles in China. By interviewing consumers (taxi drivers of methanol vehicles), the appropriate constructs that may affect the adoption of methanol vehicles were investigated. According to the results of the proposed structural equation model, market, economic, and technological concerns greatly determine the acceptance of methanol vehicles. However, the impacts of environmental, infrastructural, and policy factors are not so obvious. This paper compares data from two different cities currently leading the deployment of methanol vehicles. The results also demonstrate that taxi drivers in Xi'an are more concerned with economic and infrastructural items than drivers in Guiyang. Although the results are limited and based on interviewing taxi drivers because they are currently representing the only drivers of methanol passenger vehicles, we can draw the following policy implications for decision-makers in the central and provincial governments to formulate policies for further deploying methanol vehicles in China:

- The impact of infrastructural concerns on the acceptance of methanol vehicles is relatively small, indicating that the current construction and layout of refueling stations in Xi'an and Guiyang are acceptable. However, with the commercialization of methanol vehicles, consumer's concerns about the quality and quantity of refueling stations will increase. Therefore, the central government needs to strengthen and standardize infrastructure construction to ensure the smooth operation of methanol vehicles in the whole country.
- From an economic perspective, considering that the promotion of the commercial fleet largely relies on financial support, and it is recommended that the provincial and local governments continue to provide subsidies for methanol fuel and vehicles. In regions where the deployment of methanol vehicles is prioritized, it is important to emphasize the price advantages of both methanol fuel and methanol vehicles.
- From a market perspective, as only a few automakers are making methanol commercial fleet, and the government should encourage automakers to participate in the manufacture of methanol vehicles. As more and more automakers enter the market of methanol vehicles, consumers will have a choice in selecting an appropriate model of methanol vehicles.
- From a technical point of view, the government should further improve the technical standards of both methanol fuel and methanol vehicles and strengthen the research and development of methanol vehicles. Although the current respondents are satisfied with the safety and reliability of methanol vehicles, more data need to be collected to assess whether there are technical problems in operation.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Tasmania. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

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SUPPLEMENTARY MATERIAL

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The Development of Energy Storage in China: Policy Evolution and Public Attitude

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With the challenges posed by the intermittent nature of renewable energy, energy storage technology is the key to effectively utilize renewable energy. China's energy storage industry has experienced rapid growth in recent years. In order to reveal how China develops the energy storage industry, this study explores the promotion of energy storage from the perspective of policy support and public acceptance. Accordingly, by tracing the evolution of the energy storage policies during 2010–2020 comprehensively, a better understanding of the policy intention and implementation can be obtained. Meanwhile, this paper collects the information of Weibo users and posts related to energy storage by web crawler technology. The status of public attention and sentiment orientation toward energy storage are investigated with a text mining method. The main results are as follows. 1) The evolution of energy storage is characterized by three stages: the foundation stage, the nurturing stage, and the commercialization stage. 2) Most people have a positive attitude towards energy storage and recognize the potential of the energy storage industry, and it is discovered that the public attitudes towards energy storage exist cognitive bias. 3) More policies concerning market mechanism, R&D, and subsidies should be introduced to enhance the effect of energy storage policies and increase public recognition. These findings help to understand the energy storage policy and provide better strategies for policymaking.

Keywords: energy storage policy, policy evolution, public attitude, cognitive bias, sentiment analysis

INTRODUCTION

With continued growth in economic development and energy demand in the past decade, environmental deterioration and the energy crisis are becoming more prominent around the world (Zhang and Qin, 2018). China is a pivotal country in the energy sector and is taking proactive action to build a sustainable energy system. According to the data from China energy development report 2018 (Lin, 2019), coal and fossil oil energy consumption accounted for 59 and 18.8% separately of China's primary energy consumption. **Figure 1** showed the structure of China's energy consumption in 2018. The economic growth in China depends largely on coal power, which brings serious air pollution (Li and Li, 2011; Shang et al., 2018; Zafar et al., 2021). Solid fuels consumption such as coal will increase the concentration of PM2.5 in the air. Study has shown that air pollution caused by solid fuel burning was responsible for near 1.04 million premature deaths (Shen, 2016). Solid fuel substitution will help reduce PM2.5 emission and exposure, which will significantly reduce air pollution (Meng et al., 2019). Moreover, with the depletion of coal resources in advance, China is facing the dilemma of energy shortages for its coal-based energy structure (Zhang et al., 2016). Therefore, many energy policies have been issued by the Chinese government to

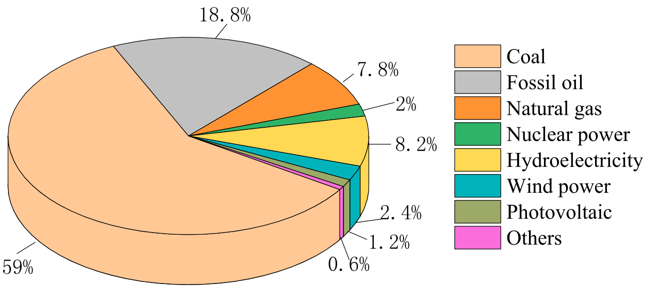

FIGURE 1 | China's energy consumption structure in 2018.

establish a clean, low-carbon, efficient and sustainable energy system. The Energy Production and Consumption Revolution Strategy proposed the targets of energy transformation as "safety, conservation, green and low carbon" (National Development and Reform Commission, National Energy Administration, 2017). However, natural and meteorological conditions make renewable energy sources such as wind and solar power intermittent and unstable (Alotto et al., 2014; Sun et al., 2019). Hence created a lot of integration and power fluctuation issues (Venkataramani et al., 2016), which limits its application in the grid (Li J. et al., 2021). In addition, these weaknesses also hold back the massive introduction of renewable systems (Yang and Zhao, 2018; Kulyk and Zgurovets, 2020). The large-scale integration of renewable energy will bring the negative impact on the safe and stable operation of the grid (Das et al., 2020). To expand the use of renewable energy, energy storage is essential. Energy storage technologies provide opportunities to solve the intermittent and unstable behavior of renewable energy (Teleke et al., 2010; Panwar et al., 2011; Kear et al., 2012; Mahlia et al., 2014). Energy storage can effectively realize peak shaving regulation and smooth out moment-to-moment variations in electricity demand, thereby reducing the impact of the grid connection of renewable energy and improving the stability of the grid (Li et al., 2016). The development of energy storage in China can help increase the proportion of renewable energy in the energy structure to build a low-carbon sustainable energy system.

Energy storage is the key to facilitating the development of smart electric grids and renewable energy (Kaldellis and Zafirakis, 2007; Zame et al., 2018). Electric demand is unstable during the day, which requires the continuous operation of power plants to meet the minimum demand (Dell and Rand, 2001; Ibrahim et al., 2008). Some large plants like thermal power units, thermal power stations, and hydropower bases, generate large amounts of electricity (Newcomb et al., 2013; Qin et al., 2020b). If the excess electricity cannot be stored, it will be lost. Energy storage can absorb the excess electricity to reduce extra waste, and facilitate arbitrage by charging during off-peak times and discharging during peak times (Zafirakis et al., 2016). Moreover, energy storage is also a potential solution to cope with the challenges that stem from the intermittency of renewable resources, such as solar and wind (Gür, 2018). These renewable resources cannot produce electricity if there is no sunlight or wind. Energy storage can smooth out their output throughout the day and can help to solve the problem of abandoning wind and sunlight (Yu et al., 2017). Therefore, the energy storage benefits the related renewable energy deployment.

The Chinese government has promulgated many policies to promote the development of energy storage. The energy storage industry had ushered in a period of development with the release of the 13th Five Year Plan (National Development and Reform Commission, 2016; China Energy Storage Alliance, 2021). The government proposed to build a batch of pilot demonstration projects of different technology types in "Guiding Opinions on Promoting Energy Storage Technology and Industry Development (2017)," to promote the development of energy storage technology and industry (National Energy Administration, 2017). In 2018, the "Opinions on Innovating and Improving the Price Mechanism for Promoting Green Development" was issued by the National Development and Reform Commission, aiming to increase subsidies for the participation of electricity storage facilities in peak shaving and valley filling (National Development and Reform Commission, 2018). The government made efforts in demonstration, subsidies and other aspects, but some problems have certainly existed (Ilieva and Rajasekharan, 2018). For example, some energy storage products exist problems with high prices and safety issues such as heat generation and combustion. The industrial policies for energy storage are complex and diverse. The development of energy storage industry requires promotion of the government in the aspect of technology, subsidies, safety and so on, thereby a complex energy storage policy system has developed. A lack of systematic research specifically regarding energy storage policies in China still prevails. This paper summarizes the evolution of energy storage policies, in order to explore the development of the energy storage industry and discover the practical problems that must be solved.

The public is the recipient of the government's energy storage policies, and their psychological perceptions and opinions of policies, that is, how they evaluate energy storage policies, will affect their wishes and behaviors. Hence, public attitudes are a potentially important factor that may determine whether storage is widely accepted (Gissey et al., 2018; Hoffmann and Mohaupt, 2020). Wu et al. (2021) argued that attitude is an important factor affecting public's municipal solid waste (MSW) sorting behavior, so the data of Sina Weibo users and their comments on related posts were analyzed to provide a better theoretical basis for subsequent decisions. Liu and Hu (2019) explored the Chinese public's attention and sentiment orientation toward green buildings from Weibo, to provide effective suggestions to popularize green buildings in China. Additionally, the public attitude toward off-site construction (Wang et al., 2019), recycled water (Li L. et al., 2021) have also been studied to help policy promotion. However, no relevant study has utilized social media data to analyze public attitude toward energy storage. Meanwhile, research showed that public's energy behavior can be influenced by the interactions between cognitive norms, energy practices, and material culture (Stephenson et al., 2015). Ambrosio-Albalá et al. (2019) argued that previous experiences, perceptions of government, and expectations about the technologies, are likely to affect the acceptance and adoption of battery storage. There is no doubt that the behaviors related to energy storage are extremely complex and are affected by many factors. Some of which are personal cognitive bias, and cognitive bias affect their attitudes. Cognitive bias refers to the situation in which human cognition reliably produces representations that are systematically distorted compared to certain aspects of objective reality (Haselton et al., 2015). For example, the choice of home heating technologies will be affected by cognitive bias (Stephenson et al., 2010). Based on technology acceptance model, sufficient understanding of the public attitude is of importance to the advancement of new technologies (Davis, 1989; Stieglitz and Dang-Xuan, 2013). Therefore, understanding the public attitudes and sentiments towards energy storage is of great significance to promoting the development of energy storage.

With the development of energy storage, policy makers need to design policies more scientifically and take a systematic approach to promote the development of energy storage. There are few comprehensive studies of Chinese energy storage policies. Therefore, this study examines energy storage policies from the perspective of the government and public. Therefore, this study will trace the evolution of energy storage policies issued by Chinese national and provincial departments from 2010 to 2020. Meanwhile, public attitudes toward energy storage are examined to look for the improvement measures for policy implementation to promote the development of the energy storage industry. Our study contributes to the existing literature in three ways. First, we provide a comprehensive understanding on the changing pattern of energy storage policies by revealing the evolution of inherent intentions adopted by the policy makers. The lack of a comprehensive introduction about energy storage policies has been a bottleneck in policy research. Second, this study utilizes social media data to analyze public opinions about energy storage policies, which can help to improve policy. Third, the research provides suggestions for China's energy storage promotion.

The remainder of the study is structured as follows: **Section 2** introduces methodology. **Section 3** demonstrates the progress of energy storage in China. **Section 4** explains public sentiment orientation. **Section 5** and **section 6** include a discussion on research findings and provides some suggestions for future work.

METHODOLOGY

Data Collection

In order to analyze energy storage policies, this paper collected 254 policies promulgated by the Chinese government from 2010 to 2020. At the same time, the public attitude towards energy storage was conducted by analyzing the collected Sina Weibo user data and comments.

Energy Storage Policy

This paper applies quantitative methods to analyze the evolution of energy storage policies and to summarize these policies. The energy storage policies selected in this paper were all from the state and provincial committees from 2010 to 2020. A total of 254 policy documents were retrieved.

To ensure the representativeness and reliability of the policies analyzed in this study, we have screened the policies on the basis of the following principles: 1) the selected policies are closely related to energy storage and 2) the type of policies retrieved comprise laws, regulations, outlines, notices, plans, and opinions. We have searched official websites of government departments, such as the State Council, the National Energy Administration, the State Grid, the Ministry of Science and Technology, the Ministry of Industry and Information Technology and other departments related to energy storage. To find more policies, we expanded the search keywords by inputting "smart grid", "energy", "solar energy", "photovoltaic" and other keywords, in order to ensure a comprehensive search.

Web Crawlers

Social networks have provided platforms for exchanging information on the Internet. More people now post real-time messages about their opinions on various topics on social networks, which express their positive or negative sentiments. Having such a large amount of social data provides an opportunity to study the public's attitudes on certain topics. In order to make full use of the social data, web crawlers as an important information retrieval tool, used to download web documents that suit the needs of users (Kausar et al., 2013). A web crawler is an important part of web search engines, which is used to collect a corpus of web pages indexed by search engines, in other words, it can efficiently and conveniently collect data from web pages or applications (Najork, 2009). Web crawlers have been used in different fields, such as data mining and social event monitoring (Wang et al., 2019). On the basis of user's purpose web crawlers can be divided into general purpose crawling and focused crawling (Hu et al., 2014). This study chooses the focused crawling to obtain the required information, as it can select and download the web pages relevant to the specific theme.

This research adopted web crawler technology to obtain public opinion from Sina Weibo, which is the largest social media platform in China (Jiang, et al., 2016). The collection process is described as follows. We initially set the crawler rules. Then filter and download were operated according to keywords in the initial information collection link. The term "energy storage" was selected as a keyword in order to understand the public's perception of energy storage. Finally, a total of 64,887 posts were obtained from January 1, 2010 to December 31, 2020.

Policy Content Analysis

A semi-quantitative analysis will be constructed to reveal the rationality of China's energy storage policy. The keywords in the policies can be determined by analyzing the policy content. These keywords present the overall evolution of the government's focus on the energy storage industry. The policy number is subjected to a descriptive statistical analysis to illustrate the policy intensity over time. To investigate the stages of energy storage policy evolution, an overall statistical analysis is performed on the keywords.

Sentiment Analysis

Sentiment analysis on social media platform data provides an economical and effective way to detect public opinion in a timely manner (Delen and Crossland, 2008); Tan et al., 2013). Text sentiment analysis refers to the analysis of sentimental subjective

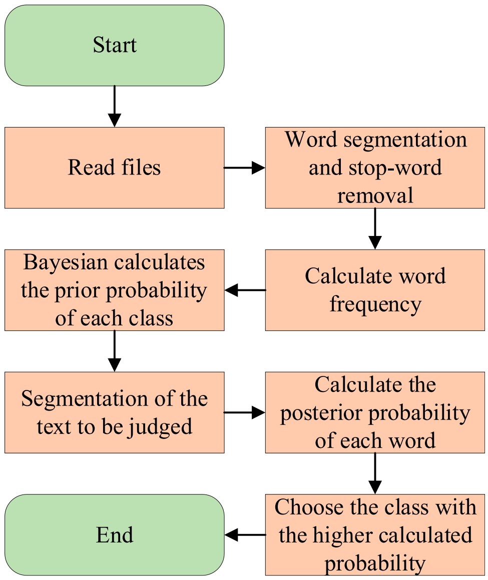

FIGURE 2 | The step of SnowNLP sentiment analysis.

texts (Chaturvedi et al., 2018), in order to find opinions, identify sentiments they express, and then classify their polarities (Medhat et al., 2014). In this study, three-class sentimental subjective texts of positive, neutral and negative reviews were mainly considered.

In this paper, sentiment analysis is performed with SnowNLP. SnowNLP is a Chinese text analysis library based on Python and all codes are completed by Unicode (Zhang et al., 2017). The basic model of sentiment classification in SnowNLP is Naive Bayes, and it provides positive and negative libraries. First, enough sample data are trained, then the appropriate classification model is selected, and sentiment classification is performed on the data according to the model. Finally, the trend probability is calculated.

The Naive Bayes classifier was used to obtain sentiment orientation of the text, which is based on Bayes' theorem and is widely used in text classification (Zhang and Gao, 2011). The principle of Naïve Bayes classifier is introduced as follows.

Assuming that A and B are two random events, if A has occurred, then the probability of occurrence of event B is as follows:

$$P(B|A) = \frac{P(AB)}{P(A)} \tag{1}$$

where $P(AB)$ is the probability of events A and B occurring at the same time; $P(A)$ is the probability of event A.

Suppose we have a set of data, X represents the characteristics of the sample; C means the class of the sample, and the Bayesian formula is as follows:

$$P(C|X) = \frac{P(X|C)P(C)}{P(X)} \tag{2}$$

Assuming that the feature X is divided into N dimensions, $X = [X_1, X_2, \ldots, X_N]$, and the Bayes' theorem can be extended to:

$$P(C|X_1, X_2, \ldots, X_N) = \frac{P(X_1, X_2, \ldots, X_N|C)P(C)}{P(X_1, X_2, \ldots, X_N)} \tag{3}$$

Using conditional independence assumption, it can be simplified to the following formula:

$$P(C|X_1, X_2, \ldots, X_N) = P(C)\prod_{j=1}^{N} P\left(X_j|C\right) \tag{4}$$

In the text tendency analysis of this study, class C consists of C_1, C_2, C_3. C_1 is expressed as positive class; C_2 is expressed as neutral class, and C_3 is expressed as negative class, so

$$P(C_i|X_1, X_2, \ldots, X_N) = P(C_i)\prod_{j=1}^{N} P\left(X_j|C_i\right),\ i = 1, 2, 3 \tag{5}$$

$P(X_j|C_i)$ means the probability of X_j in the different sample space. By solving the above formula, we can infer if X_j is in this class.

The general process of SnowNLP's sentiment analysis is shown in **Figure 2**.

The steps of the sentiment analysis were as follows:

1) Sentiment values calculation. The sentiment value of the sentence was calculated on the basis of the SnowNLP, which returned the probabilities of sentiment.
2) Sentiment orientation analysis. The sentiment orientations were divided into three intervals: [0, 0.25), [0.25, 0.75] and (0.75, 1]. The first represented negative sentiment, whereas the other two expressed neutral sentiment and positive sentiment respectively.
3) Sentiment focus analysis. Word frequency analysis on sentences with different sentiment orientations in order to obtain the sentiment focus of the public.

PROGRESS OF ENERGY STORAGE IN CHINA

Energy storage is important to achieve a low-carbon future (Landry and Gagnon, 2015). In order to clarify the development of the energy storage industry, this paper first analyzed energy storage policies from 2010 to 2020 to obtain the overall understanding of the government's attention on the energy storage industry. Then, a statistical analysis was performed on the policy keywords, revealing the priority of the energy storage policy in various periods. On the basis of the above analysis, the evolutionary stage of energy storage policy can be divided according to the specific background of the entire evolutionary process.

An Overview of China's Energy Storage Policies From 2010 to 2020

In recent years, China's economy has obtained significant achievement, accompanied with rapid development (Kong et al., 2020). At the same time, China has used resources and paid an environmental price (Qin et al., 2020a). The coal-based energy structure is inseparable from air pollution and water pollution. Therefore, energy transformation has become the

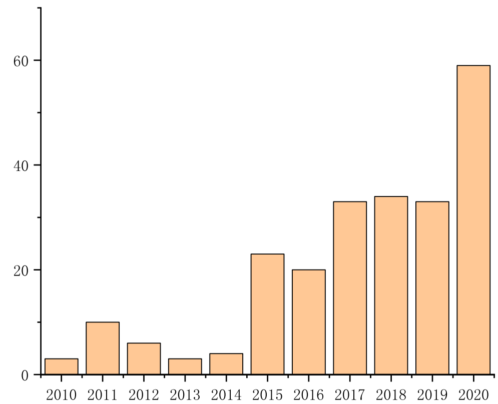

FIGURE 3 | The number of China's energy storage policies from 2010 to 2020.

core issue of the Chinese government. The energy storage industry, as a supporting industry for the adjustment of energy structure, is still in the early stages of development, with problems such as high costs, few standards, and complicated technical route (Li et al., 2015). China has encouraged the development of distributed energy. At the same time, the energy storage systems market is gradually expanding. As shown in **Figure 3**, from 2010 to 2014, the energy storage policies issued by the government were insufficient. Since 2015, the number of China's energy storage policies has shown a slow growth trend, continuing until 2019. By analyzing the content of energy storage policies, we can summarize the keywords of each policy. These keywords represent the government focus of energy storage industry in different periods. It shows the emerging trend of energy storage development. The policy keywords related to energy storage from 2010 to 2020 are given in **Figure 4**.

Of the 254 energy storage policies, some keywords appeared many times during the observation period. **Figure 4** shows that the energy storage policies emphasized "research and development (R&D)," "standards," "environmental protection," and "safety production supervision." These conformed to the aim of energy storage "industrial development" and "energy transition." As an "emerging industry," current measures mainly included "development planning," "popularization and application," "demonstration and application," "price mechanism," "improvement of auxiliary service mechanism." These policies also provided economic support, including "financial support," "encourage capital support" and so on. The government encouraged the application of large-scale energy storage systems through "smart grid," "Internet +" "distributed" and "centralized" technologies.

The Development of the Chinese Energy Storage Industry

Based on the statistical results, considering the specific timeframes and the background of key events, the evolution of energy storage industry is divided into three stages: the foundation stage, the nurturing stage and the commercialization stage. Among them, 2014 and 2017 were the big moments. Energy storage was listed as a key innovation field for the first time in 2014, and the first guiding policy for large-scale energy storage technology was released in 2017. These policies introduced the development of energy storage into a new stage.

1) The Foundation Stage, from 2010 to 2013, is the initial exploration period of the energy storage policy, laying a solid foundation for the development of the energy storage industry. In this stage, the R&D of technology became the primary problem for government. Therefore, the main task of the government at this stage was to encourage innovation in energy storage technology. In 2010, at the end of the 11th Five-Year Plan (2006–2010), the 12th Five-Year Plan (2011–2015) was issued by the government. The word "energy storage" first appeared in national documents, and proposed breakthrough technology such as energy storage, which was considered as an important part in the construction of smart grids (National Development and Reform Commission, 2010). Then more and more people recognized the importance of energy storage technology due to the guidance of the government.

With the progress of the energy industry, the energy revolution has been marked by the large-scale development and utilization of new energies, such as wind energy and electric energy. In order to further promote the innovation of energy storage technology and equipment, demonstration and application policies have attracted the attention of the government. Energy storage technology has begun to be applied in practice. China's first large-scale energy storage demonstration project, "Zhangbei landscape storage demonstration project (2011)" was issued (Ministry of Finance, 2011). This project integrated wind power generation, photovoltaic power generation, energy storage systems and smart power transmission. It enabled energy storage to lay the foundation for industrial development. In addition, in order to support the application and development of energy storage technology, the government has issued many encouraging policies. In July 2012, "Solar power development 12th Five-Year Plan" pointed out that during 2011–2015, 30 new energy microgrid demonstration projects should be built (National Energy Administration, 2012). And it is necessary to support the demonstration and application of large-scale energy storage systems, which was indicated by "Special plan of 12th Five-Year of major scientific and technological industrialization of smart grid" (Ministry of Science and Technology, 2012). Meanwhile, in the initial stage of the energy storage industry, financial support was used to reduce energy storage cost and promote large-scale applications. These policies not only created conditions for energy storage technology at large-scale popularization and application, but also removed market barriers and provided legal support.

In general, the government emphasized the necessity of continuous technical innovation, and extended strong support to the development of energy storage technologies. As a new technology, technical R&D of energy storage should be focused if it wants to be achieved rapid development. The relevant policies

2010-2012	
Word	#
Research and development	6
Smart grid	4
Industrial Development	4
Development planning	4
Demonstration and Application	3
Environmental protection	4
Popularization and Application	2
Scale development	1
Financial support	1
Standard	1
Power peak shaving	1

2013-2014	
Word	#
Safety production supervision	4
Research and development	3
Development planning	2
Industrial Development	2
Standard	1
Demonstration and Application	1
Scale development	1
Financial support	1
Smart grid	1
New mode of operation	1
Power peak shaving	1

2015-2016	
Word	#
Research and development	17
Development planning	7
Demonstration and Application	6
Facility construction	6
Environmental protection	5
Popularization and Application	4
Distributed	4
Internet+	4
Encourage capital support	4
Safety production supervision	3
Power peak shaving	2
Standard	2
Financial support	2
Industrial Development	1
Energy transition	1
Scale development	1
Emerging industry	1
Smart grid	1
Centralized	1

2017-2018	
Word	#
Research and development	23
Development planning	9
Demonstration and Application	9
Popularization and Application	9
Industrial Development	9
Price mechanism	8
Distributed	6
Environmental protection	5
Standard	5
Financial support	5
Internet+	4
improvement of auxiliary service mechanism	4
Facility construction	3
Encourage capital support	3
Power peak shaving	3
Scale development	3
Energy transition	2
Safety production supervision	1
Emerging industry	1
Smart grid	1

2019-2020	
Word	#
Research and development	26
Demonstration and Application	19
Popularization and Application	14
Development planning	12
Power peak shaving	11
Standard	10
Energy transition	10
Industrial Development	9
Environmental protection	8
Facility construction	8
Price mechanism	7
Financial support	6
Safety production supervision	6
improvement of auxiliary service mechanism	5
Emerging industry	4
Scale development	3
Distributed	3
Encourage capital support	1
Smart grid	1
Centralized	1

FIGURE 4 | Energy storage policy keywords from 2010 to 2020.

during this period were mainly about R&D on the power grids that incorporate energy storage technologies, and demonstration application of energy storage technologies in the field of renewable energy. These have laid a solid foundation for the development of energy storage.

2) The Nurturing Stage, from 2014 to 2016, is the nurturing stage of the energy storage industry. In order to promote the development of the energy storage industry, during this period, the number of energy storage policies in China increased. These policies involved power system reform, ancillary services, technical R&D, and environmental protection. In 2014, the State Council officially issued the "Energy Development Strategic Action Plan (2014–2020)". This plan was proposed to build a clean, efficient, safe, and sustainable modern energy system, and focused on the implementation of four strategies: saving, domestic, green, and innovative (General Office of the State Council, 2014). A new round of energy revolution and transitional development was booming. In order to achieve energy savings and emission reductions, the R&D of energy storage technology was still necessary at this stage.

Moreover, ancillary services were necessary functions to maintain the safe and stable operation of the power system. In order to fully develop and apply energy storage technology, it is essential to explore the application prospects of the ancillary service market for energy storage (Shang, 2019). Thus, ancillary services such as frequency modulation and peak shaving received attention at this stage. In 2016, the National Energy Administration issued a policy to further explore the role of electric energy storage in the peak and frequency modulation of the power system. This policy first combined energy storage with electricity market reform after taking energy storage into innovation account. It encouraged the market to accept the dominant position of auxiliary services for energy storage, and stimulated companies to search for a new business model for energy storage on both the power generation side and user side. It also promoted the commercial development of China's energy storage industry. Due to the lack of policies related to the price mechanism and having few clear business models, the development of the energy storage industry is still in the cultivating stage.

Overall, with respect to technology, energy storage basically has a foundation of industrialization in China. In order to build a healthy and orderly environment for energy storage, government has made a lot of effort in accelerating the construction of the auxiliary service market, while attaching great importance to technical R&D. The government has focused on verifying the application characteristics and prospects of various energy storage technologies in frequency modulation and peak shaving in completed energy storage projects.

3) The Commercialization Stage. From 2017 to 2020, China experienced a preliminary exploration period for the commercialization of energy storage industry. The National Energy Administration promulgated the "Guiding Opinions on Promoting Energy Storage Technology and Industry Development (2017)," which first clarified the strategic position of energy storage. Since this policy was published, the number of energy storage policies has risen steadily (National Energy Administration, 2017). In this stage, keywords like "popularization and application," "standard," "distributed" and "price mechanism" showed that the government was actively promoting the commercialization of energy storage, and paid more attention to energy storage in "scale development" and "industrial development." The establishment of the price mechanism provided a certain support for advancement of commercialization. In the process of commercialization of the energy storage industry, the establishment of technical standards plays an important role. If there is no technical standardization system, it is easy to cause security and other issues, and the process of commercialization will also be hindered. In addition, to solve the problem that it was difficult to guarantee profit after energy storage participating ancillary service markets, the government promoted the commercial application of energy storage industry by improving the price mechanism for ancillary service. Although the government focused on technical R&D, still, energy storage equipment innovation and development capacity were relatively weak. Energy storage technologies were in the early stage of industrialization (Tan et al., 2018). Thus, technical R&D cannot be ignored at this stage, exploring large-scale and industrial production technologies to lower the fabrication cost were urgent (Liu et al., 2017). The government also made other efforts for the commercialization of energy storage. During the 13th Five-Year Plan (2016–2020), a number of key technical specifications and standards would be formed to establish a standardization system for energy storage technology (National Development and Reform Commission, 2016). In addition, the government encouraged companies to explore a batch of generalizable business models. At this time, all this evidence showed that energy storage industry entered the initial stage of commercialization. With the support of these policies, many energy storage pilot demonstration projects were conducted, which focused on technological innovation, exploration of operating modes and institutional mechanisms, leading the energy storage industry to commercialization.

The evolution of energy storage industry is divided into three stages: the foundation stage, the nurturing stage and the commercialization stage. The government has created conditions for energy storage to participate in peak shaving and market promotion. Under the guidance of policies, the energy storage industry has stepped into a new era. However, as an emerging technology, energy storage still has a long way to go.

PUBLIC SENTIMENT ORIENTATION

In this section, sentiment analysis of the energy storage policies using the Weibo comments are conducted. Based on the result of sentiment analysis, we obtained the public sentiment orientation and emotion distribution toward energy storage policies.

The Characteristics of Public Sentiments

The Weibo posts from 2010 to 2020 were obtained by using the keyword "energy storage." From Sina Weibo, a total of 117,455 posts were retrieved. By removing non-related posts such as advertisements and articles with less than 15 words, we finally obtained 64,887 posts about energy storage. The number of posts per year has been counted and summarized in **Table 1**. Overall, the number of posts on energy storage is unstable, but showed an increasing trend. In different periods, the number of posts on energy storage is different. In the foundation stage, the 12th Five Year Plan was released (National Development and Reform Commission, 2010). Since then, the public had a certain understanding of energy storage and the number of posts increased. During the nurturing stage, the public showed more interest in the promotion of various types of clean energy, thus their attention to energy storage had declined. In the commercialization stage, the "Guiding Opinions on Promoting the Development of Energy Storage Technology and Industry (2017)" were issued to clarify the strategic position of energy storage in China, which regained the public's attention in the following years (National Energy Administration, 2017).

The research on public sentiments on energy storage policy is of great importance for ensuring the effectiveness of the policy and improving the satisfaction of the public (Sun et al., 2020). We analyzed the social data from Sina Weibo to evaluate the energy storage policies from the perspective of public sentiments. By

TABLE 1 | Number of energy storage posts from 2010 to 2020.

Time	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Number	43	694	2,945	5,638	5,247	2,290	3,950	4,395	11,307	11,820	16,558

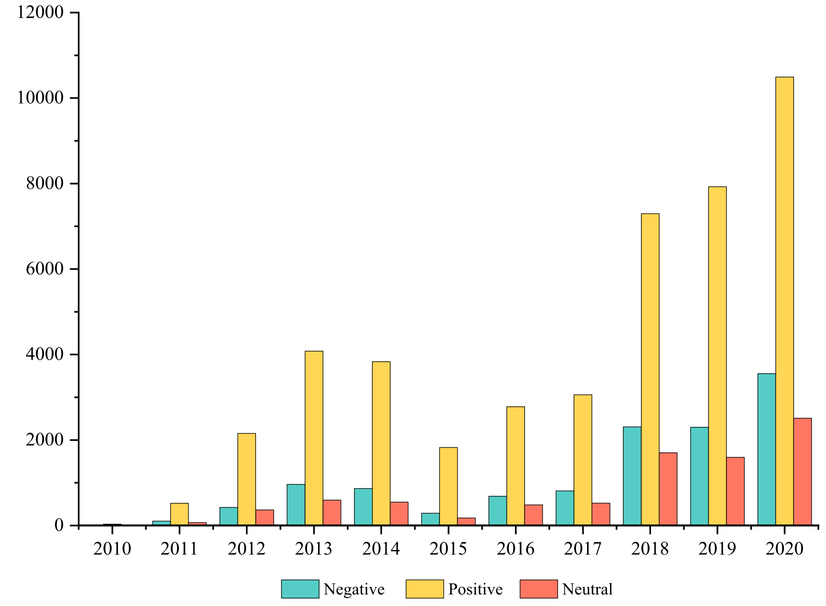

FIGURE 5 | Distribution of public sentiment towards the energy storage policies.

conducting an overall sentiment analysis, we found that the proportions of positive and negative sentiments are 67.84 and 18.98%, respectively. **Figure 5** shows the distribution of public sentiment towards energy storage policies from 2010 to 2020. The proportion of positive sentiments is greater than the proportion of negative emotions in each year. This shows that the public held a positive attitude towards the energy storage policies and recognized the role of energy storage in smart grid construction and energy transformation. However, positive sentiments showed a decreasing trend, while the proportion of negative emotions gradually increased. There are many difficulties that need to be solved in the development of energy storage, such as low technical efficiency and imperfect subsidy policies (Tong et al., 2021). These problems will inevitably impact public attitude and bring certain negative sentiment. Therefore, more efforts are needed to improve the environment of energy storage.

The Focus of Positive Sentiment Toward Energy Storage

To explore specific reasons the public had positive sentiments towards energy storage policy, this study analyzed the word frequency of Weibo posts with positive sentiment. The high frequency words (top 20) of each period were shown in **Figure 6**. According to the high frequency words, we can identify the mechanism of positive sentiments. **Figure 6** indicates that "energy storage," "technology," "battery," "photovoltaic," and "materials" are the most frequently used words in different development stages of energy storage industry. These words represent people's recognition of energy storage industry. Energy storage can be provided by diverse technologies like pumped hydroelectric storage, sodium, thermal storage, etc., (Chen et al., 2009). The different characteristic of technologies determines whether they are suitable for certain energy storage services. Therefore, technology innovation is critical for the application of energy storage, and people maintain a positive attitude to it. The battery storage has a broad range of uses in commercial and resident life. The public has paid more attention to the battery capacity and stability (Zheng et al., 2019). China is the largest market in the world for both photovoltaics and solar thermal energy (Huang et al., 2019). Photovoltaics is already an economic and practical option for residents to provide electricity, such as street lighting and solar water heater. Therefore, the public would hold a positive attitude toward it. The application and research of new materials like sodium in energy storage industry become more popular in recent years, which illustrated the positive sentiment toward it.

The focus on energy storage is quite different in different stages of energy storage industrial development. In the foundation stage, keywords like "sun," "distributed," "lithium" and "new energy" showed that people took a positive attitude to the development of various new clean energy sources and paid more attention to investment in "power grids," "enterprises,"

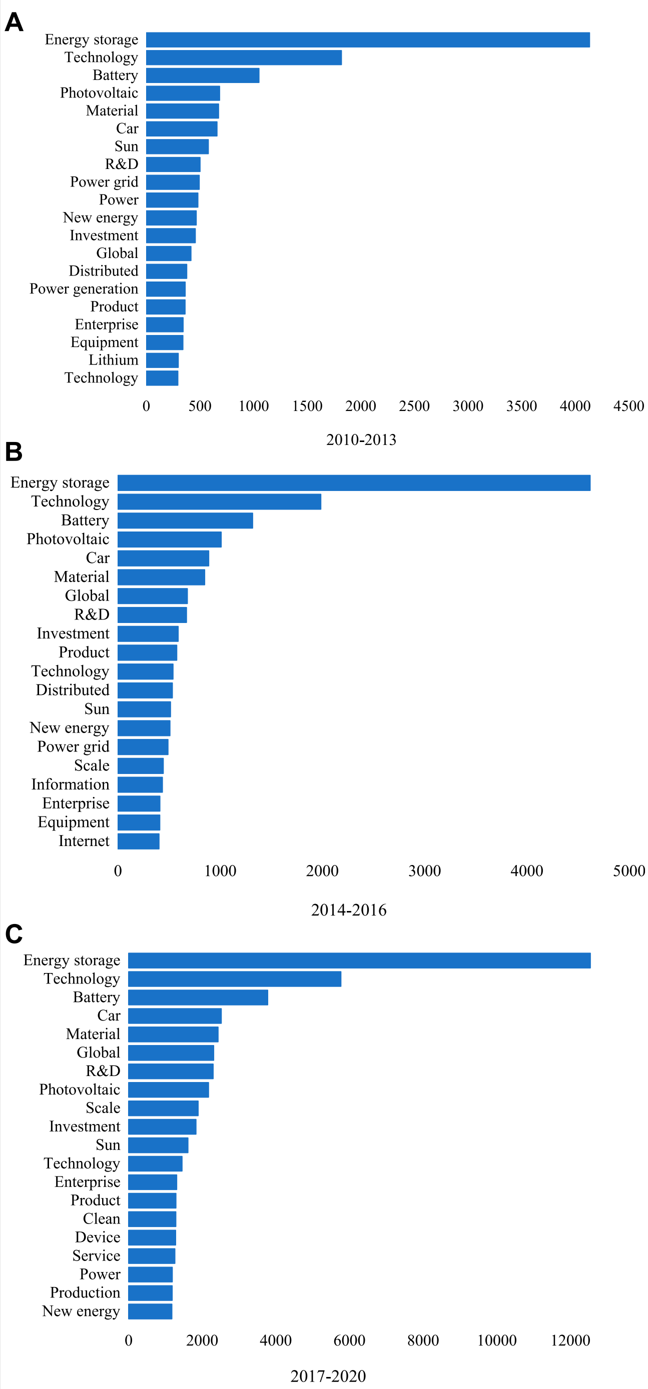

FIGURE 6 | High frequency words (top 20) of positive sentiment towards energy storage policy from 2010 to 2020.

"equipment." In the nurturing stage, the public also showed greater interest in the informatization and large-scale construction of the "grid." The intermittent characteristic of renewable energy sources hindered the power grid stability (Mohammed et al., 2014). To increase renewable energy stability, the Internet was employed in energy forecasting, leading to more effective use of renewable energy sources. In the commercialization stage, from keywords like "scale," "product," "clean," and "service," it could be seen that the public kept a positive tendency to the promotion and commercialization of energy storage. The energy storage

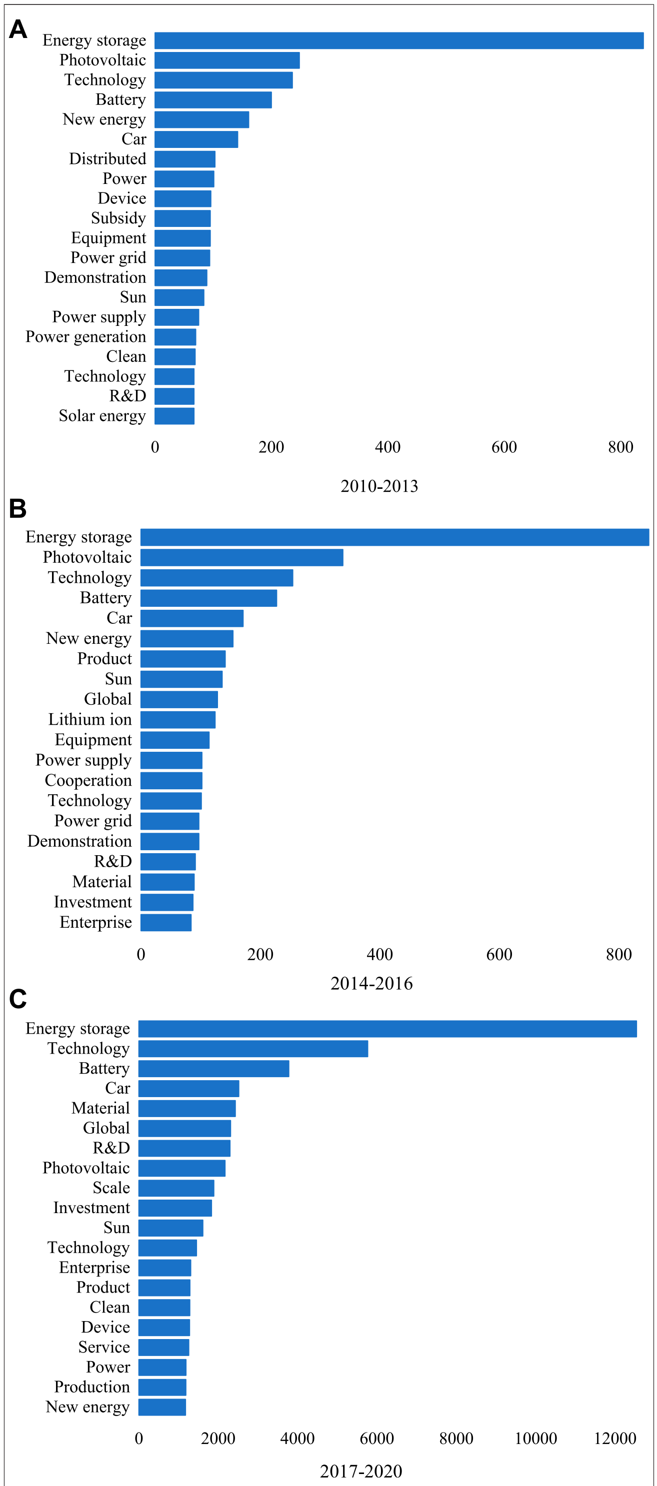

FIGURE 7 | High frequency words (top 20) of negative sentiment towards energy storage policy from 2010 to 2020.

industry had received a certain level, so how to cooperate with clean energy to carry out large-scale energy storage attracted more people's attention (Kittner et al., 2017).

The Focus of Negative Sentiment Toward Energy Storage

Word frequency analysis of the negative sentiment posts were conducted to figure out the reason that the public has negative emotions towards energy storage, and the results are presented in **Figure 7**. **Figure 7** indicates that "technology," "battery," "photovoltaic," are the main concerns expressed about energy storage. However, for the same keywords, 71% of people held a positive attitude to it. This shows the influence of cognition on public sentiments. Due to the difference in living environment, occupation, personality and others, the way the brain processes information are different (Van Overwalle, 2009). Cognitive bias arises when the person's brain attempts to simplify information processing. Therefore, opinions of energy storage are usually not the same even for the same issue, which represent the cognitive bias of the public toward energy storage. This also shows that there are still many obstacles in the development of energy storage, which leads to the cognitive bias of people. How to improve the public's perception of energy storage requires thoughtful consideration in the future.

In different periods of energy storage development, the specific reasons for the negative sentiments are not the same. In the foundation stage, the public showed negative sentiment regarding "subsidies" for various energy storage applications. The government still explored the development of energy storage, and the subsidies were sufficient at that time (Yu et al., 2017). However, the research and promotion of energy storage required huge financial funds. Without government support, enterprises would take a high risk. This caused negative sentiment among the public. In the nurturing stage, the public had negative opinions on the usage of new materials and corporate cooperation. Pumped water storage was still the main energy storage method, and progress of various new materials research was slow. Moreover, the lack of cooperation of enterprises, was not conductive to removing obstacles in technology development and promotion. These made the public hold negative sentiments on energy storage in this period. In the stage of commercialization, the public also expressed their concerns on the promotion of energy storage. From the keywords "equipment," "scale," "device," it can be seen that grid construction still faced some challenges. Also, from "Tesla," "production," "capacity" and other words, we could find that there are still many problems in the application of energy storage batteries. Therefore, the public had negative sentiments regarding the promotion of energy storage.

DISCUSSION

Energy storage is becoming a key part the electric grid as it has the advantages of absorbing excess power generation and speeding up the clean energy revolution. Through a systematic evolution analysis of energy storage policies, this study concludes that the current development of energy storage has experienced three stages: the foundation stage, the nurturing stage and the commercialization stage. At different stages, the intentions of energy policies were quite different, which shows the characteristics of industrial development. Enterprises and investors can coordinate their resources according to the characteristics of energy policies. Moreover, this study also analyzed the public attitude toward energy storage policies, which can help to improve public recognition. Sentiment analysis results showed that the public's attitude to energy storage was dominated by positive sentiments, and the proportion of positive emotions was decreasing. The decomposition of positive and negative sentiment focus can help government have a better understanding of the gap between policy intention and policy implementation, thereby optimizing policy making.

By tracing the evolution of energy storage policies, we found that China's energy storage industry remained in its infancy and has not yet reached an industrial scale. First, the inadequate policy coordination hinders the development of energy storage industry. In recent years, many energy storage policies have been introduced, covering local and central policies. However, these policies were not clarified and may confused by participants. Moreover, due to the lack of details, it was difficult to form consistency in the local and central policies. Although energy storage attracted the government's attention at the foundation stage (2010–2013), the demonstration and application of energy storage was focused in this period, thus ignoring the importance of subsidies and other detailed rules. This was one of the reasons why the public has a negative attitude towards subsidies at this stage. There was no specific implementation rules and detailed development roadmap, have been issued after the "Guiding Opinions on Promoting Energy Storage Technology and Industry Development (2017)" was promulgated at the initial stage of commercialization (2017–2020) (National Energy Administration, 2017). As a result, the implementation of the central energy storage policies in various localities lacked consistency and coordination. An external market environment conducive to the development of the energy storage industry has not yet been created. Second, there is still a lack of effective market mechanisms in energy storage industry. At present, the application of energy storage in China is mainly distributed power generation and grid connection of micro-grid and renewable energy. There were few applications of power transmission and distribution and auxiliary services. In the nurturing stage, although ancillary services have been focused gradually, the ancillary services market mechanism has not yet been formed in China. For example, the key of promoting the commercialization of energy storage, electricity spot market hasn't been established yet (Yinjun et al., 2021). Moreover, the government has proposed to combine energy storage with electricity market reforms. However, in the absence of a cost-price mechanism in the electricity market, energy storage is difficult to provide favorable conditions for large-scale development of new energy. Combined with the public negative attitude towards large-scale construction at this stage, it can be seen that the large-scale development of energy storage is indeed hindered. In addition, the compensation standards and ancillary service compensation lack a long-term mechanism, and policy guarantees are uncertain.

Based on the result of sentiment analysis, it was concluded that more people hold a positive attitude toward energy storage, and changes in public sentiment have obvious time-varying characteristics. In terms of positive sentiments, the focus shifted from technology to commercialization. This benefited from the government's support for companies to explore new business models in the nurturing stage and the commercialization stage. For negative sentiments, the concerns of the public shifted from subsidies to promotion. This shows that the focus of people's sentiments about energy storage in different periods changed according to external conditions. In addition, cognitive bias is also one of the main factors affecting public sentiment of energy storage. For some topics, such as technology, photovoltaics, the public's perceptions were different. Most people identified the development of energy storage technologies, while others lacked an objective understanding of energy storage technology and had cognitive bias to energy storage. This will inevitably affect public perceptions of energy storage. Moreover, cognitive bias is gradually increase as time goes by. The strategic position of energy storage has been widely emphasized by the government. However, the positive sentiments for energy storage were gradually decreasing, while the neutral and negative situations were increasing. This may be because people's cognitive biases are gradually strengthening. The government should actively strengthen the importance of energy storage in realizing energy transformation, and give more guidance for industrial development to reduce the cognitive bias of energy storage.

CONCLUSION

To reveal how China develops the energy storage industry, the promotion of energy storage is examined from the perspectives of policy support and public acceptance. The main contribution of this paper is to combine the two perspectives to address the development of the energy storage industry. At the government level, qualitative methods were used to track the evolution of energy storage policies issued by the government. At the public level, quantitative methods were used to obtain public attitudes towards energy storage policies. Through this analytical framework, not only the development of the energy storage industry can be obtained, but also the combination of the two perspectives reveals the dynamic interaction between policy and public attitude. It is helpful and new for energy storage policy analysis. This paper combined public attitude and policy evolution to get attitudes on different development stages of energy storage policies, by comparing the opinion and the energy storage policy. It can be revealed the interaction between them as the government adopted public opinion when making the energy storage policy. Therefore, the combination analysis can provide a reference for the policymaking. In doing so, policies can be better implemented to promote the development of energy storage industry. To trace the evolution of energy storage policies in China from 2010 to 2020, this study summarized the keywords of energy storage policy in different stages. Then social data were collected to explore public attitudes towards the energy storage policy. The analysis of the evolution of energy storage policies and public sentiment can enhance the recognition of energy policies and improve policy effectiveness. The main conclusions are as follows: 1) from 2010 to 2020, China's energy storage industry experienced three development stages: the foundation stage, the nurturing stage and the commercialization stage. 2) With the support of policies, energy storage has developed rapidly, but existing problems exist such as incoordination of policies and a lack of market mechanism. 3) The public shows more positive sentiment toward energy storage policies than negative sentiments. 4) The public expressed their positive attitude for technology and commercialization of energy storage. The negative sentiments toward energy storage mainly come from subsidies and promotion of energy storage. 5) The cognitive bias will impact public attitude towards energy storage, and this bias tend to increase. The government should make more effort to eliminate cognitive bias to enhance recognition of energy storage.

Based on the above conclusions, this paper proposes the following recommendations for the development of energy storage industry:

1) Improve the policy system. China's energy storage policy needs more centralized and unified rules like corporate financing policies, taxation policies, subsidies, price policies, and evaluation policies for energy storage demonstration projects. The government should establish a special department for energy storage, responsible for the unified formulation, planning and management of policies, and coordination of various policies. At the same time, a roadmap for energy storage technology development and a plan of energy storage development should be formulated. And evaluating the market potential of energy storage with respect of renewable energy grid connection, power system peak shaving and frequency modulation, which is provided by the power generation side, grid side and user side. Finally, government will guide the market to invest in an orderly manner. This will gradually form a long-lasting mechanism to support the sustainable development of energy storage.
2) Increase public recognition of energy storage. The government should guarantee their guidance and intention can value the benefits of energy storage systems and reduce cognitive bias of public, which is of great significance for promoting the correct and comprehensive understanding of energy storage.
3) Enlarge investment on R&D. At present, China's investment in technical research and development of energy storage is insufficient, and technology cost is still high. It's has been recommended that the state arrange a special funds for energy storage so as to strengthen the technical research and development of energy storage, in order to accelerate the realization of core technology autonomy. Meanwhile, the government should insist on diversified technology, and promote new energy storage technologies such as "wind power + energy storage" and "photovoltaic + energy

storage," and realize commercial applications in scale. In addition, the government can provide sustainable funding subsidies for technical research and development in stages according to the maturity of energy storage technology, so as to reduce the investment risk of enterprises and increase their enthusiasm in participating in technical research and development.

4) Reasonable design of subsidy policy. Financial subsidy, favorable taxation policy and favorable price policy are the common economic encouragement practice. Energy storage development is inseparable from subsidies, and the widening gap in fiscal subsidies is also a current problem. That is why governments at all levels should allocate subsidies more reasonably. For battery technology and other highly practical technologies, its technological breakthroughs are difficult to predict. If the subsidy design is improper, the market will be distorted, which is not conducive to the development of the industry. At present, the implementation effect of industrial policies will be greatly reduced, as the gradual development of China's energy storage market. Continuing to provide a large number of financial subsidies will put a certain burden on the national finances, and the reasonable allocation of subsidies will maximize the use of resources. Governments at all levels can also use market mechanisms to change the current system of preference in subsidies for the long-term and healthy development of the energy storage industry.

This research has some limitations. First, we mainly focused on the national and local energy storage policies and did not explore national, provincial and municipal energy storage policies separately. Second, due to the limitation of searching permission of Weibo, this study has not analyzed the geographic location, occupation and other factors that will impact the public sentiment. Therefore, future studies should analyze the different levels of energy policies and take the influence of user information into consideration.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

Research idea, data collection, BF, TW, JP; methodology, analysis, BF, KH, TW and YZ ; writingoriginal draft, BF, TW, KH; writing,review and editing, YZ and JP. All authors have read and agreed to the published version of the article.

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How Does the Consumers' Attention Affect the Sale Volumes of New Energy Vehicles: Evidence From China's Market

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The promotion of new energy vehicles is a grand plan across countries to achieve carbon neutrality and air purification. The sale volume of new energy vehicles is affected by many factors, yet it is the attitude of consumers themselves that has the final decisive role. We use four representative Baidu search indexes as the variables representing the attention of consumers and take variables of economic, population, and income as control variables for regression analysis from the national and sub-economic regional perspectives respectively. Results show that search indexes of "new energy vehiclek." "new energy vehicles battery", and 'charging pile' all have significant positive impacts on the sales of new energy vehicles to varying degrees while the index of 'automobile spontaneous combustion' has a significant negative impact on the sale volume. This study, therefore, verifies that the consumer attention represented by search indexes is an important yet uncovered factor affecting the sale volume of new energy vehicles. Besides, due to people's prejudice against spontaneous combustion accidents of new energy vehicles, consumers have a cognitive bias about the spontaneous combustion rate of new energy vehicles especially in less developed areas of China.

Keywords: new energy vehicle, consumer attention, sale volume, cognitive bias, search trend

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1 INTRODUCTION

The proliferation of new energy vehicles is considered an important step towards the reduction of harmful gases and achieving carbon neutrality (Thomas, 2009; Hill et al., 2019; Spangher et al., 2019). Accordingly, governments around the world plan to adopt new energy vehicles to build a sustainable transport system and have set goals to promote new energy vehicles adoption (Mock and Yang, 2014; Nie et al., 2016). Yet, despite continuous financial supports and technological advances, the current market penetration rate of new energy vehicles is still quite low (Wang et al., 2019). Therefore, the academic has conducted extensive research on the influencing factors of the sales of new energy vehicles. The existing literature investigates a comprehensive list of elements that are related to the adoption of new energy vehicles, including but not limited to the four following categories: policy, economic, socio-demographic, and personal preference factors. **Table 1** summarizes some typical literature on factors impacting the sale volume of new energy vehicles.

Although the above literature has studied the factors affecting the sales of new energy vehicles from various aspects, there exists little research focusing on the impact of consumer attention on sales of new energy vehicles. Additionally, the sale volume of commodities is ultimately determined

TABLE 1 | Literature on factors affecting new energy vehicles.

Category	References	Country	Research interest	Main results
Policy	Ma et al. (2017)	China	Purchase subsidy	Positive co-integration for the relationship between the new energy vehicles market share and the new energy vehicles purchase subsidy
	Wu et al. (2021)	China	tightened dual-credits regime	Remarkable policy pressure and inevitable execution challenges of the recently tightened dual-credits regime
	Jenn et al. (2013)	US	Energy Policy Act of 2005	It increased the sales of hybrids from 3 to 20% depending on the vehicle model considered
Economic	Palmer et al. (2018)	UK, US, and Japan	total Cost of Ownership	Market share was found to be strongly linked to hybrid electric vehicle Total Cost
	Sovacool et al. (2019)	China	cost considerations	Chinese consumers have strong preferences about the related costs when they think about purchasing electric vehicles
	Soltani-Sobh et al. (2017)	US	electricity price	Electricity price is negatively associated with electric vehicle use
Socio-demographic	Zarazua de Rubens (2019)	Nordic countries	clusters demographics	Three key elements regarding the price, the range, and the environmental attributes of electric vehicle
	Higueras-Castillo et al. (2020)	Spain	clusters demographics	The driving range is the most important factor
	Berkeley et al. (2018)	UK	clusters demographics	High purchase price and the availability of public charging stations emerged as the most substantive barriers to electric vehicle adoption
Personal preference	Ma et al. (2019)	China	preference for electric vehicles	Prices, car classification, and powertrain types were the most important factors influencing consumer response
	Liao et al. (2019)	Netherlands	preference for electric vehicles	Vehicle leasing is the most popular option while battery leasing is less preferred than full price purchase
	Wang et al. (2020)	China	preference for electric vehicles	Safety awareness is closely related to the sale volume of electric vehicle

by the behavior of consumers and the quantification of consumer attention can extract the important factors affecting the sale volume. In previous literature, the depiction of consumers' behavior is mainly obtained through the questionnaire survey (Hao et al., 2016; Liao et al., 2019; Maheshwari et al., 2016). However, the questionnaire survey has a certain lag and cannot reflect the real-time attitude and attention of consumers. On the contrary, the emergence of the Internet has changed consumers' consumption habits for the development of search engines has made it possible to provide related information immediately. Thanks to the emergence of Internet search engines, for example, Google and Baidu, the detailed information of almost all products can be easily found through the Internet and consumers are now more likely to get information from the Internet before making a shopping decision.

Because automobiles are relatively higher-value commodities, people tend to spend longer time and obtain more information in comparing potential goods to make the decision(Mitchell and Prince, 1993). Due to the convenience of Internet search engines illustrated in the previous part, customers typically use online searches to access commodity information. Searching for pre-purchase information is regarded as an integral element of the consumer's buying behavior (Akalamkam and Mitra, 2018). Specifically, about 50% of the customers spend more than ten hours identifying the best matching vehicle for their requirements(Wachter et al., 2019). Some scholars have used the search indexes in the research on the sales of new energy vehicles (Wachter et al., 2019; Yang and Zhang, 2020; Zhang et al., 2017). However, almost all the literature is aimed at sale volume forecasting and as far as we know, there is no attempt to explore the impact of consumer attitudes on sale volume through the search indexes.

To explore this possible relationship between consumer attention and commodity sales, we assume that on the whole, consumers' search volume for phrases related to new energy vehicles may have a certain impact on the sale volume of new energy vehicles. We use the Baidu Index[1], a measure of search volume similar to Google Trends, as our dependent variable for we focus on the Chinese market and Baidu is the largest search engine in China with around 79.89% market share[2]. Baidu index is based on the search volume of Internet users, taking keywords as the statistical object, scientifically calculation of the weighted sum of search frequency of the specific keyword in search engine. According to the main factors that consumers need to consider in the purchase of new energy vehicles, we choose Baidu indexes of four keywords as our research objects: "new energy vehicle" "new energy vehicle battery" "charging pile", and "automobile spontaneous combustion". Results show that the first three search indexes all have significant positive impacts on the sales of new energy vehicles to varying degrees while the index of 'automobile spontaneous combustion' has a significant negative impact on the sale volume.

The contribution of this paper is mainly reflected in the following aspects. First, to the best of our knowledge, it is the first study to explore the impacts of search indexes on new energy

[1]https://index.baidu.com/

[2]https://gs.statcounter.com/search-engine-market-share/all/china

FIGURE 1 | New energy vehicle sales and Baidu search index in China from 2016 to 2021.

vehicle sales. In addition, we not only use the straight-forward keyword of "New energy vehicle" but also commodity-related factors that may affect consumers' purchase intention as research objects, which sheds light on a new way to investigate the influence of consumer attitude on product sales. Second, the study suggests that consumers in regions of various economic development levels may have different concerns about new energy vehicles when making purchasing decisions, which provides useful information for manufacturers and governments to further promote new energy vehicles. Last, this study has found a cognitive bias in the adoption of new energy vehicles. Specifically, it reveals that people's attention to 'spontaneous combustion' of new energy vehicles has an excessively negative impact on sale volume, but in fact, the spontaneous combustion rate of new energy vehicles is much lower than that of fuel vehicles.

The rest of the paper is organized as follows. *Indexes Choice and Research Hypotheses* introduces the background and puts forward the research hypotheses. *Related Methodologies and Data* presents the data and variables used in the study and the models for the research. *Empirical Results* analyzes the empirical results and *Discussion and Conclusion* discusses the main findings, gives policy implications, and provides several future research topics.

2 INDEXES CHOICE AND RESEARCH HYPOTHESES

Baidu doesn't provide search indexes for all keywords, so in our study, we select phrases that both exist in Baidu's search index library and can point precisely to specific information. The most direct search keyword for consumers when making purchase choices is the product itself, and this choice of keywords can be found in many pieces of literature on the relationship between consumer search index and product sales(Fritzsch et al., 2020; Geva et al., 2015; Ruohonen and Hyrynsalmi, 2017). Additionally, in the previous literature about forecasting new energy vehicles sales using search indexes, researchers all use the products themselves as the search index. **Figure 1** also shows the trends of China's new energy vehicle sales and Baidu search indexes of term 'new energy vehicle' from 2016 to June 2021 and it can be seen that the two curves have a certain synchronization. Accordingly, we assume the Baidu index of 'New energy vehicle' has an important impact on the sales of new energy vehicles.

Hypothesis H1. The search index of "new energy vehicle" has a significant positive impact on the sales of new energy vehicle.

Further, we explore the important factors that influence consumers' decision to buy new energy vehicles. The main reason why it is difficult for electric vehicles to replace traditional fuel vehicles is the short range restricted by battery capacity and the lack of charging pile facilities (Sun et al., 2018). A specific term that arises from it is "range anxiety", defined as the psychological anxiety consumers feel when dealing with the limited range of new energy vehicles and it has been labeled as one of the most pressing obstacles to the adoption of new energy vehicles (Noel et al., 2019). In previous studies, Wang et al. (2020) suggest that infrastructure, battery technology, and safety awareness are three main factors influencing the market proportion of new energy vehicles in China by analyzing the comment data in Autohome.com, the most visited professional car website in China. Funke et al. (2019) also highlight the deficiencies of charging infrastructure construction in the promotion of new energy vehicles. Based on this, we choose two keywords, "new energy vehicle battery" and "charging pile" as the research objects.

Hypothesis H2. The search index of "new energy vehicles battery" has a significant positive impact on the sales of new energy vehicles.

Hypothesis H3. The search index of "charging pile" has a significant positive impact on the sales of new energy vehicles.

Another major concern for new energy vehicles is the problem of safety and it is undoubtedly an enduring issue in the automobile market. Egbue and Long (2012) found that reliability and safety are among the biggest concerns for respondents in an American technological university. Wang et al. (2020) also stress the importance of safety in consumers' purchasing intentions for new energy vehicles. Additionally, spontaneous combustion is the most common safety accident in electric vehicles. Therefore, we use the Baidu index of "automobile spontaneous combustion" as the variable of consumer attention and propose the fourth hypothesis.

Hypothesis H4. The search index of "automobile spontaneous combustion" has a significant negative impact on the sales of new energy vehicles.

3 RELATED METHODOLOGIES AND DATA

3.1 Variables and Data

3.1.1 Dependent Variable

Sales refers to the monthly sale volumes of new energy vehicles in the studied provinces during the studied period, i.e., 1st January 2016 to 30th June 2021. The data is provided by Datavision (http://www.dataisvision.com/). It should be noted that only passenger cars are included, while other types of vehicles such as new energy buses are not considered. This is because such vehicles are purchased in a predetermined way with a reasonable procurement process that can not be influenced by consumers. Additionally, the other statistics in our panel data for this study are also measured monthly.

3.1.2 Independent Variable

BI refers to the Baidu search indexes which are downloaded from Baidu.com. Baidu provides real-time data on keyword search volumes for a specific period and territorial scope. To match the monthly sales of new energy vehicles, we use the monthly Baidu index of each province from 2016 to June 2021. Additionally, we use four keywords in the empirical study: "new energy vehicle" "new energy vehicle battery" "charging pile", and "automobile spontaneous combustion" and norm them as Index1, Index2, Index3, and Index4 respectively. It should be pointed out that we use the sum of the Baidu index of "new energy vehicle" and "electric vehicle" as Index1 and the sum of "new energy vehicle battery" and "electric vehicle battery" as Index2 for new energy vehicles are mainly electric vehicles in China's market and these two kinds of terms refer to almost the same information on the Internet. We choose these four keywords as they are all directly related to the information consumers are most concerned about when buying new energy vehicles.

3.1.3 Control Variables

In this study, following Guo et al. (2020), we use provincial monthly urban population (UP), gross domestic product (GDP), and disposable income per capita (DI) as control variables.

The urban population refers to the volume of permanent urban residents in the studied provinces during the studied period. Population size determines the overall potential demand for the sales of new energy vehicles, so it is one of the determinants of energy vehicles adoption (Egnér and Trosvik, 2018). Considering that China still has a large rural population and the charging facilities in rural areas are difficult to meet the daily use needs of new energy vehicles, we use the urban population as a control variable in the empirical study.

Gross domestic product refers to the total monetary or market value of all the finished goods and services produced within a province's borders during the studied period. Some studies have found that regional economic development has a positive effect on the sales of new energy vehicles(Javid and Nejat, 2017; Kester et al., 2018). One possible explanation is that regions with better economic development have better infrastructure, and the use of electric cars relies on a large number of public charging devices which demands large-scale investment in public transit facilities(Needell et al., 2016).

Disposable income per capita is calculated by taking income earned from all sources (wages, government transfers, etc.) minus taxes, savings, and some non-tax payments. Disposable income per capita determines an individual's ability to purchase goods or services, therefore, it is considered to be a significant factor affecting the adoption of new energy vehicles (Langbroek et al., 2016; Mersky et al., 2016; Egnér and Trosvik, 2018; Priessner et al., 2018).

Since the original dataset of UP, GDP, and DI is presented annually, we use a differencing process to transform the data into a monthly form. At first, we acquire the monthly growth rate g using the following equation:

$$g = \sqrt[12]{\frac{q_i}{q_{i-1}}} - 1 \tag{1}$$

Where q_i denotes the value of the parameter (i.e., urban population, gross domestic product, or disposable income per capita) by the end of year i, q_{i-1} denotes the value of the parameter by the end of year $i-1$. Then, the monthly value of the parameter m_i can be calculated using the following equation:

$$m_i = m_{i-1}(1+g) \tag{2}$$

3.1.4 Data Description

This study uses monthly data of 30 provincial-level administrative regions in China from January 2016 to June 2021 for the database we obtained only contains sales statistics of new energy vehicles since 2016. Our study doesn't include the city of Beijing because Beijing has implemented the automobile purchase restriction policy and Beijing's new energy vehicle sales are largely determined by the number of vehicle licenses issued by the government of Beijing, but not the true market demand. We also exclude Hong Kong, Macau, and Taiwan in this paper due to missing statistical information. **Table 2** summarizes the definitions of all the variables used in the study, as well as their data sources and units of measurement.

3.2 Methodologies

3.2.1 Panel Unit Root Test

In the case of long panel type data, as non-stationary variables may lead to spurious regression, meaning that there is a high

TABLE 2 | Definitions of variables and descriptive statistics.

Category	Variables	Definition	Mean	Std.Dev	Min	Max	Obs
Dependent Variables	Sales (thousand)	Monthly sale volumes of EVs in the studied provinces during the studied period, that is Jan 2016 to June 2021	59.550	50.980	0.062	328.2	1950
Independent Variables	Index1	Baidu search index of 'new energy vehicle' and 'electric automobile' during the studied period	0.441	0.222	0.000	1.598	1950
	Index2	Baidu search index of 'charging pile' during the studied period	2.198	1.466	0.206	16.470	1950
	Index3	Baidu search index of 'new energy vehicle battery' and 'electric vehicle battery' during the studied period	0.597	0.302	0.000	1.784	1950
	Index4	Baidu search index of 'automobile spontaneous combustion' during the studied period	0.106	0.093	0.000	0.432	1950
Control Variables	UP (million)	Urban population, in terms of the volume of permanent urban residents in the studied provinces during the studied period	27.230	18.11	0.912	99.580	1950
	GDP (trillion)	Province-level GDP value in the studied provinces during the studied period	0.248	0.205	0.009	0.967	1950
	DI (thousand)	Disposable income per capita in the studied provinces during the studied period, a measurement of purchasing power	3.103	0.761	2.079	6.603	1950

The sales of new energy vehicles are obtained from Dataisvision (http://www.dataisvision.com/). The Baidu indexes are obtained from https://index.baidu.com/v2/index.html#/and the numbers of UP, GDP, and DI are obtained from the Wind database (http://www.wind.com.cn).

TABLE 3 | Unit root test results for each variable.

Variable	LLC	Fisher-ADF	Hausman test
Sales	−23.178***	−16.664***	
GDP	−4.237***	−4.9170***	
UP	1.108	0.335	
D.UP	−1.935**	−3.028***	
DI	1.405	−8.766***	
D.DI	−31.173***	−10.840***	
Index1	−3.426***	−9.897***	79.81***
Index2	4.317	−6.024***	
D.Index2	−32.255***	−17.958***	158.79***
Index3	−2.057**	−9.222***	115.25***
Index4	-20.183***	−20.999***	190.87***
All indexes			103.86***

*This table shows the unit root test for variables and the Hausmann test for models using different Baidu indexes. The first column uses the LLC, test and the second column uses the Fisher-ADF, test. If the variable has a unit root, we perform the different treatment to make the variable stationary. The third column is the Hausmann test result of Chi-Square Statistic. Asterisk ***,**, and *denote the rejection of the null hypothesis at the 1, 5, and 10% significance level, respectively.*

correlation even though variables are unrelated, we have to determine whether the variables contain panel unit roots. The unit root test is used to check whether variables in the panel model are stationary and we utilized Levin–Lin–Chu (LLC) test, and Fisher-type tests in our empirical study.

Levin et al. (2002) suggest a more powerful panel unit root test than performing individual unit root tests for each cross-section. The null hypothesis is that each time series contains a unit root against the alternative that each time series is stationary. The model used can be shown as follows:

$$\Delta y_{i,t} = \rho_i y_{i,t-1} + \sum_{j=1}^{p_i} \delta_{i,j} \Delta y_{i,t-j} + \varepsilon_{i,t} \tag{3}$$

The Fisher-type test uses an average statistic as the Im-Pesaran-Shin method (Im et al., 2003) but performs the panel unit root test by using the p-value in a meta-analysis. This test is the most commonly used unit root test and is known to have the highest power (Kim & Jun 2010). Fisher-ADF uses the p-value of the statistic obtained from the ADF unit root test while Fisher-PP uses the p-value of the individual cross-sectional data as follows:

$$P = -2 \sum_{i-1}^{N} \ln(p_i) \tag{4}$$

3.2.2 Panel Analysis

When estimating static energy demand models by panel analysis, it is common to explain unobserved heterogeneity by using fixed or random effects. The following linear regression model considers the heterogeneity of the panel data:

$$y_{it} = \alpha + \beta x_{it} + u_i + e_{it} \tag{5}$$

In the fixed-effect model, the error term u_i of the above equation is regarded as the parameter to be estimated. On the contrary, assuming u_i as a random variable would make it the random effect model.

When choosing between fixed and random effect models, the primary criterion is the inference of the heterogeneity of the panel data. If the panel data are derived from a random sampling of the population, then the error term u_i can be assumed to follow a probability distribution. In terms of econometric theory, the choice between the two models is determined based on whether the assumption $cov(x_{it}, u_i) = 0$ is established. This is called the Hausman test, which sets the null and alternative hypotheses as follows (Hausman, 1978):

$$H_0:\ cov(x_{it}, u_i) = 0 \tag{6}$$

If the null hypothesis is rejected, the random effect model is more efficient, otherwise, the fixed effect model is chosen. Therefore, in this study, we conduct a panel analysis on the unobserved heterogeneity by using the Hausman test.

We analyze the relationship between Baidu search indexes and new energy vehicles sales in China through a panel analysis. We

TABLE 4 | Model estimation results using Baidu search index in the same month.

Variables	(1) Index1	(2) Index2	(3) Index3	(4) Index4	(5) All Indexes	(6) Omit D.UP	(7) VCE
Index1	10.842***				8.828***	8.843***	8.843***
	(0.66)				(0.74)	(0.74)	(0.78)
D.Index2		27.523***			9.829	9.842	9.842**
		(7.73)			(7.33)	(7.33)	(3.73)
Index3			45.502***		26.972***	26.947***	26.947***
			(4.10)		(4.70)	(4.70)	(5.57)
Index4				−15.558	−45.185***	−45.308***	−45.308***
				(11.09)	(11.04)	(11.03)	(12.04)
GDP	27.853**	−30.882**	−34.489***	−30.480**	7.517	8.830	8.830
	(13.23)	(13.61)	(13.23)	(13.69)	(13.48)	(13.30)	(29.75)
D.UP	1.968	3.751	3.796	3.696	1.968		
	(3.33)	(3.55)	(3.45)	(3.56)	(3.30)		
D.DI	−73.44	65.7	−137.161***	92.069*	−149.729***	−149.132***	−149.132***
	(45.46)	(47.53)	(50.08)	(48.03)	(47.94)	(47.92)	(30.64)
Constant	29.850***	65.893***	42.846***	67.079***	29.179***	28.959***	28.959**
	(3.99)	(3.58)	(4.01)	(3.84)	(4.25)	(4.23)	(11.29)
Observations	1950	1950	1950	1950	1950	1950	1950
R-squared	0.127	0.011	0.065	0.006	0.145	0.145	0.145
Number of provinces	30	30	30	30	30	30	30
province FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
VCE cluster(province)	NO	NO	NO	NO	NO	NO	YES

*This table presents the estimation results for impacts of four Baidu search indexes on the sale of new energy vehicles sales of China's market in the same month. For more details of prediction models, refer to **Eqs 7, 8**. The four columns on the left indicate results of regressions using four Baidu indexes, respectively. The fifth column is the result of regression using all indexes. The sixth column presents the result of regression in which the control variable D.UP, that remains insignificant in previous regressions is removed. In column 7, the VCE, cluster method is used to improve the robustness based on column 6. Asterisk ***, **, and *denote the rejection of the null hypothesis at the1, 5, and 10% significance level, respectively. Standard errors are presented in parentheses.*

construct regression equations using four Baidu indexes, as follows:

$$Sales_{it} = \alpha + \beta Index_{k,it} + \gamma' (UP_{it}, GDP_{it}, DI_{it})' + u_i + e_{it} \quad (7)$$

Where $k = 1, 2, 3, 4$, and $Index_k$ denotes the four Baidu indexes. UP, GDP, and DI represent the urban population, province-level GDP value, and deposit income respectively. i denotes the respective province of China, and t denotes the time period. μ and e are error terms.

Then, we put all the Baidu indexes into the model for regression, as follows:

$$Sales_{it} = \alpha + \beta_1 Index1_{it} + \beta_2 Index2_{it} + \beta_3 Index3_{it} + \beta_4 Index4_{it} + \gamma' (UP_{it}, GDP_{it}, DI_{it})' + u_i + e_{it} \quad (8)$$

4 EMPIRICAL RESULTS

4.1 Stationary Check and Hausmann Test

Table 3 shows the unit root test results for each variable. If the variable has a unit root, we use the first difference to make the variable stationary. It can be seen that UP, DI, and $Index2$ cannot pass the unit root test, so we perform the difference process to obtain $D.UP$, $D.DI$, and $D.Index2$ to be stationary.

We then perform the Hausman test to choose the fixed effect or random effect model to perform the panel regressions. As shown in **Table 3**, the null hypothesis of the Hausman test is rejected at the 1% level. That is, the Hausman test shows that the fixed effect estimation is more suitable than the random effect estimation.

4.2 Consumer Attention to the Sales of New Energy Vehicles

The estimation results are shown in **Table 4**. The models in the left four columns are regressions using four different search indexes respectively. The fifth model indicates the regression result using all four search indexes and in the sixth model, we omit the control variable of $D.UP$ as it is persistently not significant in the previous regression. At last, we use the cluster method, as presented in the last column. It can be seen that the search amount of 'new energy vehicle', 'new energy vehicle battery', and 'charging pile' are significantly positive with the new energy vehicle sales indicating that the search behavior of these three kinds of terms may have an impact on the sales of new energy vehicles. Additionally, the search amount of 'automobile spontaneous combustion' is negative but not significant.

Consumers may take a longer time to compare and select commodities with higher values. It is more appropriate to use the previous month's search index if the consumers use more than 1 month to gather information and make decisions to buy cars. Moreover, using the previous month's search index can effectively avoid the possible endogeneity issue. We, therefore, use the lag terms of the four search indexes for regressions, and the results are shown in **Table 5**. The results are very similar to the

TABLE 5 | Model estimation results using Baidu search index of 1 month ahead.

Variables	(1) Index1	(2) Index2	(3) Index3	(4) Index4	(5) All Indexes	(6) All Indexes omit D.UP	(7) VCE
L.Index1	6.950***				4.917***	4.931***	4.931***
	(0.68)				(0.77)	(0.77)	(0.90)
L.D.Index2		35.262***			20.204***	20.314***	20.314**
		(7.69)			(7.68)	(7.68)	(8.32)
L.Index3			35.456***		22.849***	22.789***	22.789***
			(4.01)		(4.77)	(4.77)	(5.95)
L.Index4				−0.685	−25.956**	−26.118**	−26.118
				(11.25)	(11.60)	(11.60)	(16.65)
GDP	5.707	−31.816**	−36.460***	−28.527**	−13.169	−11.011	−11.011
	(13.69)	(13.58)	(13.39)	(13.66)	(13.99)	(13.81)	(28.76)
D.UP	3.266	3.59	4.047	3.809	3.312		
	(3.47)	(3.54)	(3.49)	(3.56)	(3.44)		
D.DI	14.842	89.686*	−41.873	80.974*	−15.438	−14.137	−14.137
	(46.69)	(47.25)	(48.59)	(48.72)	(48.63)	(48.61)	(18.85)
Constant	42.372***	65.742***	47.784***	65.040***	41.063***	40.733***	40.733***
	(4.13)	(3.56)	(4.02)	(3.79)	(4.37)	(4.35)	(11.74)
Observations	1950	1950	1950	1950	1950	1950	1950
R-squared	0.057	0.016	0.044	0.005	0.073	0.072	0.072
Number of area	30	30	30	30	30	30	30
province FE	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES
VCE cluster (province)	NO	NO	NO	NO	NO	NO	YES

This table presents the estimation results for impacts of four Baidu search indexes on the sale of new energy vehicles sales of China's market in the next month. For more details of prediction models, refer to ***Eqs 7, 8****. The four columns on the left indicate results of regressions using four Baidu indexes, respectively. The fifth column is the result of regression using all indexes. The sixth column presents the result of regression in which the control variable D.UP, that remains insignificant in previous regressions is removed. In column 7, the VCE, cluster method is used to improve the robustness based on column 6. Asterisk ***, **, and *denote the rejection of the null hypothesis at the 1, 5, and 10% significance level, respectively. Standard errors are presented in parentheses.*

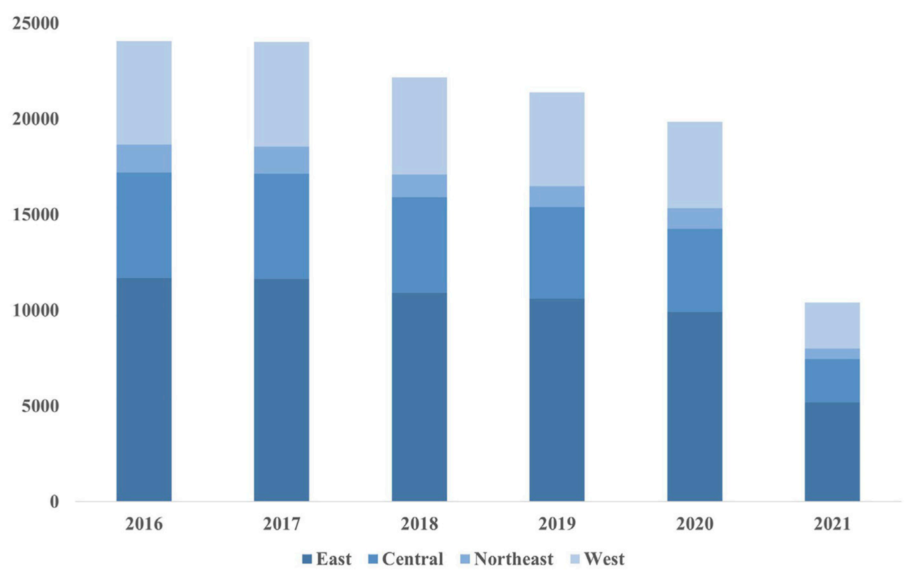

FIGURE 2 | Sales of new energy vehicles in China's four major economic regions from 2016 to the first half of 2021.

previous regressions, indicating that search amount of 'new energy vehicle', 'new energy vehicle battery', and 'charging pile' are significantly positive with the new energy vehicle sales of the next month while the term of 'automobile spontaneous combustion' is significantly negative, which is in line with our proposed hypotheses.

TABLE 6 | Model estimation results using Baidu search index regarding the east district of China.

Variables	(1) All indexes	(2) All indexes omit D.DI	(3) All indexes with VCE	(4) All lag indexes	(5) All lag indexes omit D.DI	(6) All lag indexes with VCE
Index1	9.810***	9.715***	9.715***			
	(1.56)	(1.56)	(1.16)			
D.Index2	12.880	12.895	12.895**			
	(14.25)	(14.27)	(4.56)			
Index3	38.254***	34.316***	34.316**			
	(11.70)	(11.37)	(11.53)			
Index4	−16.940	−18.486	−18.486			
	(24.67)	(24.67)	(14.16)			
L.Index1				6.368***	6.375***	6.375***
				(1.63)	(1.62)	(1.03)
L.D.Index2				4.499	4.382	4.382
				(14.95)	(14.87)	(8.29)
L.Index3				30.366**	30.477**	30.477**
				(11.96)	(11.88)	(12.17)
L.Index4				6.431	6.751	6.751
				(25.87)	(25.59)	(22.80)
GDP	31.862	35.095	35.095	22.862	22.768	22.768
	(31.89)	(31.84)	(56.86)	(33.42)	(33.38)	(51.44)
D.UP	9.880	11.112	11.112	5.621	5.490	5.490
	(11.96)	(11.94)	(16.07)	(12.66)	(12.56)	(13.88)
D.DI	-158.311			9.857		
	(112.44)			(113.73)		
Constant	23.169*	22.357*	22.357	37.656***	37.736***	37.736
	(13.57)	(13.57)	(28.60)	(13.92)	(13.87)	(27.97)
Observations	585	585	585	585	585	585
R-squared	0.154	0.151	0.151	0.085	0.085	0.085
Number of provinces	9	9	9	9	9	9
province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
VCE cluster (province)	NO	NO	YES	NO	NO	YES

This table presents the estimation results for impacts of four Baidu search indexes on the sale of new energy vehicles sales of eastern China's market. For more details of prediction models, refer to ***Eq. 8****. The left three columns indicate results of the impacts of consumer attention on the sale volume in the same month and the right three columns indicate the impacts on the sale volume of the next month. We first perform regression using all Baidu indexes and then omit the persistently insignificant control variables if any and finally use the VCE, cluster method. Asterisk ***,**, and *denote the rejection of the null hypothesis at the 1, 5, and 10% significance level, respectively. Standard errors are presented in parentheses.*

4.3 Analysis of the Different Districts of China

Sales of new energy vehicles are closely related to economic, demographic, and other factors according to the verified results. China has the world's largest population and the largest market for new energy vehicles. Meanwhile, China has a relatively complicated national condition because the regional development in China is unbalanced in economic development and the situation of the environment varies greatly in different areas. Given this, to explore the impacts of the online search indexes of consumers on new energy vehicles from a more precise perspective, we divide China into four economic regions, i.e. east region, central region, west region, and northeast region, according to the geographical classification standard of the National Bureau of Statistics of China[3]. The sale volumes of new energy vehicles of four economic regions are presented in **Figure 2**. It can be seen that eastern China accounts for the largest share of new energy vehicle sales, followed by central and western China, and the least by northeast China.

We use existing data to perform the regression analysis for each of the four economic regions to evaluate the influences of Internet search behavior on new energy vehicles sales separately. The results are shown in **Tables 6–9**. In the analysis of each area, we first perform the regression on all of the Baidu indexes as well as the control variables and then omit the non-significant control variables in the results of regressions using the single Baidu index. Using the same method in *Consumer Attention to the Sales of New Energy Vehicles*, we also use the Baidu search indexes with 1 month lag in the regressions.

With the development of modern industry in China, eastern China has become the most economically developed region and the infrastructure construction in this area is also of the highest level in China. The three largest urban agglomerations in China, the Beijing-Tianjin-Hebei Region, the Yangtze River Delta, and the Pearl River Delta, are all located in eastern China. According to China's seventh national census, the population in eastern China accounted for 39.93 percent. As illustrated in **Table 6**, the search trend of 'new energy vehicle', and 'new energy vehicle

[3]The information is found in http://www.stats.gov.cn/ztjc/zthd/sjtjr/dejtjkfr/tjkp/201106/t20110613_71947.htm.

TABLE 7 | Model estimation results using Baidu search index regarding the central district of China.

Variables	(1) All indexes	(2) All indexes VCE	(3) All lag indexes	(4) All lag indexes omit D.DI	(5) All lag indexes with VCE
Index1	8.325***	8.325***			
	(1.31)	(0.81)			
D.Index2	−14.165	−14.165			
	(18.73)	(12.86)			
Index3	36.593***	36.593***			
	(9.91)	(5.79)			
Index4	−85.775***	−85.775***			
	(20.37)	(11.91)			
L.Index1			2.398*	2.373*	2.373***
			(1.38)	(1.37)	(0.33)
L.D.Index2			63.568***	64.669***	64.669***
			(19.87)	(19.76)	(10.70)
L.Index3			33.319***	32.656***	32.656***
			(10.25)	(10.17)	(4.70)
L.Index4			−75.323***	−77.972***	−77.972**
			(21.99)	(21.48)	(28.65)
GDP	−106.897***	−106.897***	−115.136***	−113.229***	−113.229***
	(31.43)	(19.31)	(33.34)	(33.14)	(12.49)
D.UP	−8.273	−8.273**	0.441	0.071	0.071
	(5.43)	(2.56)	(5.74)	(5.70)	(1.41)
D.DI	−185.627**	−185.627*	−53.420		
	(89.17)	(87.91)	(93.30)		
Constant	65.173***	65.173***	81.203***	80.786***	80.786***
	(9.62)	(4.77)	(9.98)	(9.94)	(3.77)
Observations	390	390	390	390	390
R-squared	0.230	0.230	0.139	0.139	0.139
Number of provinces	6	6	6	6	6
province FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
VCE cluster (province)	NO	YES	NO	NO	YES

*This table presents the estimation results for impacts of four Baidu search indexes on the sale of new energy vehicles sales of central China's market. For more details of prediction models, refer to **Eq. 8**. The left two columns indicate results of the impacts of consumer attention on the sale volume in the same month and the right three columns indicate the impacts on the sale volume of the next month. We first perform regression using all Baidu indexes and then omit the persistently insignificant control variables if any and finally use the VCE, cluster method. Asterisk ***,**, and *denote the rejection of the null hypothesis at the 1, 5, and 10% significance level, respectively. Standard errors are presented in parentheses.*

battery' both have significant positive impacts on the sales of new energy vehicles while 'charging pile', and 'automobile spontaneous combustion' are not significant.

The central region of China is consists of six provinces. Because it is located inland, the development level of the central region is not balanced, and the level of economic openness is not as good as that of the eastern region. At present, the economic development level of the central region is lower than that of the eastern economic zone while higher than that of the western economic zone, but the growth rate of economic development is lower than that of west China. As shown in **Table 7**, the search trends of 'charging pile', 'new energy vehicle battery', and 'automobile spontaneous combustion' all have significant impacts on the sales of new energy vehicles of the next month. It should be noted that the attention of 'automobile spontaneous combustion' is negatively correlated with the sales indicating consumers in the central region of China is more sensitive to the new energy vehicles accidents.

Western China generally lags behind central and eastern China. It accounts for 70 percent of the country's land area and about 29 percent of the total population. Due to the terrain and climate conditions in western China, although the area is vast, the population density is relatively sparse, which magnifies the mileage problem of new energy vehicles. At the same time, the energy resources in western China are abundant and the electricity cost is low, which provides favorable conditions for the application of new energy vehicles. As shown in **Table 8**, the search trend of 'new energy automobile', 'new energy vehicle battery', and 'automobile spontaneous combustion' all have significant impacts on the sales of new energy vehicles of the next month. The attention of 'automobile spontaneous combustion' is also negatively correlated with the sales, which is similar to the facts of the central region of China.

The Northeast region of China is an old industrial area in China, but its economy develops slowly in recent years and is in a period of economic transition. According to the result presented in **Table 9**, we found that most of the variables were not significant. We believed that this is because the overall sample was too small and overall sales volume was only in the hundreds.

TABLE 8 | Model estimation results using Baidu search index regarding the west district of China.

Variables	(1) All indexes	(2) All indexes with VCE	(3) All lag indexes	(4) All lag indexes omit D.DI	(5) All lag indexes with VCE
Index1	5.669***	5.669***			
	(1.15)	(0.48)			
D.Index2	−3.072	−3.072			
	(8.73)	(4.64)			
Index3	28.089***	28.089***			
	(5.30)	(8.00)			
Index4	−86.145***	−86.145***			
	(13.51)	(15.14)			
L.Index1			3.426***	3.480***	3.480***
			(1.19)	(1.19)	(0.39)
L.D.Index2			22.763**	23.445***	23.445***
			(9.05)	(9.02)	(6.48)
L.Index3			16.183***	15.028***	15.028***
			(5.40)	(5.28)	(4.43)
L.Index4			−58.742***	−59.658***	−59.658***
			(14.00)	(13.96)	(11.41)
GDP	−38.367*	−38.367***	−50.445**	−49.006**	−49.006***
	(20.51)	(11.12)	(20.98)	(20.93)	(8.20)
D.UP	-1.294	-1.294	-9.190	-7.461	-7.461
	(12.53)	(14.77)	(13.12)	(13.00)	(12.01)
D.DI	−159.402***	−159.402**	−55.241		
	(55.15)	(63.75)	(55.46)		
Constant	27.680***	27.680***	34.582***	33.905***	33.905***
	(3.81)	(2.97)	(3.87)	(3.81)	(1.78)
Observations	780	780	780	780	780
R-squared	0.141	0.141	0.080	0.079	0.079
Number of provinces	12	12	12	12	12
province FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
VCE cluster (province)	NO	YES	NO	NO	YES

*This table presents the estimation results for impacts of four Baidu search indexes on the sale of new energy vehicles sales of western China's market. For more details of prediction models, refer to **Eq. 8**. The left two columns indicate results of the impacts of consumer attention on the sale volume in the same month and the right three columns indicate the impacts on the sale volume of the next month. We first perform regression using all Baidu indexes and then omit the persistently insignificant control variables if any and finally use the VCE, cluster method. Asterisk ***,**, and *denote the rejection of the null hypothesis at the 1, 5, and 10% significance level, respectively. Standard errors are presented in parentheses.*

The climate in Northeast China was not suitable for the use of new energy vehicles could be one of the possible reasons.

5 DISCUSSION AND CONCLUSION

Exploring the impacts of consumer attention to different aspects of new energy vehicles on the sale volume can provide effective information for the promotion of new energy vehicles. Accordingly, we use four representative Baidu search indexes, 'new energy vehicle', 'new energy vehicles battery', 'charging pile', and 'automobile spontaneous combustion', as variables representing the attention of consumers and adopt variables of economic, population, and residents income as control variables for regression analysis. We first analyzed the data of the whole China's new energy vehicle market and found that search amounts of 'new energy automobile', 'new energy vehicle battery', and 'charging pile' have significant positive impacts on the new energy vehicle sales while the term of 'automobile spontaneous combustion' has a significant negative impact. To address the problem of endogeneity and consider the likelihood that consumers may make longer purchase decisions, we also used the lagging term of Baidu indexes for regressions and the results are in line with the conclusions from models using same month indexes.

Given the unbalanced regional development in China, we perform the regressions using the data of four major economic regions with different development levels respectively. In our subregional study, we found some interesting results. First, the search index of 'charging pile' has no significant impact on the sales of new energy vehicles in the economically developed region, specifically eastern China while in less developed areas this relationship exists, that is, more search for 'charging pile' mean more sales of new energy vehicles. One possible explanation is that better infrastructure and the availability of new energy charging devices in economically developed regions have made consumers less anxious about charging piles while in the less developed area, the consumers still have such concerns. Second, the search trend of 'new energy vehicle battery' has significant positive impacts on the sale volumes in all regions of China indicating that the efficiency of new energy vehicle batteries is still an important concern of consumers.

Another interesting finding from our study is people's cognitive bias of excessive concerns about spontaneous

TABLE 9 | Model estimation results using Baidu search index regarding the northeast area of China.

Variables	(1) All indexes	(2) All indexes omit GDP and D.UP	(3) All indexes with VCE	(4) All lag indexes	(5) All lag indexes omit GDP and D.UP	(6) All lag indexes with VCE
Index1	6.266***	6.352***	6.352**			
	(1.63)	(1.62)	(1.03)			
D.Index2	48.716***	48.043***	48.043*			
	(14.99)	(14.85)	(11.91)			
Index3	−15.113**	−14.135*	−14.135			
	(7.60)	(7.49)	(6.63)			
Index4	33.945*	35.228*	35.228			
	(18.97)	(18.69)	(19.19)			
L.Index1				1.863	1.853	1.853*
				(1.73)	(1.72)	(0.46)
L.D.Index2				25.075	24.451	24.451
				(16.02)	(15.95)	(10.97)
L.Index3				−10.163	−8.699	−8.699***
				(7.88)	(7.76)	(0.84)
L.Index4				15.139	17.528	17.528
				(19.98)	(19.62)	(14.29)
GDP	28.746			48.340		
	(56.86)			(60.75)		
D.UP	7.594			8.798		
	(13.34)			(14.25)		
D.DI	121.423	123.143*	123.143**	186.762**	188.090**	188.090**
	(73.72)	(72.73)	(22.29)	(75.43)	(74.37)	(23.74)
Constant	24.408***	27.698***	27.698***	26.665***	32.553***	32.553***
	(8.59)	(3.17)	(2.33)	(9.32)	(3.38)	(1.61)
Observations	195	195	195	195	195	195
R-squared	0.165	0.161	0.161	0.063	0.055	0.055
Number of provinces	3	3	3	3	3	3
province FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
VCE cluster (province)	NO	NO	YES	NO	NO	YES

*This table presents the estimation results for impacts of four Baidu search indexes on the sale of new energy vehicles sales of the northeast region of China. For more details of prediction models, refer to **Eq. 8**. The left three columns indicate results of the impacts of consumer attention on the sale volume in the same month and the right three columns indicate the impacts on the sale volume of the next month. We first perform regression using all Baidu indexes and then omit the persistently insignificant control variables if any and finally use the VCE, cluster method. Asterisk ***,**, and *denote the rejection of the null hypothesis at the 1, 5, and 10% significance level, respectively. Standard errors are presented in parentheses.*

combustion of new energy vehicles. Cognitive bias is an error in thinking that occurs when people are processing and interpreting information in the world around them and affects the decisions and judgments that they make (Bedi and Toshniwal, 2018). The empirical study shows that the search index of 'auto spontaneous combustion' has a significant negative effect on new energy vehicles sales in less developed regions, i.e. central and western China compared to eastern China indicating that the information on automobile spontaneous combustion will significantly increase people's negative safety evaluation of new energy vehicles in certain areas. This concern about the spontaneous combustion of new energy vehicles may be exaggerated by the related news because the news of the spontaneous combustion of traditional fuel vehicles is not as attractive as that of new energy vehicles, although the spontaneous combustion rate of traditional fuel vehicles is higher than that of new energy vehicles. In fact, according to the "Travel Big Data Report of Small Pure Electric Passenger Vehicles" released by "National Big Data Alliance for New Energy Vehicles" in2020[4], the spontaneous combustion probability of domestic new energy vehicles in 2019 was 0.0049% and in 2020, the probability dropped to 0.0026%. On the other hand, according to data released by the Departments of the Public Security of China, the annual spontaneous combustion rate of traditional fuel vehicles in 2020 was about 0.01–0.02%, significantly greater than that of new energy vehicles. The different responses to spontaneous combustion of new energy vehicles between central as well as western regions, and eastern regions also reflect that this cognitive bias may be related to the level of economic development. People in economically developed regions are less likely to produce such cognitive bias.

This study provides some useful implications for the promotion of new energy vehicles. First, battery performance and charging devices are very important factors when consumers decide whether to buy new energy vehicles. Accordingly, how to

[4]The official website of "National Big Data Alliance for New Energy Vehicles" is http://www.ndanev.com/.

improve the range and charging convenience should be the first thing that automobile manufacturers need to solve. Second, the safety of new energy vehicles should be more publicized, so that the cognitive bias that new energy vehicles are more prone to spontaneous combustion can be appropriately alleviated.

This study has several limitations that bode well for future research opportunities. First, as Baidu only provides search index information for specific keywords, some search terms related to new energy vehicles that do not appear in the search database may also provide interesting findings. Therefore, we can further study the impact of consumer attention on new energy vehicles through other proxies. Second, since relevant Baidu search terms can have an impact on the sales of new energy vehicles, we can try to predict the sales by integrating these indexes to provide effective information for new energy vehicle manufacturers and the government. Last, the potential relationship between economic development level and cognitive bias needs to be further demonstrated through social empirical research.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

ZJ carried out methodology, coded, and wrote the original manuscript YL collected the data did the review and edition LZ acquired the fund and did the thesis modification.

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Switching Intent of Disruptive Green Products: The Roles of Comparative Economic Value and Green Trust

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This study explores consumers' motivations to switch to new products in the context of disruptive innovation and investigates the role of comparative economic value and green trust. Switching from an existing product to a disruptive green product not only involves benefits but also requires major sacrifices, which are not encountered in the context of continuous innovation. In this study, the relationships between comparative economic value, green trust, self-accountability, and disruptive green product switching intent are examined. Data were collected from China with self-administered questionnaires regarding the disruptive green product. Results of a structural model reveal positive relationships between comparative economic value, green trust, and disruptive green product switching intent. In addition, green trust mediates the effects of the comparative economic value on the disruptive green product switching intent, and self-accountability moderates the relationship between green trust and disruptive green product switching intent. From a practitioner perspective, the research is important because it illuminates the consumer's motivations regarding product switching in the hitherto unexplored field of automobiles, for which we have shown that our extended model yields meaningful results.

Keywords: comparative economic value, comparative superiority, comparative monetary value, comparative long-term benefit, disruptive green product switching intent, green trust, self-accountability

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INTRODUCTION

Since consumers pay more attention to the rise of environmental protection activities and the impact of pollution, consumer environmentalism has become more popular in the world (McIntosh, 1991). In the environmental era, consumers may switch from their current products to green products (Chen and Chang, 2012). The topic of consumers' switching intentions and behaviors has received extensive attention from scholars and practitioners due to their important impact on the survival, performance, and growth of enterprises (Asimakopoulos and Asimakopoulos, 1980; Kamolsook et al., 2019). Existing literature has extensively explored the motivation of consumers to maintain brand loyalty (Frank et al., 2012), while the literature on the consumer's motivation to switch to alternative products is scarce. In addition, some research has explained the consumer's switching intent from current products to upgraded products and disruptive technologic products (Ye and Potter, 2011; Bhattacherjee et al., 2012; Kamolsook et al., 2019). Few studies have paid attention to the consumer's switching intention in green products under the context of disruptive innovation.

The rapid development and changes of disruptive innovation (Hopp et al., 2018) have an influence on the existing markets and consumers. Disruptive green products can not only provide new functionality (Sandstrom et al., 2014) but also long-term social and environmental value. Prior studies related to disruptive products have paid attention to the organizational issues, such as the effect of disruptive innovation on the business performance of both the incumbents and new entrants (Christensen, 1997; Christensen et al., 2018; Zach et al., 2020). Few studies have focused on the personal topics (Danneels, 2004). Therefore, under the context of disruptive innovation, it is not clear whether the existing research conclusions on the switching intent of consumers can explain the consumer's willingness to switch from current products to disruptive green products.

In this study, we explored consumer switching to disruptive green products, which are based on the green products introduced by the enterprise in the process of disruptive innovation (hereafter abbreviated as DGP). A disruptive product has many opportunities to enter existing and new markets (Christensen et al., 2018). Also, consumers switching from the current product to a disruptive product will involve higher risks (Walsh et al., 2002) because they can not only gain benefits but also need to make sacrifices (Kamolsook et al., 2019). Moreover, under most circumstances, consumers generally own the current product and the DGP simultaneously. In this situation, switching means that consumers need to invest more time and energy, and the sunk cost of the current product leads to greater sacrifices (Moore, 1991); thus, DGP switching has become a trade-off. This research assumes that the consumers have experience in using the existing product and can use the disruptive green product without changing their behavior too much. Moreover, the DGP is inclined to be at least as good as the existing product in terms of functionality or usability, so the new product will not cause significant losses to consumers.

The first purpose of this research is to examine the formation mechanism of the consumer's switching intent from current products to DGPs. Previous studies have confirmed that there is a positive correlation between perceived value and intention (Zeithaml, 1988; Kuo et al., 2009). A product can deliver value to consumers by distinguishing it from competitors' products and providing them with benefit (Zeithaml, 1988). Taking into account the consumer's trade-off of switching costs, we depend on the theory of comparative economic value to construct our model. We argue that compared to continuous innovation, the choice of switching to a DGP contains greater attention to the comparative economic value of the DGP are more often associated with the current product and that the higher the comparative economic value of the DGP, the higher the probability of DGP switching intent.

Second, we contend that green trust plays an essential mediating role in the process of the consumer intent to switch to a DGP. Positive expectations of the intention or behavior of the other party would lead to trust related to the intention to take vulnerability (Rousseau et al., 1998). Green trust is a willingness to rely on a product or service based on the beliefs or expectations arising from its reputation, credibility, benevolence, and ability for environmental performance (Chen, 2010). Indeed, green trust is an important premise of green consumption willingness (Wasaya et al., 2021); when consumers trust green products, their intent to switch from current products to green products will also increase. Existing research argued that green trust has a positive effect on consumers' purchasing intention, but its effect on consumers' switching intention has not been fully explored. In addition, the misgiving of the ecosystem and environmental protection have become one of the most concerning issues for citizens; consumers believe that taking social and environmental responsibility is a self-standard held by individuals (Tran and Paparoidamis, 2021). This supports the foundation of the current study, which is that if an individual believes that they will be achieving this kind of self-accountability, they may be motivated to act in an environmentally or socially sustainable way. A previous study has argued that consumers are likely to have varying degrees of self-accountability (Peloza et al., 2013; Dhiman et al., 2018). Although prior study has shown that self-accountability may influence purchase intention (Rowe et al., 2017), the relationship between self-accountability and consumer switching intent has not been fully explored. To explore this formation process and extend the existing literature, our study examines the moderating effect of the self-accountability.

Our study aims at making at least three contributions. First, previous studies paid less attention to the topic of green consumption in the context of disruptive innovation. To break through the limitation, this study expands the focus to a series of more fundamental issues, in view of the fact that new energy vehicles are both disruptive products and green products, focusing on the automotive industry, exploring the impact of the comparative economic value of new energy vehicles on consumers' DGP switching behavior. Second, we introduced green trust to reveal its intermediary mechanism between the comparative economic value and the DGP switching intent. This helps to reveal the specific mechanism of the comparative economic value on the DGP switching intent and helps to deepen the research on consumers purchasing disruptive products in the context of green consumption. Third, when considering the relationship between green trust and DGP switching intent, we further investigate the moderating effect of self-accountability, which can make the research results more consistent with the actual situation.

THEORETICAL BACKGROUND AND HYPOTHESES

From Comparative Economic Value to Disruptive Green Product Switching Intent

Comparative economic value is the consumer's perception of the overall economic benefits of the DGP as compared to those of the consumer's current product. It is composed of 1) comparative monetary cost, 2) comparative long-term benefit, and 3) comparative superiority (Holbrook, 1999; Kamolsook et al., 2019). These three economic dimensions belong to perceived value and have been affirmed to be important elements of consumer value (Sánchez-Fernández and Iniesta-Bonillo, 2009). The switching intent of consumers is the intention of individuals to migrate or not to migrate to a new product (Ajzen, 1991). Switching intention usually represents a favorable result because it often refers to consumers to transfer from an old product to an upgraded product with more advanced technical functions and benefits (Kamolsook et al., 2019). Previous research further explained that switching intent and behavior occurs when consumers are dissatisfied with their previous choices and take notice of other specific alternative products (Bhattacherjee et al., 2012; Frank et al., 2012; Hsieh et al., 2012). Our work extends the existing literature by exploring the switching intent of the disruptive green product.

It is generally believed that the overall structure of the perceived value will influence the repurchasing intent (Frank et al., 2012; Frank et al., 2014), the switching behavior (Gale and Wood, 1994), and the acceptance and usage of green products (Chen and Chang, 2012; 2013; Gonçalves et al., 2016). Previous studies have largely supported the influence of the perceived value on environment-related behaviors (Gonçalves et al., 2016). Based on the theory of consumption values (Sheth et al., 1991), different aspects of the perceived value have be confirmed that can affect behavior (Papadas et al., 2019) with regard to consumers' perceptions of the proper functions and benefits of disruptive green products. Comparative economic value is an extended concept of the perceived value that compares the expected benefits of disruptive green products with both the expected economic sacrifice and the comparative benefits of the consumer's current product (Kamolsook et al., 2019). Compared with non-green products and traditional green products, disruptive green products should possess the novel function to enhance purchase intentions (such as DGP switching intent). Existing study has identified comparative economic value as a significant predictor of disruptive technology product switching intent (Mathwick et al., 2001). The intention of switching involves exiting a current relationship (Keaveney, 1995), which means—in our study—replacement of a current product that consumers already own with a disruptive green product. High comparative economic value can lead to an increase in switching intent (Kamolsook et al., 2019). With the rise and popularity of environmentalism, comparative economic value is also essential to disruptive green product switching intent. We thus hypothesize the following:

H1: Comparative economic value is positively related to disruptive green product switching intent.

From Comparative Economic Value to Green Trust

Perceived value is related to a trade-off between the perceived benefits and affordability of a product (Monroe and Krishnan, 1985). The essence of trust is the individual's psychological response to a certain object in a specific social environment; specifically, it is a willingness to accept a certain object (Rousseau et al., 1998; Lin et al., 2003). Concerning the context of the environmental era, (Chen, 2010) reported that green trust is a willingness to depend on an object based on the belief or expectation attributable to its credibility, benevolence, and ability with regard to environmental performance. Past research hypothesized that there is a positive correlation between perceived value and consumer trust, since a high level of perceived value can increase post-purchase confidence of the product (Sweeney et al., 1999; Sánchez-Fernández and Iniesta-Bonillo, 2009; Rasheed and Abadi, 2014). Comparative economic value, as a part of perceived value, is also important in influencing green trust. In the process of consumers choosing disruptive green products, the higher the value of environmental protection performance and quality delivered by the product itself, the higher the comparative economic value perceived by consumers, which will ultimately enhance the green trust of the disruptive green product (Laufer, 2003). On the contrary, some companies exaggerate the environmental value of their products to the extent that their customers distrust their products more (Kalafatis et al., 1999). Hence, we hypothesize that the comparative economic value of consumers positively affects their green trust and propose the following hypothesis:

H2: Comparative economic value is positively related to green trust.

From Green Trust to Disruptive Green Products Switching Intent

Green trust refers to consumers who believe that a green product is reliable and trustworthy, and it is committed to complying with environmental commitments (Li et al., 2021; Wasaya et al., 2021). Indeed, previous research on green marketing has determined how green trust affects green behavior. Chen and Chang (2012) demonstrated the positive relationship between green trust and green intentions. Green trust means that another party will abide by their pro-environmental commitment, thereby helping to increase the intention of green behavior (Li et al., 2021). Due to the green nature of the DGP, consumers will also be affected by green trust when switching from the current product to disruptive green products. Hence, we hypothesize a direct positive link between green trust and disruptive green product switching intent. More specifically, we hypothesize the following:

H3: Green trust is positively related to disruptive green product switching intent.

Comparative Economic Value Associated With Disruptive Green Product Switching Intent Vis-à-Vis Green Trust

Prior research asserts that perceived value would impact not only an expectation of products (such as green trust) but also influence the purchase intent (such as the DGP switching intent) (Lalicic and Weismayer, 2021). Perceived value refers to the consumer's overall assessment of the utility of a product based on the consumers' perceptions of what they are obtaining and what they are sacrificing (Zeithaml, 1988). By comparing the value of disruptive green products with that of existing products, this comparative value will have an impact on consumers' green trust (Sirdeshmukh et al., 2002; Anderson and Srinivasan, 2003). Moreover, Flavián et al. (2006) suggested that perceived value contributes to enhancing the consumer's level of trust, which eventually reduces decision risk and facilitates purchase decision (Flavián et al., 2006).

We suggest that comparative economic value exerts its influence on DGP switching intent *via* green trust. According to the reasoned action (TRA) theory (Fishbein and Ajzen, 1975; Ajzen and Fishbein, 1980), an individual's behavioral intentions are determined by cognitive factors such as attitudes and subjective norms, and behavioral intentions will further determine personal performance. If consumers perceive a product as a high risk, they would be unwilling to trust the product (Mitchell, 1999). In the context of green consumption, green trust can help consumers' perceived risks and encourage consumers to show positive green purchase behavior (Rahbar and Abdul Wahid, 2011; Chen and Chang, 2013). Taken together, these arguments suggest that the relationship between comparative economic value and DGP switching intent will be mediated by green trust. We thus hypothesize the following:

H4: Green trust mediates the relationship between comparative economic value and disruptive green product switching intent.

The Role of Self-Accountability With Environmental Protection

We further argue that the extent to which green trust will influence the switching intent of DGP may be further contingent on the extent of self-accountability. Self-accountability refers to an activation of a person's desire to live up to internal self-standards (Peloza et al., 2013). Most consumers report that they should make consumption choices according to ethical and sustainability criteria (Trudel and Cotte, 2009). In other words, consumers maintain their self-standard that they should behave in an ethical and sustainable manner (Peloza et al., 2013; Dhiman et al., 2018). Consumers' green consumption behavior is consistent with ethical or responsible consumption, which refers to consumption in a sustainable and responsible way (Peattie, 2010). Moreover, when an individual decides to avoid feelings of guilt from choosing unethical choices, such expected results have been shown to be associated with ethical purchase decisions (Onwezen et al., 2013; Antonetti and Maklan, 2014; Antonetti et al., 2015). Accordingly, consumers are likely to be characterized by varying degrees of self-accountability (Tran and Paparoidamis, 2021). Individuals with higher self-accountability are more likely to engage in sustainable and environmentally friendly purchase behaviors. Therefore, when self-accountability to this salient self-standard is heightened, if consumers have had a green trust, they would possess a higher level of DGP switching intent. Conversely, when individuals have low levels of self-accountability, it can result in loss of DGP switching intent. We thus hypothesize the following:

H5: Self-accountability moderates the relationship between green trust and disruptive green product switching intent.

In summary, the conceptual model of this study is proposed in **Figure 1**.

METHODOLOGY AND MEASUREMENT

Data Collection and Sample

In order to verify our hypothesis and promote our conclusions, we selected the automobile contexts that consumers consider switching from the current product to the DGP. After literature research and interviews with experts who had substantial research experience in the field of disruptive innovation (Wells and Erskine, 2016), we selected the new energy vehicle as the disruptive green product because the new energy vehicle has two important attributes of disruptive and green. From a technology perspective, the new energy vehicle is based on an entirely different power mechanism than fuel automobiles. From a consumer perspective, with the development of science and technology, new energy vehicles have numerous advantages and benefits, but they still have many disadvantages in comparison with fuel automobiles. Before reaching a switching decision, consumers have to weigh the benefits against the drawbacks of new energy vehicles compared to fuel automobiles. We targeted consumers from China where the transition from fuel automobiles to new energy vehicles is currently underway.

TABLE 1 | Description of the sample (N = 317).

Profile of respondents	Class	Frequency	%
Gender	Male	142	44.80
	Female	175	55.20
Age (years)	<25	126	39.75
	25 to <30	60	18.93
	30 to <35	47	14.83
	>35	84	26.99
Education	College degree or below	101	31.86
	Bachelor's degree	126	39.75
	Masters' degree or above	90	28.39
Monthly income	<3,000	101	31.86
	3,000 to <5,000	53	16.72
	5,000 to <7,000	82	25.87
	>7,000	81	25.55

To verify the hypotheses and the research framework, we applied the questionnaire survey from April 1, 2021 to July 25, 2021. The research object of this study focuses on Chinese consumers who have the purchase or use experience of the DGP (new energy vehicles) in China. The questionnaires were randomly sent to consumers who had experience in purchasing or using fuel automobiles. The research assistants use electronic questionnaires with each randomly selected consumer to confirm that he or she has the purchase or use experience of automobiles. If he or she had the purchase or use experience of automobiles, the research assistants would undertake the subsequent procedures. A total of 400 consumers were surveyed. After deleting invalid responses with missing or incomplete information, our final sample consists of 317 consumers, with a valid rate of 79.25%. The detailed demographic characteristics of respondents are shown in **Table 1**.

Variable Measurement

Most measurement items of key research variables were adopted from prior research to ensure the rationality and validity of the questionnaire to a certain extent, and all the items were measured by using a 7-point Likert scale. The appendix lists the scales and their literature sources, with respect to the product context of new energy vehicles. We asked experts to translate the questionnaire into Chinese and back into English, held a pre-test with thirty independent Chinese consumers followed by interviews, refined the survey structure and item of the questionnaire, and secured the questionnaire quality.

Synthesizing the ideas of Sánchez-Fernández and Iniesta-Bonillo, (2009), we assessed comparative superiority, comparative monetary value, and comparative long-term benefit as three main aspects of comparative economic value. Comparative superiority is measured

TABLE 2 | Descriptive statistics and Pearson's correlations (N = 317).

Construct	1	2	3	4	5	6	7
First-order constructs	—	—	—	—	—	—	—
1 Comparative superiority (CS)	**0.867**	—	—	—	—	—	—
2 Comparative monetary value (CMV)	0.883**	**0.843**	—	—	—	—	—
3 Comparative long-term benefit (CLB)	0.806**	0.838**	**0.833**	—	—	—	—
4 Green trust (GT)	0.695**	0.660**	0.658**	**0.859**	—	—	—
5 Self-accountability (SA)	0.762**	0.726**	0.701**	0.784**	**0.882**	—	—
6 DGP switching intent (DGPSI)	0.763**	0.741**	0.724**	0.721**	0.861**	**0.882**	—
Second-order construct (indicators: variables 1–3)							
7 Comparative economic value (CEV)	0.951**	0.959**	0.928**	0.710**	0.772**	0.785**	**0.847**
Mean	5.138	5.102	5.187	5.18	5.219	5.104	5.142
SD	1.107	1.044	0.996	1.004	1.107	1.079	0.993

Notes: Squared root of AVE is on the diagonal. Pearson's correlations are below the diagonal. *$p < 0.05$; **$p < 0.01$; ***$p < 0.01$.

by three items along a single dimension (α = 0.900). Respondents were asked to compare new energy vehicles with traditional fuel automobiles in terms of diversified functions and quality (Xu et al., 2010). Meanwhile, the scale of comparative monetary value was based on a scale used by Dodds et al. (1991) and Sánchez-Fernández and Iniesta-Bonillo, (2009), which includes three items measured along a single dimension (α = 0.881). Respondents were asked to rate the extent of trade-off between the monetary sacrifice of using new energy vehicles and the additional value of the new energy vehicle over the fuel automobile. Finally, consistent with the work of Thompson et al. (1991), Thompson et al. (1994) and Chang and Cheung (2001), we measured comparative long-term benefit using a three-item scale (α = 0.830). Respondents were asked to rate the degree of insight that switching to the new energy vehicle would lead to long-term economic and social benefits.

Green trust was measured using four items (α = 0.918) based on the study by Chen (2010) to evaluate the degree of a willingness to depend on new energy vehicles based on the belief or expectation resulting from its credibility, benevolence, and ability with regard to its environmental performance.

Self-accountability was measured using four items (α = 0.933) based on the study by Peloza et al., 2013. Respondents were asked to rate the activation of a person's desire to live up to internal self-standards.

Disruptive green product switching intent was measured using three items (α = 0.913) that were adapted from the study by Kamolsook et al., 2019. Respondents were asked to rate the intent to replace the current product (fuel automobiles) with the disruptive green product (new energy vehicles).

All the items used in these instruments were measured using a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree). **Appendix A** contains all the scales used in the study.

ANALYSIS AND RESULTS

Descriptive Statistics of the Latent Constructs

The statistical analyses were conducted using SPSS 25.0 and AMOS 24.0. We report the correlation between the main constructs in this research in **Table 2**. There are positive correlations among comparative superiority, comparative monetary value, comparative long-term benefit, green trust, self-accountability, and disruptive green product switching intent. The results show that it is suitable for further regression analysis.

TABLE 3 | Confirmatory factor analysis (N = 317).

Fit index	χ^2/df	GFI	CFI	TLI	SRMR	RMSEA
Six-factor model	1.891	0.913	0.978	0.973	0.025	0.053
One-factor model	6.797	0.811	0.843	0.825	0.060	0.135

Notes: ①Six-factor model: CS, CMV, CLB, GT, SA, DGPSI; ②Four-factor model: CS + CMV + CLB + GT + SA + DGPSI.

Reliability and Validity

We first performed confirmatory factor analysis (CFA) to evaluate the goodness of our proposed six-factor model fit. As is shown in **Table 3**, the CFA results showed that our six-factor baseline model produced good fit with the data: χ^2/df = 1.891, GFI = 0.913, CFI = 0.978, TLI = 0.973, SRMR = 0.025, RMSEA = 0.053. Then, we performed CFA to assess the fit of one-factor models. The one-factor model 1 in which we loaded all items onto one single latent variable: χ^2/df = 6.797, GFI = 0.811, CFI = 0.843, TLI = 0.825, SRMR = 0.060, RMSEA = 0.135. The results showed that the six-factor model was significantly better than the one-factor model. We can thus deduce that the possibility of common method bias in this study is low (Iverson and Maguire, 2000).

Next, we found that the corrected item-total correlation (CITC) of all items was above 0.7. As shown in **Table 4**, all Cronbach's alpha values and CR values are higher than the accepted value of 0.7. Therefore, we concluded that the scales used in this study were reliable. Furthermore, it can be seen that the AVE values are greater than the minimum accepted value of 0.5 (see **Table 2**), thus supporting the discriminant validity between the constructs. Based on the above results, we believed that the reliability and validity of the measurements in this study were within an acceptable range.

Hypothesis Testing

We use hierarchical regression to test the theoretical hypotheses about comparative economic value, green trust, self-accountability, and DGP switching intent, and the empirical results are shown in **Table 5**. We found a positive relationship between the comparative

TABLE 4 | Constructs, items, and measurement model (*N* = 317).

Construct	Items	Factor loading	CITC	Average variances extracted (AVE)	Cronbach's alpha (CR)
Comparative superiority	CS1	0.875	0.814	0.752	0.900
	CS2	0.881	0.815		
	CS3	0.840	0.793		
Comparative monetary value	CMV1	0.850	0.778	0.711	0.881
	CMV2	0.837	0.788		
	CMV3	0.844	0.771		
Comparative long-term benefit	CLB1	0.838	0.772	0.694	0.872
	CLB2	0.822	0.717		
	CLB3	0.838	0.761		
Green trust	GT1	0.853	0.773	0.737	0.918
	GT2	0.862	0.734		
	GT3	0.855	0.729		
	GT4	0.864	0.736		
Self-accountability	SA1	0.885	0.833	0.777	0.933
	SA2	0.897	0.836		
	SA3	0.890	0.816		
	SA4	0.851	0.773		
Disruptive green product switching intent	SI1	0.908	0.839	0.778	0.913
	SI2	0.881	0.806		
	SI3	0.856	0.789		

TABLE 5 | Results of hierarchical linear modeling.

	Disruptive green product switching intent						Green trust	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Control variables								
Gender	–0.01	0.016	–0.036	–0.113	–0.020	–0.042	0.169	0.159
Age	–0.024	–0.044	–0.002	0.059	0.068	0.067	–0.132	–0.131
Income	–0.015	0.031	0.005	–0.043	–0.008	0.000	0.082	0.080
Main effect								
First order								
Comparative superiority	—	0.413***	0.277***	—	—	—	—	0.418***
Comparative monetary value	—	0.165*	0.138	—	—	—	—	0.082
Comparative long-term benefit	—	0.255***	0.170**	—	—	—	—	0.260***
Second order								
Comparative economic value	—	0.794***	0.554***	—	—	—	0.722***	—
Mediation effect								
Green trust (GT)	—	—	0.327***	0.736***	0.128**	–0.315*	—	—
Moderation effect								
Self-accountability (SA)	—	—	—	—	0.776***	0.307⁺	—	—
GT*SA	—	—	—	—	—	0.866**	—	—
R^2	0.002	0.624	0.672	0.529	0.757	0.763	0.540	0.546
$\triangle R^2$	0.002	0.622	0.049	0.527	0.228	0.006	0.512	0.518
F-value	0.23	85.66***	90.60***	87.59***	193.51***	166.54***	91.48***	62.04***

Note: Standardized coefficients are reported; ⁺p < 0.1, *p < 0.05, **p < 0.01, ***p < 0.001; two-tailed tests.

economic value and DGP switching intent (β = 0.794, p < 0.001, Model 2). Moreover, the relationships between comparative superiority and DGP switching intent (β = 0.413, p < 0.001, Model 2), comparative monetary value and DGP switching intent (β = 0.165, p < 0.05, Model 2), and comparative long-term benefit and DGP switching intent (β = 0.255, p < 0.001, Model 2) have been analyzed, which is significant, thus supporting H1. As illustrated in Model 7 and Model 3, the comparative economic value is positively related to green trust (β = 0.722, p < 0.001) and green trust is positively related to DGP switching intent (β = 0.255, p < 0.001), thus supporting H2 and H3.

H4 proposed the mediation role of green trust in the relationship between comparative economic value and DGP switching intent. As shown in Model 3, when green trust was entered, the effect of comparative superiority on DGP switching intent decreased while remaining significant (β = 0.277, p < 0.001), and this indicated that green trust partially mediated the effect of comparative superiority on DGP switching intent; the effect of comparative superiority on DGP switching was not significant (β = 0.138, n. s), and this suggested that green trust fully mediated the effect of the comparative monetary value on DGP switching intent; the effect of comparative long-

TABLE 6 | Bootstrapped result of moderation.

Indirect path	Total effect	Direct effect	Indirect effect	(95% BootCI)
CS=>GT=>SI	0.761***	0.511***	0.249***	0.148 to 0.351
CMV=>GT=>SI	0.913***	0.583***	0.330***	0.221 to 0.455
CLB=>GT=>SI	0.901***	0.556***	0.345***	0.240 to 0.479
CEV=>GT=>SI	0.772***	0.526***	0.247***	0.402 to 0.655

Note: *p < 0.05, **p < 0.01, ***p < 0.001.

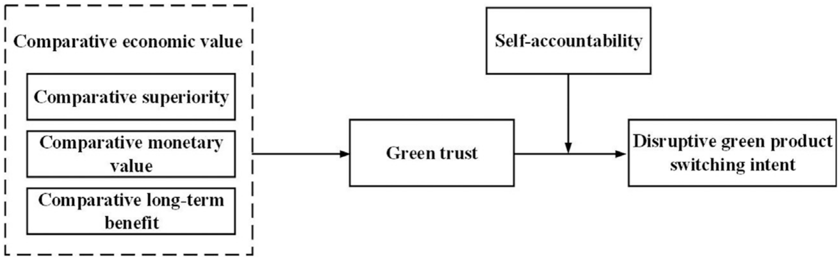

FIGURE 1 | Conceptual model of this study.

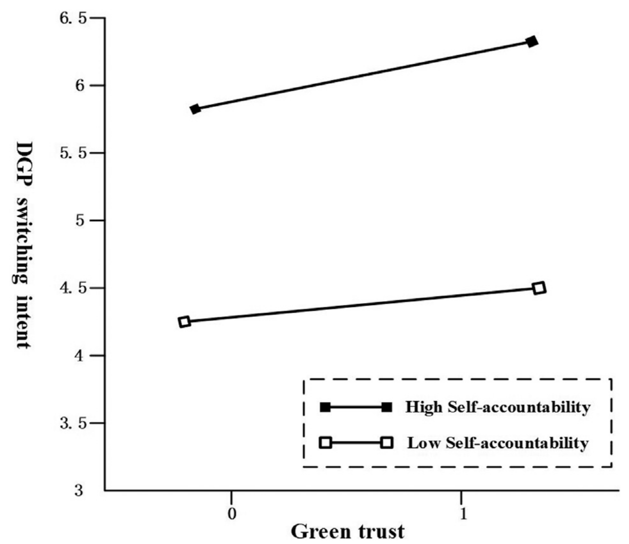

FIGURE 2 | Moderating role of self-accountability.

term benefit on DGP switching intent decreased while remaining significant (β = 0.170, $p < 0.01$), and this indicated that green trust partially mediated the effect of comparative long-term benefit on DGP switching intent. We further tested the mediation effects using path analysis and the bootstrapping method (Edwards and Lambert, 2007). As illustrated in **Table 6**, the indirect paths of "Comparative superiority → Green trust → DGP switching intent" (0.148–0.351), "Comparative monetary value → Green trust → DGP switching intent" (0.221–0.455), and "Comparative long-term benefit → Green trust → DGP switching intent" (0.240–0.479) were significant, in support of H4.

In order to test H5, we test our moderating effect according to the procedure recommended by Cohen et al. (2003). Before generating the interaction terms, we mean-centered all the variables involved. Model 6 showed that the interaction term between green trust and self-accountability was positively and significantly related to DGP switching intent (β = 0.866, $p < 0.01$). In addition, as shown in **Figure 2**, we drew a graph of the moderating effect of self-accountability, and thus H5 was supported.

DISCUSSION

Theoretical Contributions

This study contributes to the literature on comparative economic value and disruptive green product switching intent in several ways. Our first contribution is to reveal the direct and indirect pathway whereby comparative economic value links with DGP switching intent through the mediation of green trust. First of all, we find that comparative superiority, comparative monetary value, and comparative long-term benefit are positively associated with DGP switching intent. Previous studies have shown that comparative economic value has an important impact on the consumer's switching intent (Gale and Wood, 1994; Kamolsook et al., 2019). Our research results have further verified and expanded this view. In addition, Kamolsook et al. (2019) have pointed out that disruptive innovation is the key to improving the environmental performance of products and have suggested that future research on the switching intent can focus on the environmental performance of products and the personal attributes of consumers. Our research responds to this question. Second, researchers have highlighted that the green trust is an essential factor in raising the consumer's green purchase intentions (Chen and Chang, 2012). Confente et al. (2020) found that switching intention is differently affected by the independent variables. However, little research has considered green trust as a vital psychological factor situated between comparative economic value regarding the DGP and the consumer's switching intent. We find that green trust has a mediating effect on the relationship between the comparative economic value and DGP switching intent. The results show that consumers would be willing to accept the DGP if the products' comparative value and environmental features were made clear and if these products' environmental commitments are generally trustworthy. Taken together, these findings contribute significantly to understandings of the correlation between the comparative economic value and DGP switching intent and form a more systematic foundation for theoretical and empirical research on perceived value and switching intent.

Our second contribution is that we clarify how the comparative economic value becomes variables that correlate with the consumer's green trust. Building on recent work on the trust, we hold that the green trust is a willingness to depend on a product based on belief or expectation about environmental performance (Ganesan, 1994; Chen, 2010), with this willingness being affected by perceived value (Kim et al., 2008). We find that the green trust is not only a positive emotion that influences DGP switching intent; what is more, it is influenced by comparative economic value. It is positively correlated with the comparative economic value. Previous studies have revealed that certain values associated with environmental quality are positively correlated with environmentally friendly behaviors and other intermediate elements such as psychological factors (Neuman, 1986; Li et al., 2021). For its part, the green trust is a key element allowing consumers to improve their behavior to search for and analyze green products' information (Laufer, 2003). However, only a few studies have explored the role of green trust in the relationship between values and purchase intention. Our study analyzes the role of the green trust as an intermediary, while enriching the research on the variables that we treat as antecedents of that intermediary.

The third contribution is that self-accountability positively moderates the relationship between green trust and DGP switching intent. Specifically, switching from the old (fuel automobiles) to the new products (new energy vehicles) is more driven by self-accountability. This highlights self-accountability as a potential trigger of the consumer's disruptive green products switching intent. Peloza et al. (2013) advanced that self-accountability is related to ordinary green products, while little is known about consumer perceptions of disruptive green products because of their novelty and relevance to disruptive innovation. Our research refines the conclusions in this area and addresses the fact that the consumers are treated as unique individuals with unique psychological judgments. Their acceptance of disruptive green products is guided by self-accountability.

Managerial Implications

Our findings have important managerial implications for understanding consumers' DGP switching intent. First, our findings indicate the significance of comparative economic value as a driver to switch from existing products to disruptive green products. Most consumers would not sacrifice their needs just for environmental protection when choosing products, because this requires consumers to make a trade-off between the general attributes and environmental friendliness of the product (Ginsberg and Bloom, 2004). Thus, consumers need to understand the DGP in an all-round way. By comparing with existing products, the higher the comparative economic value perceived by consumers, the more willing they are to switch to the DGP. In order to successfully make consumers accept the DGP, it is necessary that companies provide overall information about the benefits and advantages of DGPs and their usage. Companies can use green marketing activities to help change consumers' attitudes toward disruptive green products and usage intention. Second, our results demonstrate that the more consumers who trust the DGP's environmental commitments, the easier it is for consumers to switch to the DGP. This requires companies to eliminate consumers' concerns about DGPs and enhance their confidence in DGPs when conducting green marketing, thereby enhancing consumers' switching intent and behavior.

Limitations and Future Research

This study has some limitations and avenues for future research. First of all, the generalizability of this study's conclusions is constrained by the fact that one special kind of consumer (e.g., automobile users) within a single text (e.g., disruptive innovation) is examined. Future research could replicate this model on products or services in different industries, to see whether our research results are still valid. Second, our study uses cross-sectional data, which limits our design about causality. Although cross-sectional data can illuminate the temporary relationship between comparative economic value and DGP switching intent, whether the relationship between comparative economic value and green trust and the consumer's switching intent will change over time is best to pass verification of longitudinal data. Third, this study estimates the fitting of comparative economic value without considering the relationship between different dimensions of comparative economic value and switching behavior. This may become an interesting research topic in the future.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

CL, XL, and CY contributed to conception and design of the study. CL and XL organized the database. XL performed the statistical analysis and wrote the first draft of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX A:

TABLE 7 | Measurement scales and items (new energy vehicle context).

Comparative superiority (CS) adapted from Xu et al. (2010)	
—	Compared with my current fuel automobile, new energy vehicle will . . .
CS1	. . . provide more diversified functionality
CS2	. . . provide higher quality
CS3	. . . provide more functions
Comparative monetary value (CMV) adapted from Dodds et al. (1991) and Sánchez-Fernández and Iniesta-Bonillo (2009)	
CMV1	The necessary additional costs of new energy vehicle are reasonably priced
CMV2	New energy vehicle offers better value for money than my current fuel automobile
CMV3	The necessary additional cost is acceptable when compared to the value received from my current fuel automobile
Comparative long-term benefit (CLB) adapted from Thompson et al. (1991, Thompson et al. (1994) and Chang and Cheung (2001)	
—	Compared with my current fuel automobile, in the long run, new energy vehicle
CLB1	. . . will reduce expenditures
CLB2	. . . will yield more social benefits
CLB3	. . . will have more economic benefits
Green trust (GT) adapted from Chen (2010)	
GT1	I feel that environmental commitments of new energy vehicle are generally reliable
GT2	I feel that environmental performance of new energy vehicle is generally dependable
GT3	I feel that environmental argument of new energy vehicle is generally trustworthy
GT4	New energy vehicle keeps promises and commitments for environmental protection
Self-accountability (SA) adapted from Peloza et al. (2013)	
SA1	I feel accountable to behave in an ethical manner
SA2	I am strongly motivated to live up to my own self-standards
SA3	I feel accountable toward my own self-standards
SA4	I will work hard to practice my environmental self-standards
Disruptive green product switching intent (DGPSI) adapted from Davis (1989) and Venkatesh et al. (2003), Venkatesh et al. (2012)	
DGPSI1	I intend to use new energy vehicle in the near future
DGPSI2	I predict that I would use new energy vehicle in the near future
DGPSI3	I plan to use new energy vehicle in the near future

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Impact of Social Capital on Environmental Governance Efficiency—Behavior of Guangdong, China

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The main purpose of this article is to investigate the impact of social capital level on environmental governance efficiency in economically developed areas. We choose China's richest province Guangdong. Compared with other Chinese provinces, Guangdong's local governments are in better fiscal status, and they can allocate environmental spending in line with the trend of gross domestic product per capita. We want to observe the important factors related to social cognition other than capital investment to gain a more profound influence on the efficiency of local environmental governance. This article assumes that the degree of local social capital will have a great positive impact on the efficiency of regional environmental governance. Super-efficiency slacks-based measure method of data envelopment analysis is adopted to calculate the environmental governance efficiency by considering the expected output and the nonexpected output. Then, short-panel regression was used to analyze the relationship between social capital and environmental governance efficiency. Through an empirical analysis of urban panel data of Guangdong province from 2001 to 2019, it is found that the degree of social capital does have a significant positive impact on the efficiency of local environmental governance. After the research conclusion, we propose some policy suggestions to local governments.

Keywords: social capital, environmental governance, governance efficiency, local governance, China study

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INTRODUCTION

The ecological environment protection has become a major quandary of local governance in developed areas of China, as China has experienced more than 40 years of rapid economic growth since the reform and open-up policy and has realized that economic growth must change from high-speed to high-quality way. Rapid economic growth at the expense of the environment has been very intuitively felt by citizens in their daily lives, and environmental deterioration has become the main cause of many serious diseases. In the southeastern coastal areas of China, local economic development has made great achievements, and people are beginning to pay attention to their own health problems. As southeast China is a manufacturing hub, economic growth has had a big impact on environmental protection. This has forced the government to consider policies that balance economic development and environmental governance. We chose social capital to observe the influencing factors of environmental governance efficiency in affluent areas. This is because social capital, as opposed to capital input and technology application, is a matter of community consciousness that is highly relevant to a region (Kaasa, 2016).

Local governments in China have been increasing investment in environmental governance, and good results have been achieved (Liu et al., 2017; Zheng et al., 2020). For residents in Chinese affluent areas, environmental governance has become a hot topic of social concern. People put forward higher request to environmental management. But the way of environmental pollution control in developed areas is obviously different from that in less developed areas, and the resulting efficiency of pollution control is also different. Therefore, it is a very meaningful topic to find the factors that affect the efficiency of environmental governance. Government spending is the main driving force for environmental pollution control across China, especially from local governments. The economically developed urban areas are relatively abundant in the investment of environmental governance, and the efficiency of environmental governance is generally not affected by the pressure of funds. Environmental protection fundamentally depends on the long-term accumulation of good cognitive foundation of residents (Moynihan & Lavertu, 2012). Therefore, to explore the factors affecting the efficiency of environmental governance in rich areas may need to look beyond money.

An increasing number of research shows that social capital has an important impact on sustainable development such as growth, equity, and the environment (Putnam, 1995). In the long run, the efficiency of environmental governance in economically developed areas is not only related to the government's public expenditures, but also closely related to the social capital that can significantly improve the social culture and institutional environment. Regional social capital formed after long-term cognitive repair will have a positive impact on the efficiency of government governance (Krause, 2006). Social interaction and social modernization even play a decisive role in public governance (Jones and Clark, 2013). From the perspective of social cognition, strengthening the function of information transmission among people in social networks is conducive to the implementation of common decisions. Environmental protection is a positive example of this kind (Hetherington, 2001; Lyons & Kashima, 2001; Aarøe and Petersen, 2018). Relations of social trust, common rules, norms, and sanctions and connectedness in institutions may have a vital role in evaluating governance efficiency (Pretty and Ward, 2001; Dulal et al., 2011). Each stage of environmental governance involves the behavior of enterprises and the daily life of residents, and many regulations would have a positive effect through the social environment. Social capital can improve governance performance when governmental policy fails. Effective social communication, networks, and organizations can expand the scale and effectiveness of information dissemination, which will lead to more effective enforcement of environmental governance regulations (Du and Li, 2020; Hu and Wang, 2020; Song et al., 2020). As long as social capital reaches a certain level, social trust, social norms, and participation will significantly improve the efficiency of regional environmental governance. Moreover, social capital greatly promotes the transparency of local government, and transparent government is more conducive to the utilization efficiency and supervision of environmental protection resources (Wang et al., 2020).

Some other research also reveals that the impact of social capital on environmental governance efficiency varies with regional differences (Lu et al., 2017; Yi et al., 2021). In China's eastern Yangtze delta area, this effect is even more pronounced. The supervision of environmental protection is mostly binding behavior, and residents with higher social capital level are more willing to provide information convenience and action coordination through the supervision network. Such as Yangtze delta urban agglomeration, the developed business network in the region makes it easier for people to communicate information and trust rules, which plays an important fundamental role in the improvement of social capital. A good level of trust in the rules can obviously help improve the efficiency of the government's environmental governance (Tu et al., 2019; Yi et al., 2021). In this article, the major cities of Guangdong Province, the most developed province in China, were selected as the research targets. The growth trend of environmental governance input and per-capita gross domestic product (GDP) in major cities in Guangdong is basically consistent, indicating that the influencing factor of environmental governance efficiency in each region is not mainly government funds (Barman and Gupta, 2010; Chen, 2015). We should observe the important factors related to social cognition other than capital investment to gain a more profound influence on the efficiency of local environmental governance.

Guangdong Province is a very wealthy region in China. Cities generally have plenty of financial aid to support environmental protection. Our research tries to find substantial factors beyond fund which would contribute a lot to the efficiency of environmental governance. This article assumes that the degree of local social capital will have a great positive impact on the efficiency of regional environmental governance. The data envelopment analysis (DEA) method is adopted to calculate the environmental governance efficiency by considering the expected output and the nonexpected output. Then short-panel regression was used to analyze the relationship between social capital and environmental governance efficiency. Through an empirical analysis of urban panel data of Guangdong province from 2001 to 2019, it is found that the degree of social capital does have a significant positive impact on the efficiency of local environmental governance. During the article's quantitative analysis, we took the influences of regional economic performance, openness degree, governmental public financial competence, fiscal transparency and local industrial structure, and the scale of area into consideration and controlled relative variables (Zhang et al., 2012; Zhao, 2010).

VARIABLES AND DATA

The data in this article are from the Statistical Yearbook of Chinese Cities and the Statistical Yearbook of Guangdong

Province from 2001 to 2019. There are 21 cities in Guangdong Province, China. The panel data are strongly balanced, and that the number of areas is more than the number of years means it is a short panel. The dependent variable of this article is the efficiency of local environmental governance. Regional governments have invested a lot of financial expenditure to protect the ecological environment. To observe the environmental governance efficiency of regions completely, we need to take expected output and undesired output of environmental governance expenditure into consideration together.

We estimate regional efficiency based on super-efficiency slacks-based measure (SBM) method (Tone, 2001, 2010). In the analysis of traditional non–super-efficiency DEA model, multiple decision-making units (DMUs) are usually evaluated as effective; especially when the number of input–output is large, the number of effective DMU is also large. The maximum efficiency value obtained by this model is 1, and the efficiency value of the effective DMU is the same. The efficiency of these effective DMU cannot be further distinguished. Super-efficiency model (Andersen and Petersen, 1993; Ray, 2008) by removing the evaluated DMU from the reference set, that is, the efficiency of the evaluated DMU is obtained by referring to the Frontier formed by other DMUs, solves the problem that the efficiency of effective DMU cannot be distinguished. Suppose the total number of decision units (DMU) in period T is K, and each DMU uses M input factors and produces I desired outputs and R undesired outputs, $x_k \in \mathrm{R}^M$, $y_k \in R^I$, and $b_k \in R^R$, respectively, represent the input vector, expected output vector, and unexpected output vector of the k DMU; then, the input–output of the k DMU in period t is expressed as (x_k^t, y_k^t, b_k^t). Define the production possibility set constructed by DMU other than DMU_k as follows:

$$P^t = \left\{ (x^t, y^t, b^t) \,\middle|\, x^t \geq \sum_{j=1, j\neq k}^{K} x_j^t \lambda_j,\ y^t \leq \sum_{j=1, j\neq k}^{K} y_j^t \lambda_j,\ b^t \geq \sum_{j=1, j\neq k}^{K} b_j^t \lambda_j,\ \lambda_j \geq 0 \right\} \tag{1}$$

where λ_j is the weight coefficient vector (intensity vector); here we assume that scale returns are variable (i.e., VRS), so the sum of weight coefficients of all DMUs is equal to 1, i.e., $\sum_{j=1, j\neq k}^{K} \lambda_j = 1$. Here, DMU is each district in Guangdong Province, and the input variable of each area is environmental input. The expected output variable is wastewater utilization rate and solid waste treatment rate, and the unexpected output variable is sulfur dioxide and nitrogen oxide. Therefore, $M = 1$, $I = 2$, $R = 2$.

The super-efficiency SBM efficiency value of decision unit K $k \in \{1, 2, \cdots, K\}$ can be obtained by solving the following programming problem:

$$IE_{SuperSBM}^t (x_k^t, y_k^t, b_k^t, \lambda) = \min \frac{1 + (1/M) \sum_{m=1}^{M} \left(s_m^{x,-} / x_{m,k}^t \right)}{1 - [1/(I+R)] \left[\sum_{i=1}^{I} \left(s_i^{y,+} / y_{i,k}^t \right) + \sum_{r=1}^{R} \left(s_r^{b,-} / b_{r,k}^t \right) \right]} \tag{2}$$

$$s.t. \quad \sum_{j=1, j\neq k}^{K} x_{m,j}^t \lambda_j - s_m^{x,-} \leq x_{m,k}^t$$

$$\sum_{j=1, j\neq k}^{K} y_j^t \lambda_j + s_i^{y,+} \geq y_{i,k}^t \qquad \sum_{j=1, j\neq k}^{K} b_j^t \lambda_j - s_{r,k}^{b,-} \leq b_{r,k}^t$$

$$s^{x,-} \geq 0,\ s^{y,+} \geq 0,\ s^{b,-} \geq 0,\ \lambda \geq 0,\ \sum_{j=1, j\neq k}^{K} \lambda_j = 1$$

$$m = 1, 2, \cdots, M; \quad i = 1, 2, \cdots, I; \quad r = 1, 2, \cdots, R$$

Among them, $IE_{SuperSBM}$ stands for regional efficiency, and its value is between (0,1). The larger the value is, the higher the regional efficiency is. When $IE_{SuperSBM} = 1$, it means that the DMU is an effective unit; that is, it is located on the production Frontier. $s_m^{x,-}$, $s_i^{y,+}$, $s_r^{b,-}$, respectively, represent the relaxation variables corresponding to input variables, expected output variables, and nonexpected output variables. To solve **Eq. 2**, we use the method of Charnes and Cooper (1978) to convert the equation into the following linear programming problem.

$$IE_{SuperSBM\_L}^t (x_k^t, y_k^t, b_k^t, \lambda) = \min \tau + (1/M) \sum_{m=1}^{M} \left(S_m^{x,-} / x_{m,k}^t \right) \tag{3}$$

$$s.t. \quad 1 = \tau - [1/(I+R)] \left[\sum_{i=1}^{I} \left(S_i^{y,+} / y_{i,k}^t \right) + \sum_{r=1}^{R} \left(S_r^{b,-} / b_{r,k}^t \right) \right]$$

$$\sum_{j=1, j\neq k}^{K} x_{m,j}^t \Lambda_j - S_m^{x,-} \leq \tau x_{m,k}^t$$

$$\sum_{j=1, j\neq k}^{K} y_j^t \Lambda_j + S_i^{y,+} \geq \tau y_{i,k}^t$$

$$\sum_{j=1, j\neq k}^{K} b_j^t \Lambda_j - S_{r,k}^{b,-} \leq \tau b_{r,k}^t$$

$$S^{x,-} \geq 0,\ S^{y,+} \geq 0,\ S^{b,-} \geq 0,\ \Lambda_j \geq 0,\ \tau > 0,\ \sum_{j=1, j\neq k}^{K} \Lambda_j = \tau$$

$$m = 1, 2, \cdots, M; \quad i = 1, 2, \cdots, I; \quad r = 1, 2, \cdots, R$$

Let the optimal solution of **Eq. 3** of linear programming be $(IE_{SuperSBM\_L}^*, S^{x,-,*}, S^{y,+,*}, S^{b,-,*}, \tau^*, \Lambda^*)$, then the optimal solution of the original nonlinear programming problem (2) is:

$$IE_{SuperSBM}^* = IE_{SuperSBM\_L}^*, \quad \lambda^* = \Lambda^* / \tau^* \tag{4}$$
$$s^{x,-,*} = S^{x,-,*} / \tau^*, \quad s^{y,+,*} = S^{y,+,*} / \tau^*, \quad s^{b,-,*} = S^{b,-,*} / \tau^*$$

Accordingly, we can also get the efficiency of each input–output variable:

$$DE_{k,t}^{in} = \left(x_{k,t}^{in} - s_{k,t}^{in} \right) / x_{k,t}^{in} \tag{5}$$
$$DE_{k,t}^{uo} = \left(b_{k,t}^{uo} - s_{k,t}^{uo} \right) / b_{k,t}^{uo}$$
$$DE_{k,t}^{do} = y_{k,t}^{do} / \left(y_{k,t}^{do} + s_{k,t}^{do} \right)$$

Among them, $DE_{k,t}^{in}$, $DE_{k,t}^{uo}$, $DE_{k,t}^{do}$, respectively, represent the efficiency of input variable, expected output variable, and unexpected output variable, and its value is between (0,1). The larger the value is, the higher the efficiency of the input or output factor is.

TABLE 1 | Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
Efficiency	399	0.9543444	0.6591516	0.032399	5.139752
SC	399	0.0003918	0.0005669	0.000066	0.0046407
GDPpc	399	43,545.62	38,414.11	3,164.33	203489
FDI	399	97,821.26	151,007.8	1,611	820301
Industry	399	3.80e+07	5.86e+07	334,569	3.73e+08
Popu	399	482.7468	269.9292	128.45	1530.59
AreaDummy	399	0.4285714	0.495493	0	1
Sufficiency	399	0.5742114	0.2496258	0.1354	1.168413
Transparency	399	0.7169706	0.0953241	0.4427	0.9533
Tertiary	399	41.04193	8.142568	24.44	71.75
Electron	399	1,621,149	2,217,050	24,663	1.01e+07

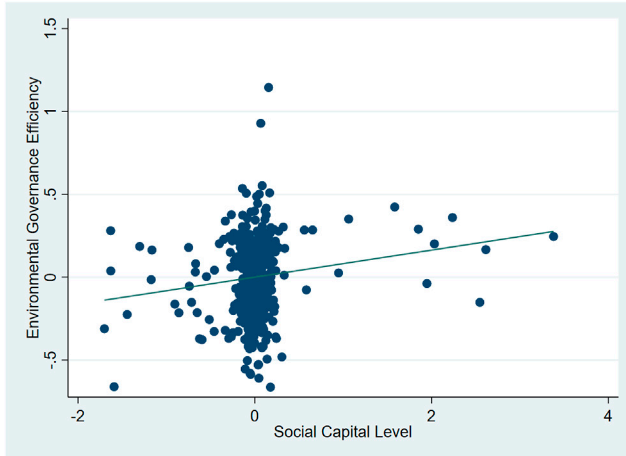

FIGURE 1 | Partial correlation graph between the core variable and the explained variable.

Regional social capital level (SC) is the explanatory variable in the research. Social capital is calculated based on the ratio of welfare, network, cultural, sports, and entertainment employees to total employees on duty (Villalonga-Olives and Kawachi, 2015). In local statistical yearbooks from 2001–2019 in Guangdong Province, this kind of data has good continuity and comparability and ensures panel data's overall stability (Grafton and Knowles, 2004). We chose per-capita GDP (GDPpc) and total population at the end of the year (Popu) as variables to observe the population and economic development level that have a fundamental impact on the environment. In addition, we control some industrial and economic variables related to environmental protection. Generally, regional industrial structure would affect emission level so that we take the proportion of tertiary (Tertiary) as a control variable (Gonzalez and Ho, 2018). Power consumption of whole society (Electron) and regional industrial output value (Industry) indicate the level of energy consumption in the area, which are very basic variables in environment-related issues (Liang and Langbein., 2015; Xie et al., 2018). We also controlled some variables that have local characteristics in terms of openness and economic development level. The regional annual amount of foreign capital actually utilized (FDI) represents the degree of city's openness. Guangdong province has a great difference in economic development level, and the Pearl River Delta region is relatively developed. Therefore, we divide the 21 regions into two categories and take the regional dummy variable (AreaDummy) as the control variable. Below is the descriptive statistics table of variables (**Table 1**), which reports the summary statistics. We took the Napierian logarithm value of dependent variable environmental governance efficiency (lnEfficiency) and standardized the independent variable social capital (stdSC) before using it in the regression model. We also took the Napierian logarithm value of variable of GDPpc, FDI, Industry, Popu, and Electron. As mentioned previously, Guangdong is a province with uneven development among regions. The degree of fiscal self-sufficiency varies greatly in regions (Bao and Guan, 2019; Lopez et al., 2011; Bai et al., 2019).

MODEL AND RESULTS

First, based on controlling other variables, we show the partial correlation graph between the core variable and the explained variable (**Figure 1**). We can initially observe the general trend of correlation between environmental governance efficiency and social capital. As each city in the province is different, there may be omitted variables that do not vary over time, and there may be time effects that do not vary geographically. Based on the above reasons, we adopted the two-way fixed-effects model:

$$\ln Efficiency_{it} = \beta_0 + \beta_1 SC_{it} + \delta Controls_{it} + \mu_i + \gamma_t + \varepsilon_{it}$$
$$(i = 1, \cdots, 21; t = 1, \cdots 19)$$

We estimate the two-way fixed-effects model with its null hypothesis is H_0: *all* $\mu_i = 0$ and obtain the p value corresponding to F test result as 0. It is much less than 0.01, which indicates it refuses the null hypothesis, and we should choose the fixed-effects model. But if the error term is cross-sectional dependent, then the F test result is unreliable, and we could not choose the fixed-effects model. We tested the cross-section problem, and the cross-sectional independence value is 0.653, which is larger than the critical value of 0.1 α level 0.136. This indicates that the null hypothesis that there is no cross-sectional correlation is rejected; that is, the model has cross-sectional correlation problems. Then, we do F test of the regional dummy variable, and the p value is less than 0.1, which indicates that we can refuse the null hypothesis, and the individual effects exist. Finally, the model passes the Hausman test. The result strongly rejects the null hypothesis, and we choose the fixed-effects model.

To ensure the robustness of the model, we observe three more regression results through controlling different important variables. The theme of this article is to study the impact of social capital on the efficiency of environmental governance. Traditionally, the influence of economic factors, development model factors, and public finance factors on environmental governance is generally emphasized (Gupta and Miranda, 1995). Therefore, when we test the stability of the influence of social capital, we give special consideration to controlling variables with such factors. In different regressions, we, respectively, control the fiscal self-sufficiency level, economic development level, economic openness, industrial structure, energy consumption, and production capacity of different cities and observe the stability of the model results from different perspectives. The results show that the results of the model are stable in all aspects, and social capital has a significant positive

TABLE 2 | Benchmark regression results.

	(1)	(2)	(3)	(4)	(5)
	OLS	FE	FE	FE	FE
stdSC	0.129***	0.111***	0.107***	0.121***	0.118***
	(7.54)	(8.15)	(8.03)	(8.12)	(7.95)
lnPopu	−0.0974*	0.0511	−0.112	0.118	0.122
	(−2.26)	(0.22)	(−0.50)	(0.50)	(0.53)
AreaDummy	−0.100	0	0	0	0
	(−1.56)	(.)	(.)	(.)	(.)
lnGDPpc	−0.0610	−0.145**		−0.145*	−0.0914
	(−1.24)	(−2.59)		(−2.31)	(−1.86)
Sufficiency			−0.0222		
			(−0.21)		
lnFDI	0.0290	0.0184	0.0340		0.0277
	(1.39)	(0.67)	(1.23)		(0.98)
Tertiary				−0.000971	
				(−0.25)	
lnIndustry	0.0404	0.0727*	−0.000124	0.0713	
	(1.15)	(2.02)	(−0.01)	(1.88)	
lnElectron					0.0330
					(1.01)
_cons	0.911**	0.417	0.958	0.266	0.0982
	(3.17)	(0.37)	(0.86)	(0.22)	(0.09)
N	399	399	399	399	399

t *Statistics in parentheses.*
*p < *0.05*, **p < *0.01*, *and* ***p < *0.001*.

impact on the efficiency of environmental governance. **Table 2** shows the result report of all regressions in this article.

CONCLUSION AND POLICY SUGGESTIONS

This article studies the efficiency of environmental governance from a relatively new perspective of social cognition, and we have obtained good research results. Especially in Guangdong province of China, where the economy is developed and government governance is relatively transparent, this study is of great practical significance. Compared with the underdeveloped central and western regions in China, the local governments of Guangdong province are generally abundant in financial funds. To investigate the level of government governance in rich areas, we must pay more attention to social factors. Of course, the regional differences within Guangdong province are also obvious. We have controlled for that in our study.

The improvement of environmental governance efficiency is not a pure administrative or an absolute economic efficiency problem. Under the premise of sufficient government input, whether people's awareness of social community will be transmitted to the efficiency of environmental governance is a problem worthy of discussion. Our article attempted this effort. We maintain the objectivity of the data and the continuity and balance of the availability of the data in the processing of the explained variables and the main explained variables. We estimate regional efficiency based on super-efficiency SBM method, fully considering reasonable expected and unexpected output. The results are very encouraging.

Social capital is a concept in which social cognition influences social norms and thus the behavior of the society as a whole. A good level of social capital is conducive to the better implementation of many regulations of the government. Environmental governance involves all aspects of the society, which requires the government to strictly supervise the behavior of enterprises, and at the same time, it also needs to strengthen the guidance of the behavior norms of all social members. This is the fundamental way to improve the efficiency of environmental governance. From the research results, we believe that social capital does have a significant positive impact on the efficiency of environmental governance. It is even more important to study such issues in an affluent region such as Guangdong. China also attaches great importance to improving social capital while building its economy.

We believe that this conclusion is a positive signal for the government to step up efforts to improve the level of social capital in the region. First, the government can achieve the basic goal of improving social capital by promoting the concept of harmonious coexistence between man and nature. This is one of the important tasks of the current government on the construction of ecological civilization. People will gradually realize the long-term positive impact of overall environmental protection awareness on improving the efficiency of environmental governance. Second, the government needs to build more abundant social and environmental governance organizations. Improving social capital requires not only the cognitive base of all social members, but also more participation in relevant environmental protection organizations. People can better share relevant information and scientific knowledge in more organizations, thus promoting the active support of social members for environmental governance policies. Again, the government should encourage social supervision of environmental governance behavior. Specific incentive measures may include regular or irregular knowledge tests, competitions, and other activities, relying on some organizations, which help publicize the environmental protection concepts. The government can provide both material and nonmaterial incentives for related activities. This can make more and more residents willing to join in the big network of improving environmental governance. It also encourages people to be more willing to contribute ideas and share them on improving the efficiency of environmental governance. Each of these policies will promote the level of social capital associated with environmental protection.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SZ contributed in quantitative research part and ZG contributed in qualitative research part.

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Environmental Performance Assessment of Energy-Consuming Sectors Through Novel Data Envelopment Analysis

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This study evaluates the role of information in the environmental performance index (EPI) in different energy-consuming sectors in Pakistan through a novel slack-based data envelopment analysis (DEA). The index combines energy consumption as the primary input and gross domestic product (GDP) as the desirable output and CO_2 emissions as the undesirable output. Yale's EPI measures the efficiency of the sectoral level environmental performance of primary energy consumption in the country. Performance analysis was conducted from 2009 to 2018. The sectors were assigned scores between one and zero, with zero indicating maximum decision-making unit (DMU) inefficiency and one indicating maximum DMU efficiency. Despite being in the top-performing sector, agriculture scored only 0.51 in 2018, and the electricity sector obtained 0.412. Results also show that even the best-performing sector operates below the efficiency level. The mining and quarrying sector ranked second by obtaining 0.623 EPI and 0.035 SBEPI. Results also show that much of the energy supply of Pakistan (60.17%) is focused on fossil fuels, supplemented by hydropower (33%), while nuclear, wind, biogas, and solar power account for 5.15%, 0.47%, 0.32%, and 0.03%, respectively. Nonetheless, the overall results for both measures remained reasonably consistent. According to the literature and the energy crisis and climate instability dilemma, the authors conclude that changes to a diverse green power network are a possibility and an imminent need. Similarly, the government should penalize companies with poor performance. Furthermore, to ensure the capacity development and stability of environmental management and associated actions in the country, providing access to knowledge and training to groom human resources and achieve the highest performance is crucial.

Keywords: CO_2 emission, green energy, electricity, energy consuming, environmental performance index

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INTRODUCTION

In the late 1960s, the Environmental Impact Assessment (EIA) methodology was developed. It has now been widely accepted and enacted in over 100 nations across the globe. According to Mohsin et al. (2019c), the purpose of an EIA is to identify possible environmental effects of activities and evaluate various alternatives before deciding whether to approve or reject a proposed development.

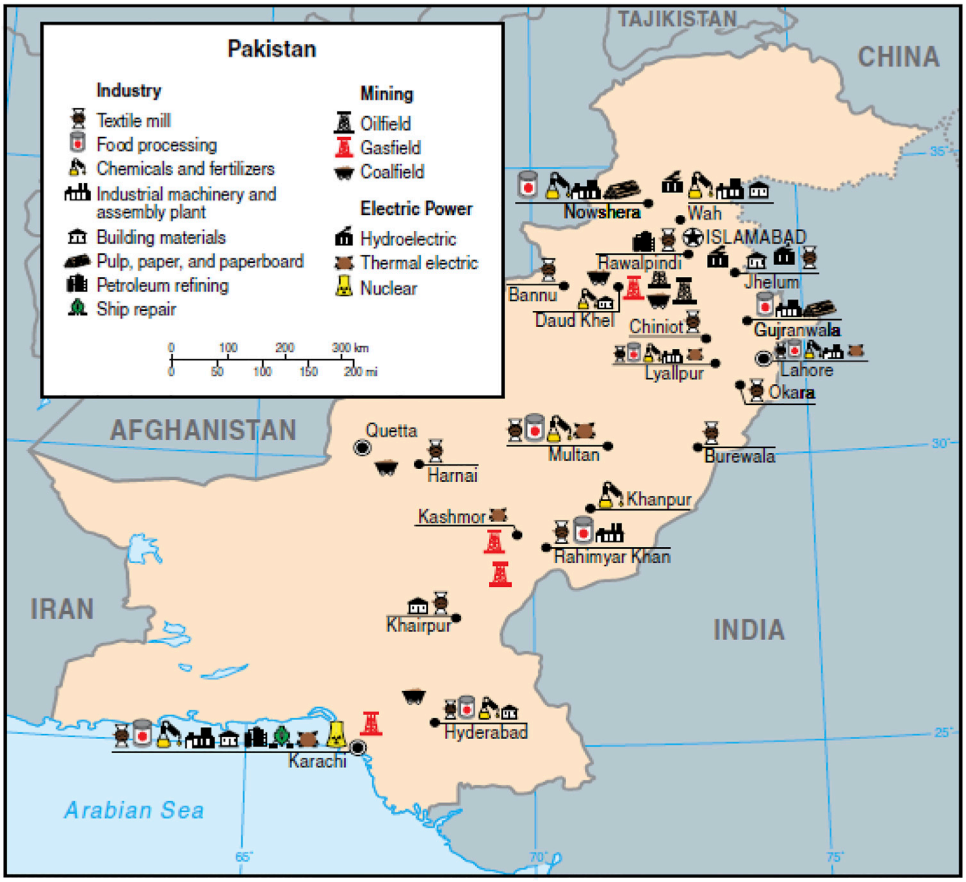

FIGURE 1 | Crude, gas, and coal production of Pakistan.

The EIA system is based on fundamental environmental protection and development concepts, and it represents common responses to similar problems (Hou et al., 2019). Although EIA is also founded on the same set of principles in developing nations, its implementation often falls short of international standards (Iqbal et al., 2020). The creation of EIA in developing nations has frequently been a consequence of a catastrophe or financial needs from foreign donor organizations, according to previous experience. According to Sun et al. (2020b), many developing nations adopted Western EIA methods without considering local politics and context. **Figure 1** represents the crude, gas, and coal production in Pakistan.

Enablers such as EIA system evaluation, training, and capacity development are among the foundational steps to enhance the performance of the EIA system. The EMA established the Sustainable Advisory Committee in Namibia to offer recommendations on policy changes. In 2018, the government held a series of stakeholder meetings to discuss changes to the EMA and regulations. According to a DEA official, the consultations' feedback was effectively integrated; nevertheless, cabinet approval is required before the revised law can be gazetted and implemented.

The environmental performance index (EPI) is an approach to quantify and express environmental performance numerically. The pilot EPI introduced this index, which was published in 2002. The EPI was promoted by the environmental sustainability index (ESI) developed by Yale University. Hence, it is known as Yale's EPI (YEPI). This is used as a benchmark index by policymakers, environmental scientists, advocates, and the general public. YEPI measures the ecological execution depending on 24 pointers, which can be applied to assess natural well-being and biological systems. The low ranking of Pakistan, almost at the base, shows the nation's weak strategy implementation of decoupling greenhouse gas (GHG) emissions from monetary exercises, thus failing to protect the atmosphere and environment, and improve air quality. The scorecard of YEPI provides a significant check of ecological execution on a national scale. Nonetheless, it did not delve into the sectors. In contrast, a sectoral ecological effectiveness investigation reveals a few aspects that YEPI cannot detect because it is a national-level measure. Hence, YEPI alone is not a sufficient measure for effective natural policymaking. Similarly, an increasingly thorough examination is required, which can help refine ecological arrangements and understand the determinants of sectoral environmental advancements (Mohsin et al., 2018; Mohsin et al., 2020b; Mohsin et al., 2021). This paper examines the responsibility of Pakistan by assessing the ecological yield of the country on six crucial monetary fields: agriculture, manufacturing, fuel,

FIGURE 2 | Transportation network in Pakistan.

transport, mining and quarrying, and construction. An increase in the population of Pakistan and the development of its economy has increased the environmental pressure on Earth (Zhang et al., 2018). For example, the creation of merchandise and ventures into different financial fields require vitality and materials—water, minerals, metals, food, and fiber—which are all obtained from nature. **Figure 2** illustrates the transportation network in Pakistan. In Pakistan, the vast majority of expended vitality is from petroleum derivatives, such as oil and gas (Shah et al., 2018). Subsequently, expanded vitality utilization heightens ozone-depleting substances (i.e., GHGs, mainly CO_2). It is evident that an expansion in monetary exercises resembles a "two-edged sword." The development of the economy can raise the quality of life but can also harm the Earth (Shah et al., 2019a). Nevertheless, financial development and maintainable advancement are predictable, for the most part, through elective vitality utilization, improved mechanical effectiveness, institutional advancement, and changes in population rate (Fankhauser and Jotzo, 2018).

In Pakistan, energy policies and planning are mostly *ad hoc*, created in reaction to crises and requirements of certain subsectors (Sun et al., 2020a). Plans related to electricity, oil, gas, coal, and renewable and nuclear energy are generally developed separately (Malik et al., 2020). The first energy strategies for the oil, gas, and coal sectors were established in 1991, with the aim to use national fuel resources with an emphasis on exploration, production, and investment (Malik et al., 2020). On the one hand, Pakistan remains reliant on oil imports (He et al., 2020). The government utilizes indigenous natural gas in the electricity and transportation sectors to maintain low prices, resulting in the fast depletion of gas reserves (Raza et al., 2021).

On the other hand, the electricity sector of the country has received the most significant attention, and a range of policies has been adopted over the years. The Pakistan Atomic Energy Commission (PAEC) is responsible for nuclear power plant design, building, and maintenance of nuclear power production. The PAEC provides the Pakistani government with administrative and technical assistance to guarantee the safe use of nuclear energy sources (Yasmin et al., 2020). In recent years, drought, heavy rainfall, floods, pollution, and other climate change indicators have hit Pakistani cities, particularly in Lahore (Tiep, et al., 2021). Floods in the country affected 20 million people in 2010 and 2011.

Consequently, the government adopted the National Climate Change Policy in 2012 and created the Ministry of Climate Change (Iqbal et al., 2021a). The concept of supportable improvement has drawn attention from scientists, experts, and policymakers (Mohsin et al., 2019b; Mohsin et al., 2020a; Mohsin et al., 2021). It has been perceived as the focal answer to offset financial improvement through ecological assurance and environmental change relief (Emas, 2015). The factors crucial for policymaking regarding feasible advancement include careful

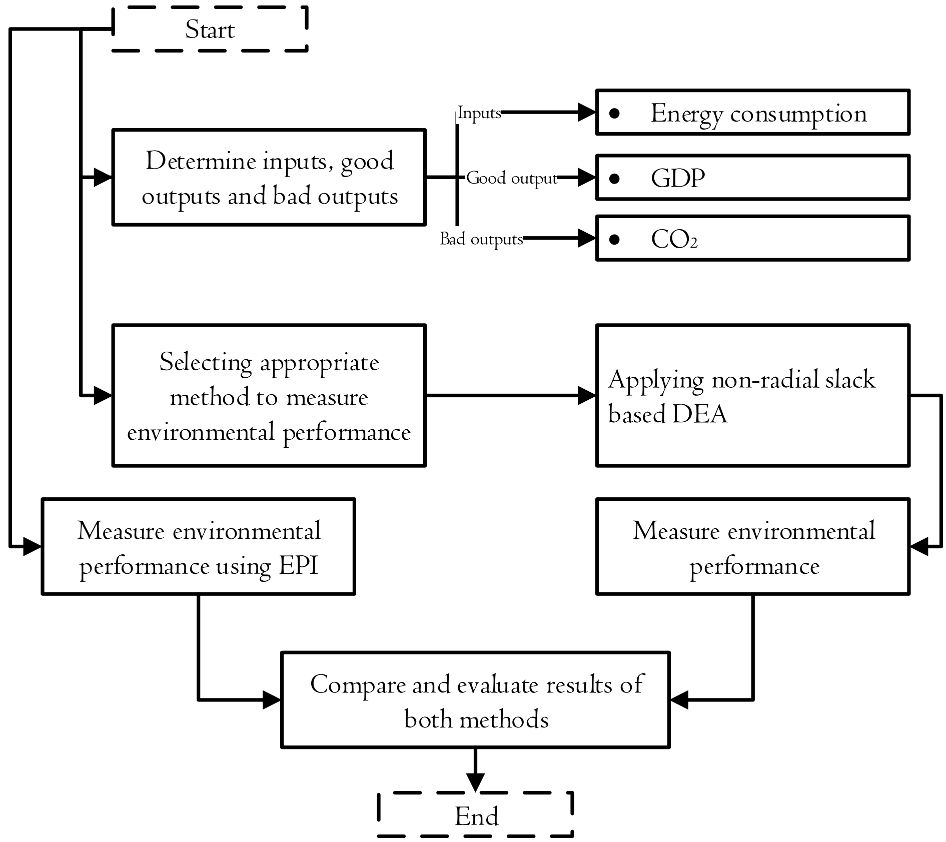

FIGURE 3 | Research design (source: authors' depiction).

and suitable assessment of every natural execution of the industry (Mohsin et al., 2020b; He et al., 2020; Yang et al., 2021). Correspondingly, the appraisal of natural execution has received one of the critical issues applicable for the appropriate outcome of events. There is a limited investigation concerning the ecological disorder at the sectoral level in Pakistan. **Figure 3** shows authors research design. The absence of such an investigation makes our examination all the more significant, with a special focus on the natural proficiency of the major monetary areas of the country. The motivation for this study is to formulate a methodology that could provide adequate data for cutting-edge investigation into natural execution. The correlation analysis from the existing literature demonstrates various procedures for formulating an EPI, such as a methodology for natural bookkeeping, life cycle examination, and creation hypothesis (Wang et al., 2018). In production theory, the production process is supposed to generate useful outputs as well as pollutants (i.e., wrong outputs) (Faere et al., 1989). In particular, technologies to filter out pollutants are recommended for analyzing useful and harmful outputs in environmental performance evaluation. A directive range factor or Shephard range factor may be used to consider the potential output based on the description of production technology. Further, specific parametric approaches can be used in the distance model, such as stochastic Frontier research (Taghizadeh-Hesary and Yoshino, 2016).

Most related studies employed the non-parameter approach, that is, reviewing the data envelopment (Ikram et al., 2019a; Shah et al., 2019b). The data envelopment analysis (DEA) is a model that constructs the processing system as a linear piece-wise mixture of inputs, positive outputs, and weak outputs. In these instances, as linearity is built inside the DEA system, Färe et al. (2004) claimed low disposability reference technology as environmental DEA technology. The DEA is commonly used to measure the relative efficiency of a set of decision-making units (DMUs) with multiple inputs and outputs, as suggested by Charnes et al. (1978). They present numerous guidelines for the DEA and analytical studies. Baležentis et al. (2016) used the DEA to measure Lithuania's economic sectors in the Hicks–Moorsteen indices' spirits (Tiep et al., 2021).

Other experiments used the DEA to calculate eco-efficiency. For example, Ikram et al. (2019a) and Shah et al. (2019a) suggested that the DEA approach used over 700 research studies based on environmental performance evaluation. Most DEA based on environmental performance evaluation models predicts relative improvements in positive outputs and declines in negative or weak outputs (or inputs). This indicates that such studies do not account for slack in inputs and outputs while evaluating environmental performance. Although such models

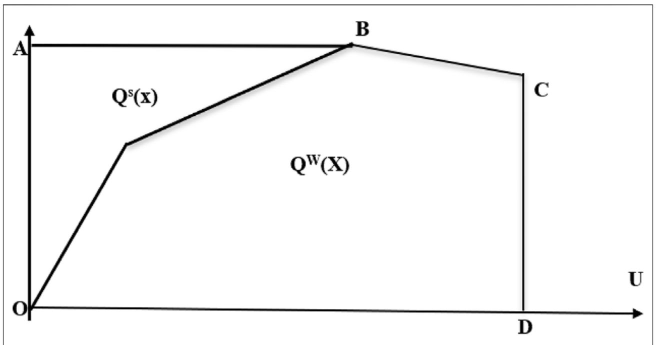

FIGURE 4 | Description of ecological data envelopment analysis (DEA) outcomes (source: authors' depiction).

have some desirable theoretical properties, the environmental performance scores of many comparable entities can be 1. Hence, making a detailed comparison is challenging. However, according to the DEA, even if a DMU obtains an efficiency score of 1, it may still not be fully efficient due to the misutilization of inputs or the old production system. Therefore, including output shortfalls and input excesses in the objective function of the study is crucial. **Figure 4** explains description of ecological data envelopment analysis (DEA) outcomes. The contribution of this study is that the model focuses on the DEA when environmental efficiency is calculated. Accordingly, this study used the slack-based DEA approach, which was suggested by Zhou et al. (2018), to evaluate environmental efficacy for different economic sectors. Additionally, we assess the sector-level EPI.

The remainder of this paper is organized as follows. The *Background of the key economic sectors of Pakistan* section provides the background of the key economic sectors of Pakistan. The *Research design* section presents the research methodology developed for sectoral environmental performance analysis. The *Results and discussion* section presents the results and a discussion of the results. Finally, the *Discussion* section provides the conclusion.

BACKGROUND OF THE KEY ECONOMIC SECTORS OF PAKISTAN

Pakistan is a leading country in southwestern Asia to connect the other states of the region. It is bordered by China on the northwest, India on the east, Iran on the southwest, and Afghanistan on the northwest. The nation has the 6th largest population in the world, which is about 226 million. The economy of Pakistan is the 23rd largest economy on the planet in terms of market proportion. However, it ranks 46th globally in terms of nominal gross domestic product (GDP). Significant sectors that help the economy of the country are farming, production, power, transportation, mining, quarrying, and manufacturing. Farming is the foundation of the economy of Pakistan. The majority of the population of the country depends on this farming and industry, which contributed 22.69% and 17.69%, respectively, to the GDP in 2020 and accounted for 42.3% and 25.79% of the workforce. The farming sector supplies essential raw materials to the modern industries of the nation and supports a rapidly increasing population (Baloch et al., 2020; Sun et al., 2020c). Additionally, it significantly contributes to the trade revenue of the country through exports. The main crops include maize, corn, cotton, sugarcane, grapes, and vegetables. **Figure 5** represent gross domestic product (GDP) from 2000 to 2018. According to UNFAO, Pakistan is the World's 13th largest increasing agricultural products producer among rice, cotton, maize, sugar cane, and fruit producers (Ikram et al., 2019a; Ikram et al., 2019b; Sun et al., 2019). Additionally, approximately one-fourth of the land in Pakistan is arable.

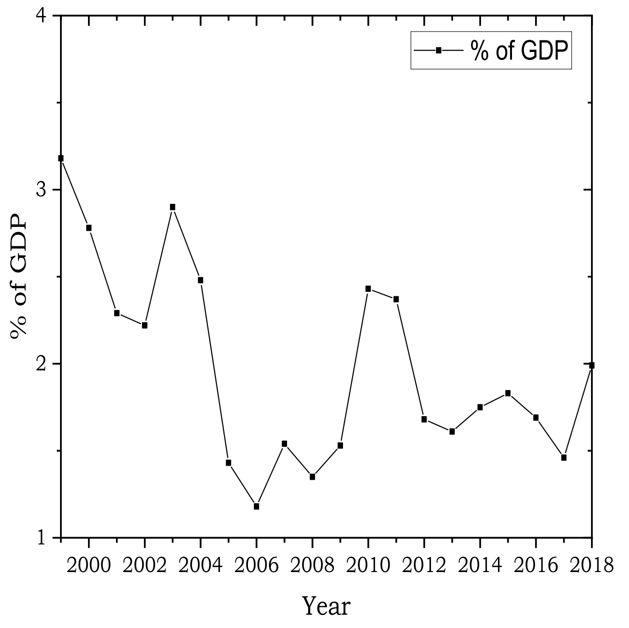

FIGURE 5 | Gross domestic product (GDP) from 2000 to 2018.

Despite a large number of obstacles, the economy of Pakistan has steadily improved. Various strategies and policies have resulted in inclusive and sustainable development paths. The country started implementing stabilization policies after the 2017–2018 crisis, which helped its economy recover from macroeconomic imbalances. However, COVID-19 slowed the recovery pace that had been achieved previously. The arrival of the second and third waves brought significant challenges that were addressed by timely cautious policies. Although pandemics such as COVID-19 occur only once in a lifetime, they cause significant devastation worldwide.

The government has formulated several significant policies, taken monetary and fiscal measures, implemented smart lockdowns, and hastened to vaccinate its citizens. The National Command and Operating Centre was tasked with making important decisions with the cooperation of provinces as a unified entity. Due to the prompt decision-making of the government, the situation has stabilized, and the number of COVID-19 cases is now decreasing daily. Before COVID-19

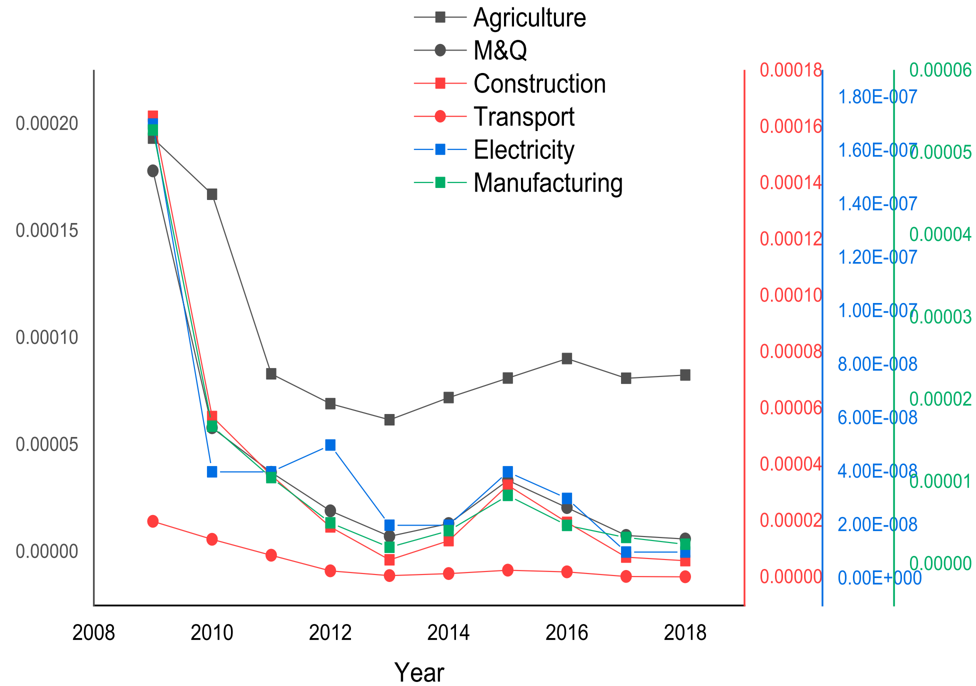

FIGURE 6 | Slack-based environmental performance index.

TABLE 1 | Growth rates (%) of descriptive statistics indicators.

		Agricultural sector	Mining and quarrying sector	Manufacturing sector	Transport sector	Construction sector	Electricity sector
Energy consumption	Mean values	−0.16	−0.12	−0.11	−0.06	−0.10	0.04
	Median values	−0.21	−0.11	−0.02	0.03	−0.03	0.02
	SD values	0.34	0.25	0.29	0.22	0.23	0.03
	Range Values	1.09	0.81	0.87	0.64	0.71	0.14
	Minimum values	−0.62	−0.74	−0.81	−0.53	−0.63	−0.02
	Max values	0.46	0.17	0.04	0.11	0.08	0.11
GDP	Mean values	0.15	0.08	0.12	0.21	0.12	0.15
	Median values	0.13	0.05	0.10	0.12	0.14	0.09
	SD values	0.11	0.12	0.08	0.34	0.02	0.17
	Range values	0.31	0.37	0.32	1.11	0.14	0.65
	Minimum values	0.02	−0.02	0.01	−0.15	0.04	−0.01
	Maximum values	0.35	0.35	0.32	0.91	0.16	0.57
CO_2	Mean values	−0.18	−0.04	0.03	0.04	0.04	0.04
	Median values	−0.22	−0.03	0.01	0.03	0.04	0.05
	SD values	0.36	0.15	0.06	0.04	0.13	0.08
	Range values	1.10	0.40	0.22	0.16	0.53	0.16
	Minimum values	−0.65	−0.25	−0.05	−0.09	−0.24	−0.04
	Maximum values	0.51	0.17	0.16	0.12	0.30	0.13

Note. GDP, gross domestic product.

pandemic, the working population was 55.74 million, which fell to 35.04 million due to the pandemic. This indicates that individuals have either lost their employment, or are unable to work due to COVID crises. Because of the wise decisions of the government, the working population in October 2020 increased to 52.56 million, and the economy recovered in a V-shaped

TABLE 2 | EPI and SBEPI scores within 2009–2018.

Sectors	EPI									
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Agricultural sector	0.62	0.6	0.653	0.554	1	0.695	0.699	0.65	1	0.669
Mining and quarrying sector	0.53	0.506	0.535	0.571	0.588	0.58	0.592	0.619	0.624	0.623
Manufacturing sector	0.43	0.417	0.405	0.389	0.383	0.416	0.432	0.427	0.451	0.471
Electricity sector	0.391	0.368	0.353	0.367	0.388	0.429	0.403	0.404	0.405	0.412
Construction sector	0.504	0.52	0.5	0.526	1	0.534	1	0.58	0.55	0.571
Transport sector	0.526	0.601	0.502	0.459	0.468	0.492	1	0.444	0.41	0.431
	Slack-based environmental performance index									
Agricultural sector	0.051	0.058	0.049	0.052	0.048	0.053	0.055	0.048	0.053	0.049
Mining and quarrying sector	0.032	0.033	0.036	0.029	0.035	0.031	0.031	0.028	0.037	0.035
Manufacturing sector	0.016	0.018	0.017	0.016	0.016	0.018	0.013	0.02	0.021	0.02
Electricity sector	0.001	0.003	0.003	0.004	0.006	0.005	0.004	0.006	0.012	0.011
Construction sector	0.023	0.019	0.018	0.024	0.026	0.025	0.021	0.026	0.02	0.029
Transport sector	0.007	0.008	0.007	0.008	0.009	0.01	0.011	0.006	0.012	0.014

Note. EPI, environmental performance index.
In ***Table 2****, none of the sectors achieved the SBEPI of 1 from 2009 to 2018, which shows that all sectors have poor energy and environmental performance.*

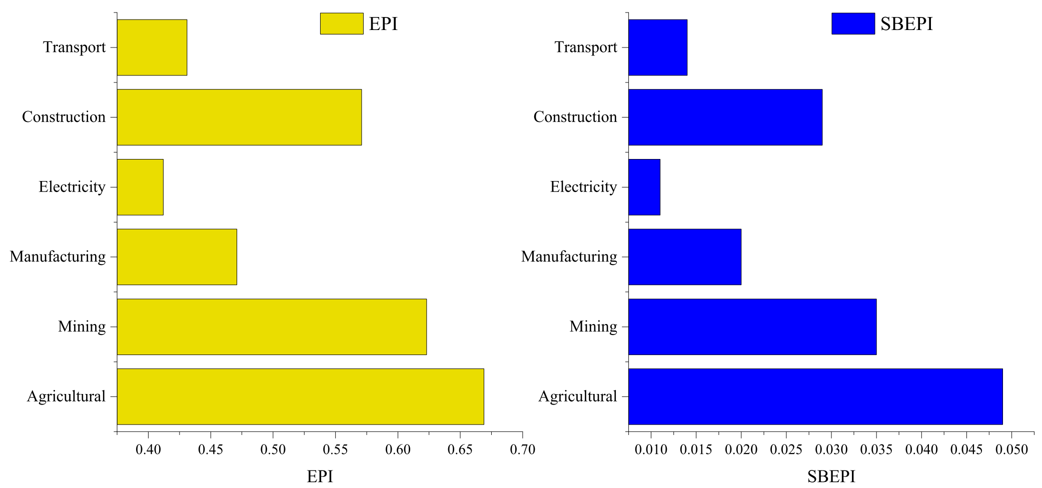

FIGURE 7 | Environmental performance index (EPI) and SBEPI ranking of sectors in 2018.

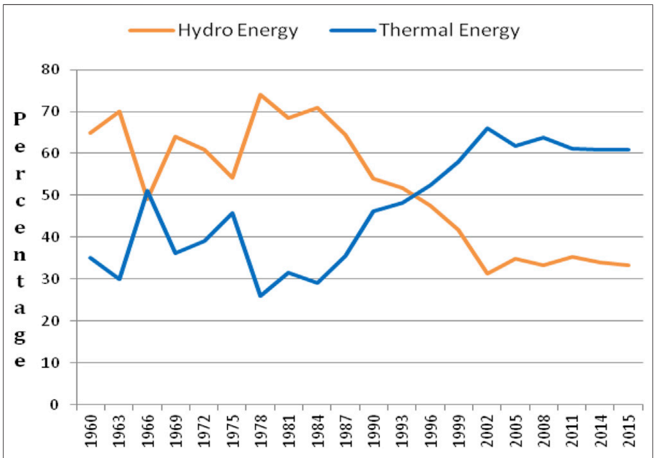

FIGURE 8 | Electricity production.

pattern. Internal and external stability has not been jeopardized in the present economic recovery. **Figure 6** shows slack-based environmental performance index. Manufacturing has shown impressive development, with major large-scale manufacturing (LSM) sectors, such as textiles, foods and beverages, tobacco, non-metallic mineral products, and automobiles, all showing considerable progress. **Table 1** states growth rates percentage of descriptive statistics indicators. Since FY2007, the first 9 months of FY2021 showed the greatest period-wise increase of 8.99%.

Figure 7 shows the rankings of all sectors under both measures in 2018. The best performing sectors achieved the EPI and SBEPI values of 0.669 and 0.051, respectively. This implies that even the best-performing sector operates below the efficiency level. For the first time in 17 years, the current account of the country recorded a US$ 0.8 billion surpluses from July to April of FY2021. Foreign currency inflows *via* the Roshan Digital Account surpassed

TABLE 3 | Built power production in MW and electrical power in GWh by form.

	Installed capability (MW as of June 2016)	5-year change (%)	Power generation (GWh as of June 2016)	5-year change (%)
Hydel				
WAPDA hydel	6,902	0.06	33,433	0.19
IPPs hydel	214		1,121	1.57
Thermal				
GENCOs with PEPCO	5,762	0.20	14,490	0.15
K-EL own	1874	−0.21	10,323	0.29
IPPs connected with PEPCO	8,696	0.05	44,591	0.06
Connected with K-EL	252	0.00	1,421	0.52
CPPs/SPPs	35	−0.85	390	−0.56
Nuclear				
CHASNUPP	650	0.00	3,854	−0.13
KANUPP	137	0.00	362	−0.21
Renewable energy (wind, solar, and bagasse)				
REpower plants connected with PEPCO	852	851.00	1,549	257.17
Imports from Iran			463	0.56
Total installed capacity of the country	25,374	0.08	111,997	0.14

TABLE 4 | Display transmission and dispatch (T&D) failures in percentage GWh of overall power generated in Pakistan (source NTDC).

DISCO/ Years	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016
TESCO	–	–	–	21.4	19.0
PESCO	36.9	34.2	33.5	34.8	33.8
GEPCO	11.2	10.8	11.0	10.7	10.6
IESCO	9.5	9.4	9.5	9.4	9.1
QESCO	20.9	22.7	28.3	24.4	23.8
LESCO	13.5	13.2	13.4	14.1	13.9
FESCO	10.8	10.8	11.3	11.0	10.2
MEPCO	13.0	14.8	17.5	16.7	16.4
HESCO	27.7	27.3	26.5	27.1	26.5
SEPCO	—	39.5	38.6	38.3	37.7
K-EL	29.7	27.8	25.3	23.7	22.2
Average	19.3	21.0	21.5	21.1	20.3

$1 billion. Remittances of workers increased by 29% from July to April of FY2021, reaching $24.2 billion, which is a high record.

Manufacturing sector

Pakistan, which had practically no large-scale producing units at the time of autonomy in 1947, presently has an appropriate and broad assembling base. The assembling area represented 17% of the total GDP in 2018 and utilized 55.88 million individuals. **Figure 8** shows Electricity production of several years. The cotton material creation and apparel industry is by far the biggest assembling industry in the country, representing 66% of all essential goods and almost 40% of the manpower in the assembling segment in 2018 (Wadho et al., 2019; Baloch et al., 2020). **Table 3** shows built power production in MW and electrical power in GWh by form.

Power sector

The increasing electricity demand is a concern in the power sector of Pakistan. The current demand and supply gap is 3–5 GW, which has resulted in 2.5% GDP loss and unemployment of more than half a million people in industrial sectors as scores of industries have been shut down due to power shortage (Xu et al., 2019). **Table 4** explains the display transmission and dispatch (T&D) failures in percentage GWh of overall power generated in Pakistan. The country produces 60.16% of the total electricity from fossil fuels, and 72% are imported. It has been pointed out that heavy reliance on fossil fuels is the primary reason for power supply failure in Pakistan. Imported fuels are costly; therefore, payments to oil and gas suppliers are often delayed, leading to halting supply (Shah et al., 2019b). In addition to reliance on fossil fuels, the other primary reason for the inadequate supply is the transmission and dispatch (T&D) network (Chandio et al., 2020b; Sun et al., 2020b). Due to poor T&D, electricity losses were calculated to be 20% in 2016–2017. The T&D losses have remained consistent, and no improvement can be observed during these years. The electricity demand in 2016–2017 was higher than 25,000 MW. However, only 12,500 MW could be transmitted, resulting in a massive shortage of electricity; thus, the capability of the T&D network was questioned. As a result, electricity breakdowns are frequent during the summers because the grid cannot manage the maximum electricity supply by distribution companies (NEPRA, 2018).

Mining and quarrying sector

In Pakistan, valuable reserves are carbon, precious stones, chromium, zinc, copper, salt stone, mineral ores, acrylic, granite, blast furnace slag, and silica. The country also mines a variety of precious stones, such as ruby, emerald, and topaz. The Khewra salt mine in Punjab province is the most significant salt deposit worldwide. Baluchistan province and parts of Sindh province have enriched oil and gas reserves. However, these deposits are yet to be fully exploited or explored. In 2006, vast deposits of copper and gold were

TABLE 5 | Slack-based environmental performance index for different sectors in Pakistan.

Sectors	Slack-based environmental performance index									
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Agriculture	0.62	0.6	0.653	0.554	1	0.695	0.699	0.65	1	0.669
Mining and quarrying	0.53	0.506	0.535	0.571	0.588	0.58	0.592	0.619	0.624	0.623
Manufacturing	0.43	0.417	0.405	0.389	0.383	0.416	0.432	0.427	0.451	0.471
Electricity	0.391	0.368	0.353	0.367	0.388	0.429	0.403	0.404	0.405	0.412
Construction	0.504	0.52	0.5	0.526	1	0.534	1	0.58	0.55	0.571
Transport	0.526	0.601	0.502	0.459	0.468	0.492	1	0.444	0.41	0.431

found in the Reko Dig region of Baluchistan. These deposits contain approximately 20 million ounces of gold and 2 billion tons of copper. Reko Dig copper reserves are the seventh-largest in the world (Alemzero et al., 2020b; Sun et al., 2020b; Alemzero et al., 2020a). Pakistan specified its first national mineral policy in 1995, which led to the expansion of mining and quarrying sectors. However, a large quantity of metallic, non-metallic, and industrial rocks has not been explored, and the mineral sector contributed significantly to the GDP of the country until the introduction of the 18th Constitutional Amendment. Under this provision, provinces are extremely autonomous in finding and exploiting their mineral reserves and environmental assets. Consequently, the provinces implemented several projects on their own or cooperated with the federal government or investors to explore and develop these resources.

Transport field

Transportation is one of the leading energy-user sectors of Pakistan. This sector accounted for almost 12% of the overall energy consumption in 2017. In the form of diesel and gasoline, oil is the dominant fuel used in the transport sector, accounting for 78% of the total fuel used in this sector in 2018 (Taghizadeh-Hesary et al., 2021). The remaining 22% fuel requirement was met using compressed natural gas and electricity (HDIP, 2018). In this study, the transport sector included road transport, railways, and aviation. **Figure 2** shows the transportation network across the country (Agyekum et al., 2021; Zhang et al., 2021). There is a network of major highways that connect all main cities. The major rail route of the country runs more than a thousand miles north of Karachi to Peshawar. Another primary line runs northwest from Sukkur to Quetta. Road transport is the most important in the economy of the country, accounting for 13% of Pakistan's GDP (MoF, 2018). Transportation usage has multiplied over the past few decades. The country reported an increased number of vehicles, from 11.77 million vehicles in 2012 to 12.13 million in 2018. Currently, the transportation market is of considerable significance, primarily owing to the introduction of projects on the China Pakistan Economic Corridor (CPEC). These initiatives establish an effective transportation system connecting Pakistan with neighboring countries, including China. **Figure 2** indicates that the growth of the transportation system would positively affect demand extension, flexibility of productive resources, stimulation of business, and jobs (Ahmed et al., 2019).

The construction industry performs an essential task in the socio-economic growth of the country. Subsequently, the entire industry has grown tremendously, hiring more than three million citizens. This market expanded to 9.1% in FY2017 of the preceding year and contributed 2.7% to GDP. The construction industry is huge and is closely linked to industries related to oil, accommodation, communications, automotive, public health engineering, water resources, and dam production (Iqbal et al., 2021b; Chien et al., 2021; Li et al., 2021). Furthermore, the construction industry is a major beneficiary of FDI inflows. The most recent numbers of the Pakistan State Bank show that the gross influx of the construction industry in August 2017 amounted to $35.7 million (Iqbal et al., 2021a; Zhang et al., 2021). Additionally, the government expects that the construction sector will continue to gain strength, leading to higher expenditure on civil service growth links alongside the power sector and economic development of CPEC.

RESEARCH DESIGN

Figure 3 illustrates the research design adopted in this study. The initial process included the selection of indicators (i.e., inputs, useful outputs, and wrong outputs). Indicators were selected based on the significance of indicators and data quality. Then we applied two methods, that is, 1) the Environmental Performance Index (EPI) and 2) the slack-DEA with indexing, to evaluate the difference in the environmental performance of selected economic sectors. Finally, we compared the results obtained from both methods to identify any discrimination in the results.

Methods and materials

Information entropy plays an important role in the slack-based DEA. The DEA is a non-parametric computational tool and, therefore, is used in the data collection to estimate the job or quantify the result or involving different concerns; it is not constrained by any functional form, and is useful for evaluating the DMU performance. A variety of factors have been used extensively for assessment, such as medical benchmark tests (Prior, 2006; Du et al., 2014), company supply chains, and other entities (Chu et al., 1992; Chang et al., 2014). The DEA also offers essential features for assessing ecological performance. As a result, the DEA method is apt to assess the sector-wide environmental performance of Pakistan; however, awareness of environmental DEA technologies is required before introducing the model.

Environmental data envelopment analysis technology

In DEA technology, we find a manufacturing process that produces both good and bad results simultaneously. Suppose that input values, useful outcomes, and bad outcomes are $x \in R^N$, $x \in R^M$, $x \in R^J$. The development technique feature is therefore described as

$$P = (x, y, u) \text{ and x inputs produce} (y, u) \quad (1)$$

Development theories imply that P is small and close and ensures that the ultimate input produces limited results. Moreover, P, input, and useful outcomes are easy and effective in production technologies. For example, $(x,\ y,\ u) \in P$, while $(x^{'} \geq x)$ or $(y^{'} \leq y)$, then $(x,\ y^{'},{'}u) \in P$ or $(x^{'},\ y,\ u) \in P$. The development concept details are available in Färe and Primont (2012).

To establish a feature of developing technologies that generates good and bad outcomes (Zhang et al., 2021).

1) For example, for slightly reusable outcomes, if $(x,\ y,\ u) \in P$, while $one \geq \theta \geq 0$, then $(x,\ y\theta,\ u\theta) \in P$.
2) There are zero-jointing excellent and bad results; for example, if $(x,\ y,\ u) \in P$ while u is nil, then y is nil.

In the first statement, the positive and negative outputs are weakly discarded. This implies that, without reducing good outcomes, weak outcomes cannot be minimized. The methodological framework indicates that the manufacturing method can simply avoid removing bad outcomes. To date, P has a low disability, indicating that polluting equipment is frequently referred to as being scientifically well modeled to produce both strong and poor outputs. It is defined as follows based on the collection of outputs:

$$Q(x) = \{(y, u):\ where((x, y, u) \in P)\} \quad (2)$$

where $Q(x)$ is the technically viable ratings for these input values. In essence, it can be argued that the (y,u) parameter and the (y, u) parameter(x) are regarded as the ecological performance package since in P, high disempowerment of lousy performance is forbidden. Although development technology P is well established, it is not directly used in empirical applications. Thus, an equivalent relationship with P and Shephard separation methods, known to simplify the extra functionality of independent product development, must be established. The gap feature is parametrically and non-parametrically defined; further descriptions are available in Mohsin et al. (2018). Typically, empirical analysis designs and uses linear construction methods in sections for non-parametric configurations. Färe et al. (2004) identified the model as an ecological DEA installed in the DEA framework. Suppose that DMUs are $d = 1, 2, 3, \ldots, D$. For DMU $_d$, inputs, outputs, and bad output data on the vectors are $x_d = (x_{1d}, x_{2d}, \ldots, x_{nd})$, $y_d = (y_{1d}, y_{2d}, \ldots, y_{md})$, and $u_d = (u_{1d}, u_{2d}, \ldots, u_{jd})$, respectively. Further, suppose that $\sum_{j=1}^{j} u_{jd} > 0,\ (d = 1, 2, \ldots, D)$ and $\sum_{d=1}^{D} u_{jd} > 0,\ (j = 1, 2, \ldots, J)$. Environmental continuous scale return (CRS) DEA technologies can be expressed as follows:

$$\begin{aligned} P = \Bigg\{ &(x, y, u):\ \sum_{d=1}^{D} z_d x_{nd} \leq x_n,\ (n = 1, 2, \cdots, N) \\ &\sum_{d=1}^{D} z_d y_{md} \geq y_m,\ (m = 1, 2, \cdots, M) \sum_{d=1}^{D} z_d u_{jd} = u_j, \\ &(j = 1, 2, \cdots, J) z_d \geq 0,\ (d = 1, 2, \cdots, D) \Bigg\} \end{aligned} \quad (3)$$

It can be observed that Model **3** substantiates all the properties stated above (e.g., weak disability between positive and negative results and null-jointness). **Figure 4** displays the environmental DEA development production package in which three DMUs generate one positive output (y) and one weak output (u) from the same quantities of inputs (x). The three product sets are correspondingly written as A, B, and C. The environmental DEA development is denoted by the Q^w (x) performance collection, and OABCD is restricted. When we provide good disposability of low outputs, Q^s (x) will become the OECD region, as shown in **Figure 4**.

Non-radial data envelopment analysis-based climate

Standard DEA methods, such as CCR-DEA, assume that all outcomes for a given input will be maximized (Song et al., 2012). Consequently, the simple manufacturing method generates even poor outcomes as sub-products of positive outcomes, such as many contaminants (Rao et al., 2012). In comparison, better results and fewer bad outcomes should be achieved using minimal inputs (i.e., natural resources). In such situations, conventional DEA methods are not suitable for measuring ecological effectiveness, as poor results need special attention to ensure the more precise outcome of this approach. To date, many DEA methods calculate ecological efficiency by measuring poor performance into the standard DEA system. In addition to these methods, the bad performance method 4) from the DEA proposed by Tyteca (1996) is widely used. In Model 4, the subscript "0" represents the DMU being evaluated in this process. The method offers a systematic and cumulative estimation of ecological sustainability assessment (more than 0 and less than 1). In addition, the environmental factor of this method is the inverse feature of the Shephard distance in (Färe et al., 2004; Zaim, 2004).

$$\begin{aligned} &EPI = \lambda^* = min\lambda \\ &\text{St.} \sum_{d=1}^{D} z_d x_{nd} \leq x_{n0},\ (n = 1, 2, \cdots, N) \\ &\sum_{d=1}^{D} z_d y_{md} \geq y_{m0},\ (m = 1, 2, \cdots, M) \\ &\sum_{d=1}^{D} z_d u_{jd} = \lambda u_{j0},\ (j = 1, 2, \cdots, J) \\ &z_d \geq 0,\ (d = 1, 2, \cdots, D) \end{aligned} \quad (4)$$

Method **4** is beneficial, but slacks in the input and strong outcomes do not exist. That is, while the DMU runs significantly higher, the EPI value will be 1. Only a few of these two DMUs performed well below the maximum effectiveness rate in the DEA technique. Consequently, such deficiencies can be calculated and expressed in EPI (Zhou et al., 2006) using the traditional DEA slack optimization method (Cooper et al., 2007) and presented as follows:

$$\begin{aligned} &\text{s.t.}\sum_{d=1}^{D} z_d x_{nd} + s_n^- = x_{n0},\ (n = 1, 2, \cdots, N) \\ &\sum_{d=1}^{D} z_d y_{md} - s_m^+ = y_{m0},\ (m = 1, 2, \cdots, M) \\ &\sum_{d=1}^{D} z_d u_{jd} = \lambda^* u_{j0},\ (j = 1, 2, \cdots, J) \\ &z_d \geq 0,\ (d = 1, 2, \cdots, D) \\ &s_m^+,\ s_n^- \geq 0 \end{aligned} \tag{5}$$

Method **5** places several limitations on poor results. Such limitations ensure the effective use of DMU_0 in a strictly ecological manner. It even functions ρ^* (a slack performance test), following minimum amounts of DMU_0 contaminants. Therefore, this approach can be considered appropriate for assessing the inefficiency of DMU0. To identify the causes of financial incompetence, slack variables $s_n^-, s_m^+ \{(n = 1, 2, \ldots, N),\ (m = 1, 2, \ldots, M)\}$ may be used. The slack assessment of quality (ρ^*) verifies that $one \geq \rho^* > 0$ achieves monotonous and unit distortion properties. A higher value of ρ^* indicates that DMU_0 is significantly greater in purely financial efficiency. However, if we delete input and input slacks, for example, $s_n^- = s_m^+ = 0$, we obtain $\rho^* = 1$, indicating that two DMUs have no financial deficiencies. Thus, if we combine socio-economic incompetence with mere ecological efficiency, the slack EPI will be achieved.

$$Slack\ Based\ Environmatal\ Performance\ Index = \lambda^* \times \rho^* \tag{6}$$

The slack-based EPI incorporates socio-economic inefficiencies and is also known as an integrated socio-economic performance evaluation index. The slack-based EPI is indeed a structured index because it provides a range of (0,1) and meets the "greater, stronger property." Moreover, compared with environmental effectiveness, the discriminatory energy of the slack-based EPI is typically more important than that of Method **5**. The slack-based EPI may largely represent the views of suppliers and policymakers. Processing companies with reduced socio-economic deficiencies prefer the slack-based EPI, as it penalizes suppliers with high economic deficiencies by ρ^*. In addition, this index encourages inefficient producers to raise their preferred financial efficiency through socio-economic managers and policymakers. It is worth noting that Method **5** requires complicated calculations because it is a partial programming issue. Thus, by applying Charnes–Cooper transformation theories, the process is converted into a linear program. If we let $z_d^{'} = g z_d,\ s_n^- = g s_n^-,\ s_m^+ = g s_m^+$, then we have

$$\begin{aligned} &\rho^* = min\left\{ g - \frac{1}{N}\sum_{n=1}^{N}\frac{s_n^-}{xn_0} \right\} \\ &s.t.\sum_{d=1}^{D} z_d^{'} x_{nd} + S_n^- = g x_{n0},\ (n = 1, 2, \cdots, N) \\ &\sum_{d=1}^{D} z_d^{'} y_{md} - S_m^+ = g y_{m0},\ (m = 1, 2, \cdots, M) \\ &\sum_{d=1}^{D} z_d^{'} u_{jd} = g\lambda^* u_{j0},\ (j = 1, 2, \cdots, J) \\ &g + \frac{1}{M}\sum_{m=1}^{M}\frac{S_m^+}{ym_0} = 1 z_d^{'} \geq 0,\ (k = 1, 2, \cdots, K) \\ &s_m^+,\ s_n^- \geq 0 \end{aligned} \tag{7}$$

Therefore, we can easily obtain the slack-based EPI of DMU0 by solving 4, 6, and 7 models.

Data sources

This study chooses the six most important economic sectors: agriculture, manufacturing, fuel, transport, mining and quarrying, and construction. Three major indicators of economic and environmental performance were selected. Such input and output indicators include the widespread use of primary energy (TPES) as data, GDP as a positive output, and CO_2 as an undesirable output. The units used for the data were TPES, in tons of oil; GDP, in a million Pakistani rupees; and CO_2, in kg. The TPES details were managed by the Oil and Gas Regulatory Authority (OGRA), Centre for Agri-Industrial Technology (CAIT) and World's Resource Institute and Hydrocarbon Development Institute of Pakistan are the sources of CO_2 data, and the Ministry of Finance and the State Bank of Pakistan record GDP data. Initially, we also included SO_2 as a lousy output in our analysis. However, owing to a lack of authenticated data, we excluded SO_2 from our analysis. The data contained in our study are for 10 years, ranging from 2009 to 2019.

RESULTS AND DISCUSSION

Methods were selected based on the significance of indicators and data quality. Then, we applied two methods, and these are 1) the Environmental Performance Index (EPI) and 2) the slack-DEA with indexing, to evaluate the difference in environmental performance of the selected economic sectors.

Information entropy plays an essential role in the slack-based DEA. The DEA also offers essential features for assessing ecological performance. As a result, the DEA method is apt to assess the sector-wide environmental performance of Pakistan; however, awareness of environmental DEA technologies is required before introducing the model.

In the slack-based DEA literature, a context-dependent DEA is developed to provide finer evaluation results by examining the efficiency of DMUs in specific performance levels based upon

DEA efficiency scores. The slack-based EPI may largely represent the views of suppliers and policymakers.

The circular debt of the country is continuously increasing due to the reliance on imported and costly fossil fuel energy usage. Meanwhile, fossil fuel resources are quite limited in the country. Thus, it imports most of the fossil fuels, which are quite costly and, thus, increase the burden on the economy of the country.

Input (I) and output (O) indicators

Table 1 presents illustrative figures for the growth rates of specific factors in different industries between 2009 and 2018. The average use of power in all industries, including transportation, is reduced. The agricultural sector saw the highest decrease in power consumption of 15%, while the energy sector decreased by 5%. Nevertheless, the electric services industry grew by 3% over time. The total GDP for all the industries increased. The largest GDP increase was recorded in the power industry (20%), while the mining and quarrying industry experienced a lower annual GDP increase rate. Carbon dioxide emissions displayed a massive decline in the agricultural industry (i.e., 15%)—additionally, the mining and quarrying industry record reducing CO_2 emissions, with a 2% decrease. **Table 1** also shows that the rest of the sectors (i.e., construction, transportation, manufacturing, and electricity) have increased the CO_2 levels by 1%, 1%, 2%, and 5%, respectively.

Therefore, despite the challenge of meeting the demand for electricity and combating climate change, Pakistan undoubtedly wants to use its immense renewable energy to generate power. It has a large number of sustainable natural resources, including wind, solar, and water resources, while it is the world's 5th highest producer of sugarcane.

According to the 2012–2013 economic survey, livestock inventory amounts to 70 million. Both cultivation and animals contain significant amounts of crop residues and animal waste that can be used as contributions to the biogas network. The current demand for electricity in the country is 25,000 MW, which could increase by 2025 to 40,000 MW. Studies indicate that Pakistan can produce 360,000 MW (Alternative Energy Development Board Pakistan) of wind power (Javed et al., 2016; Khokhar et al., 2017). The existing green energy program accounts for only 1% of the power production of the country, and the government intends to raise it by 2030 to 5%. The hostility of the Pakistani government toward the Pakistan Renewable Energy Target (RET) is quite disappointing. In the Pakistani market (MOPDR), these new technologies should grow (Ehsanullah et al., 2021; Hsu et al., 2021).

Environmental efficiency performance

Based on the data from 2009 to 2018, we first computed the environmental performance of the key sectors of Pakistan using an EPI. We obtained an environmental performance efficiency score using the slack-based EPI. **Table 2** presents the results obtained using both methods. It can be observed from the table that, in contrast to the environmental efficiency of various sectors, the SBEPI has more inequality than the EPI. For example, the EPI of the agricultural and construction sectors is 1 in 2012, and the EPI of the construction and transportation sectors is 1 in 2014. In addition, the EPI of the agricultural sector in 2016 was 1. However, the non-radial SBEPI shows that no country achieved a score of 1 during the study period. In addition to having higher discriminating power, the SBEPI offers a distinct CO_2 efficiency metric relative to the EPI, as it combines economic and environmental inefficiencies into a structured graph. Therefore, SBEPI scores of all sectors are much lower than EPI scores because of sectoral economic inefficiencies. Nonetheless, despite their differences, both measures provide fairly consistent rankings of sectors in terms of CO_2 emissions. The Spearman's rank correlation coefficient between the SBEPI and EPI in the 10 years was more significant than 0.9. This is because the SBEPI is derived from the EPI.

The mining and quarrying sector ranked second by obtaining 0.623 EPI and 0.035 SBEPI. The construction sector had an EPI of 0.571 and SBEPI of 0.029. The manufacturing sector was fourth, with EPI and SBEPI values of 0.471 and 0.02, respectively. The transportation sector received the second last position, achieving 0.431 EPI and 0.014 SBEPI. The least efficient sector in the country was the electricity sector, which obtained 0.412 EPI and 0.011 SBEPI.

The current Pakistani government has mainly emphasized decreasing the electricity shortage and shifting transportation from oil toward renewable energy. Nevertheless, the question is as follows: How can the Pakistani government authorities use the current and conventional policies to overcome electricity shortage? The total electricity mix of Pakistan includes nearly 60% of fossil fuel energy and is part of Kessides (2013a). The circular debt of the country is continuously increasing due to the reliance on imported and costly fossil fuel energy usage. Meanwhile, fossil fuel resources are quite limited in the country. Thus, it imports most of the fossil fuels, which are quite costly and, thus, increase the burden on the economy of the country. As shown in **Figure 8**, much of the energy supply (60.17%) of Pakistan is focused on fossil fuels, supplemented by hydropower (33%), while nuclear, wind, biogas, and solar power account for 5.15%, 0.47%, 0.32%, and 0.03%, respectively. Approximately 3 decades ago, they controlled the electricity system. Subsequently, as shown in **Figure 8**, this pattern moved to thermal power generation to satisfy the rising demand (NEPRA, 2016; Zameer and Wang, 2018) and investment in the power sector (Kessides (2013b)). **Table 3** shows that only after the institutional reforms did the private sector become active and contribute substantially to the scheme (NEPRA, 2016): Pakistan has decided to exploit its vast local gas reserves. Approximately 175 billion tons of lignite are present in the Thar region. The US$ 8.8 billion will be invested in coal power ventures under the China–Pakistan Economic Corridor. The first step of the project would generate 7,560 MW of gas. Construction on the site is ongoing, and a 650 MW coal-fired power plant has been supplying the national grid station since June 2019.

Reliable and safe transmission and distribution of electricity in Pakistan are significant challenges. As shown in **Table 2**, due to poor infrastructure and severe power theft, transmission and distribution losses (**Table 4**) accounted for 20.63% in 2015–2016 (NTDC, 2016). However, compared with that in 2014–2015, all

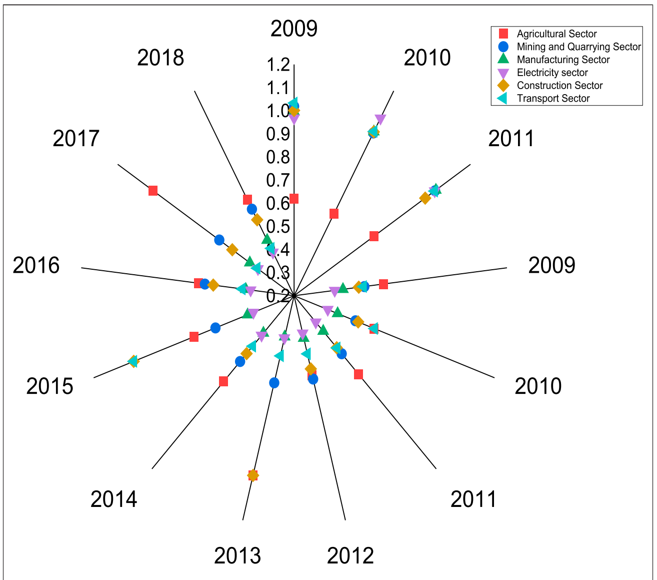

FIGURE 9 | Sensitivity analysis.

DISCO transmission and distribution losses in 2015–2016 were lower. In addition, transmitting ability poses a significant barrier to consumer control. The need for power in 2015–2016 exceeded 25,000 MW, but the transmission and distribution system was only able to provide approximately 12,500 MW (Kato et al., 2013; Shakeel et al., 2016).

Currently, 5,357 biogas plants are deployed in different sections of the world. However, to exploit this abundant renewable resource, Pakistan needs to increase biomass investment to a significant level. This will help mitigate the energy crisis and create employment opportunities with environmental benefits (Butt et al., 2013; Malik and Maqbool, 2017).

Sensitivity analysis

Sensitivity analysis examines whether the findings are affected by specific shifts in parameter weights. In seven more cases, we used the slack-based environmental efficiency index of various economic sectors in different studies in 10 years (from 2009 to 2018) to explain any effect on the outcome. **Table 5** illustrates the various weights used in the seven sectors, while **Figure 9** highlights the effects of these sectors. We can observe in **Figure 9** that agriculture protection is the highest score of all years of research, affecting the economic system of Pakistan. Hence, it can be assumed that the findings are robust.

DISCUSSION

Pakistan has a strategic physical position, and its socio-economic survival is crucial to the total sustainability of its territory (Chandio et al., 2020a; He et al., 2020; Zhang et al., 2020; Yang et al., 2021). In comparison, almost 40% of the country's population lives in extreme poverty. Thus, the country is under enormous strain to boost its socio-economic growth to enhance the quality of life of its population. However, the promotion of economic development has detrimental environmental effects. In this study, the leading six sectors, which are significant contributors to the economy of the country, are specifically selected. The economy is categorized into the input and output of the sectors. These sectors of the study were selected based on the topic's scope and relevance in the extant literature. The location of the country indicates the geographical importance of the country worldwide. Hence, geographical location is strategically crucial in the region (Liu et al., 2020; Chien et al., 2021). Thus, financial stability and economic growth are significant concerns for the region. Pointing out that the full ecological DEA modes anticipate that the boom or lower output in ideal and unwanted performance is relative. This indicates that such modes no longer consider the lack of input and production when comparing the overall ecological performances. However, while these modes have many important theoretical features, one key drawback is that few DMUs will acquire one rating of the use of those modes, making it difficult to compare them substantially. This leads to uncertainty and doubts that even DMUs receiving performance rankings may not be working satisfactorily. Thus, featuring input and output slack will become significant to obtain additional practical performance measures. As such, this observation follows the slack-primarily-based DEA version proposed by Zhou et al. (2006) in the direction of modeling the environmental performance of the financial sectors of Pakistan. The version tests slackness and provides a better specific ability, so the performance ranking is more accurate (Mohsin et al., 2019a; Mohsin et al., 2019b; Mohsin et al., 2019c).

This report provides an integrated ecological performance review covering nearly all significant economic industries. In Pakistan, similar research has never been conducted. Consequently, not much has been done to enhance ecological efficiency, which was low, as observed in this paper. This study provides a significant contribution by presenting an environmental analysis of the major sectors, which are the engine of the economy; it ensures that these sectors are efficient, sufficient, and useful as well as being frontiers (Taghizadeh-Hesary and Yoshino, 2019; Taghizadeh-Hesary and Yoshino, 2020). The innovative contribution of the study entails that these environmental laws are well framed, but not appropriately implemented. Studies at the sectoral level are sporadic in Pakistan and express distinctions in contribution to the literature of the topic. Several scholars have endorsed this study. However, Davis and Kahn (2008) mostly preset evidence that macroeconomic vitality is trended in different countries and different periods, which has its own agitation, as in the United States in the poster situation (Asbahi et al., 2019; Anser et al., 2020; Chandio et al., 2020b; Iram et al., 2020).

CONCLUSION AND POLICY IMPLICATIONS

The environmental efficiency of the primary business fields of Pakistan, such as agriculture, production, mining and quarrying, building, electricity, and transport, have been analyzed. The analysis is conducted based on the three most relevant and significant indicators: TPES as input, GDP as sound output, and CO_2 as lousy output. Two different models were used to measure the environmental performance. These models included an EPI and a non-radial SBEPI. The reason for using the SBEPI is that the conventional EPI can provide an efficiency score of 1 to many comparable DMUs. Therefore, the validity of the comparison between these DMUs is vague. The SBEPI, on the other hand, has higher discriminating power and provides a more comprehensive measure. A comparison of the results confirms that the results obtained from the SBEPI are more reliable than those obtained from the EPI. Overall, the results reveal that the environmental performance of all sectors remained poor.

This, study makes a significant contribution by analyzing the environment of the main sectors that serve as the economy's engine, ensuring that these sectors are efficient, adequate, and helpful, as well as being frontiers. The unique contribution of the study is that environmental regulations are well drafted but ineffectively executed. In Pakistan, sectoral research is scarce, although it significantly adds to the literature on the subject. This study has received support from a number of academicians and researchers (Iqbal et al., 2020; Liu et al., 2020; Taghizadeh-Hesary et al., 2020). Meanwhile, Davis and Kahn (2008) mainly provided evidence that macroeconomic vitality has trended in different nations and times, creating an agitating situation, such as in the United States in the poster situation.

Policy implication

To improve the environmental performance, this study has provided some policy implications. First, it suggests that a government's contribution and role are tangible in strengthening and promoting environmental performance through different means and methods that directly and indirectly positively affect the business and economic system of a country. Furthermore, the government urgently needs to utilize a rating system to incentivize and accelerate environmental performance.

Similarly, the government should punish poorly performing entities. To ensure capacity enhancement and stability of environmental management and related measures, access to information, training of human resources, and infrastructure to enable best performance should be provided. SMEs can undertake such initiatives in a country. Note that progress does not occur overnight but goes through several phases of development to appear as visible progress. Hence, improving environmental performance is a long journey to achievement. However, consistent command and control are required to ensure gradual progress. All necessary steps must be taken, and all required milestones should be followed to avoid procrastination and unnecessary delays in implementation. The approach to measuring ecological quality will play a critical role in determining whether an organization is on the right track to meet the goal. The strategy of using fossil fuels to produce energy in Pakistan has not been successful as a means of resolving power shortages; therefore, it is unlikely that using the same method would yield significant results. The other significant reason not to rely on traditional energy is that Pakistan is ranked among the world's top 10 climatically endangered countries. Thus, Pakistan should shift to renewable resources that abound in it.

- First, the study indicates that the participation and function of the government in improving and boosting environmental performance are tangible by using various methods and techniques that directly and indirectly impact the business and economic system of the country.
- The government must immediately implement a grading system to encourage and expedite environmental performance.
- Providing access to knowledge and training to groom human resources and allow the highest performance is critical to ensuring environmental management's capacity development and stability, and associated actions.
- To prevent procrastination and unnecessary delays in execution, all essential measures must be implemented, and all guidelines must be followed.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

The conceptualization, methodology, and writing of the original draft were performed by YX and MM. The data curation was performed by MM. The formal analysis and software were handled by MM and NI. NI was in charge of the project administration. FT-H investigated and validated the study. NI and FT-H reviewed, edited, and wrote the manuscript.

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frontiers in Energy Research

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How Digital Finance Affects the Continuous Technological Innovation of Chinese Energy Companies?

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This paper discusses the impact of digital finance development on the continuous technological innovation and its mechanism in China's energy companies. Analyzing the data of A-share listed energy companies in China's Shanghai and Shenzhen stock markets from 2011 to 2018, using a fixed effects model, we find that digital finance development played a positive role in stimulating continuous technological innovation in Chinese energy companies. Moreover, we find that risk-taking plays a mediating effect, which is the development of digital finance encourages Chinese energy companies to carry out continuously innovative activities by increasing the level of corporate risk-taking. Finally, we find that in non-state-owned, small and highly externally funded energy companies, digital finance development shows a stronger effect in driving continuous technological innovation in Chinese energy companies through risk-taking. Our results highlight the role of risk-taking as an important mediator in the relationship between digital finance development and continuous technological innovation. It has enlightenment for China to make better use of digital finance to empower energy companies to continue to innovate.

Keywords: digital finance, energy companies, continuous technological innovation, risk-taking, mediating mechanism

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1 INTRODUCTION

The continuous technological innovation of energy companies is important to lead the energy transition and develop sustainable economic. Throughout the historical development trajectory of global innovative companies, most of their growth process cannot be separated from the strong support of financial development (Wang et al., 2019). Continuous technological innovation is a long-term, high-risk activity with large capital requirements, irreversible processes, and uncertain output. The traditional financial system with commercial banks generally has a low level of risk-taking (Huang, 2018), which cannot match high-risk continuous technological innovation activities. This makes innovative companies with development potential often meet "financial discrimination" problems. Therefore, discussing how to provide stable and adequate financial support for continuous technological innovation of energy companies has become a major theoretical and practical problem of governments, companies and academia.

The dilemmas faced by traditional financial development need to be addressed by innovative financial models. Driven by emerging technologies such as big data, cloud computing, and the

Internet, China's digital finance has achieved rapid development in recent years. Digital finance refers to the use of digital technology by traditional financial institutions and Internet companies to realize financing, payment, investment and other new financial business models (Tang et al., 2020). As a new service format with high efficiency and low price, digital finance has the advantages of cross-temporal, low-cost, and information visualization (Huang, 2018). It breaks through many limitations of traditional financial and provides new ideas for making up for the shortcomings of traditional financial services (Huang, 2018). Given the relatively short history of digital finance, there is little literature on whether and by what mechanisms digital finance helps to incentivize corporate innovation. In the evaluation of the impact effects, existing literature mainly provides two viewpoints. One view holds that the "inclusive" and "grassroots" characteristics of digital finance can significantly promote corporate innovation, especially small and micro enterprises (Tang et al., 2020; Liang and Zhang, 2019; Li et al., 2020; Yao et al., 2021). The other point of view is that the development history of digital finance is short, and it is difficult to effectively match digital financial products with innovative activities (Gomber et al., 2018). In terms of mechanism, existing literature reveals that digital finance can stimulate enterprise innovation through financing channels including financing constraint mitigation and financing cost reduction (Liang and Zhang, 2019; Li et al., 2020; Tang et al., 2020; Chen and Yoon, 2021).

In conclusion, the existing literature reveals that digital finance may stimulate corporate innovation, and proposes financing mitigation and financing cost reduction as specific mechanisms. However, there are still some shortcomings in the existing literature that need to be filled. First, existing research focuses on general technological innovation, and has not analyzed the impact of digital finance on continuous technological innovation. Second, the existing research only analyzes the financing mechanism, and lacks the discussion of other mechanisms. Third, most of the samples used in existing researches are full samples including all industries, they do not take into account the effects of industry heterogeneity.

Specifically, energy technology innovation activities tend to have higher uncertainty and risk (Noailly and Smeets, 2016), and continuous technological innovation by energy companies requires more long-term and continuous investment (Yu and Fan, 2021). Therefore, the continuous innovation of energy companies is more dependent on financial support, and digital finance is more likely to play a role in making up for the insufficiency of traditional finance. Meanwhile, the innovation process consists of four stages: innovation willingness-innovation resource input-innovation management-Innovation output. The lack of any stage will lead to the inability of innovation to be carried out effectively. For high-risk and long-term projects such as continuous technological innovation, before companies decide to invest "real money", they must first stimulate their willingness to innovate. Increasing the level of risk taking can help stimulate a firm's willingness to innovate (García-Granero et al., 2015; Roper and Tapinos, 2016). Therefore, stimulating risk-taking is the front-end mechanism of promoting corporate innovation. This paper empirically examines the impact of digital finance development on the continuous technological innovation of Chinese energy companies, and further examines the mechanism from the perspective of risk-taking. It can further expand related research in the field of financial development and continuous technological innovation, and at the same time, it has important policy implications for Chinese energy companies to make better use of digital finance to enhance continuous innovation.

This paper discusses the impact of digital finance development on the continuous technological innovation and its mechanism in China's energy companies. Compared with existing research, the marginal contribution of this research is mainly reflected in three aspects: First, we provide a pioneering discussion how the development of digital finance affects the continuous technological innovation of Chinese energy companies. With China's increasing focus on ecological issues, continuous technological innovation in energy companies has become a key concern for society. Given the scale of digital finance development in China and its leadership in world technological practice, it is important to select Chinese energy companies to study the impact of digital finance development on their continuous technological innovation. In recent years, some literature has begun to focus on the impact of digital financial development on general technological innovation, but there is no literature that takes continuous technological innovation as the research object. We found that the development of digital finance helps to stimulate the continuous technological innovation of Chinese listed energy companies, indicating that digital finance can facilitate the innovation transformation of energy companies and contribute to the implementation of China's innovation-driven strategy.

Second, this paper extends the literature by empirically exploring the mechanisms of risk-taking to explain how digital finance development affect continuous technological innovation in Chinese listed energy companies. Existing studies have focused on testing the impact of digital finance on general technological innovation. As for the mechanism, the discussion mainly focuses on the mitigation of financing constraints and the reduction of financing costs. This study reveals that the development of digital finance can motivate Chinese energy companies to continue to innovate by increasing their level of risk-taking. Therefore, we fill the gap in the research on risk-taking mechanism.

Finally, this paper examines individual differences between state-owned and non-state-owned enterprises, small and large enterprises, high dependence on external finance and low dependence on external finance. Our results show that in non-state-owned energy companies, small energy companies, and energy companies that highly rely on external funds, digital financial development is more effective in promoting continuous technological innovation through risk-taking mechanisms. This paper clarifies the conditions and boundaries of the risk-taking mechanism that digital finance affects the continuous innovation of Chinese energy companies.

The rest of this paper is organized as follows. **Section 2** is literature review and research hypotheses. **Section 3** includes data

TABLE 1 | Related literature review.

	General technological innovation		Continuous technological innovation	
	Impact effects	Mechanism	Impact effects	Mechanism
Traditional Finance	Positive impact: Zhang et al. (2019), Hsu et al. (2020), Ling et al. (2020) Negative impact: Hsu et al. (2020), Ling et al (2020) No impact: Brown et al. (2013)	Financing channels: Zhang et al. (2019), Moshirian et al. (2021) Risk channels: Moshirian et al. (2021) Governance channels: Luong et al. (2017), Moshirian et al. (2021)	Positive impact: Gan and Ma (2021)	—
Digital Finance	Positive impact: Tang et al. (2020); Li et al. (2020), Psarrakis and Kaili (2019), Yao et al. (2021) No impact: Gomber et al. (2018)	Financing channels: Tang et al. (2020), Liang and Zhang (2019), Li et al. (2020), Chen and Yoon (2021)	—	—

sources, variable definitions and empirical model settings. **Section 4** presents the empirical results. **Section 5** demonstrates the heterogeneous effects from enterprises' attributes. Finally, **Section 6** concludes.

2 LITERATURE REVIEW AND RESEARCH HYPOTHESIS

2.1 Literature Review

Continuous technological innovation refers to the nature and tendency of companies to have feedback, accumulation and lock-in effects in terms of technology, etc., to keep subsequent technological innovation activities going over time (Geroski et al., 1997). Continuous technological innovation not only contributes to long-term economic growth, but is also important for firms to build dynamic competitive advantage (Kang et al., 2017). Allen et al. (2005) argues that because the competitive environment in product markets is constantly changing, firms must sustain innovation through long-term capital investment to maintain a competitive advantage. Financial markets are an important source of funding for continuous technological innovation. As indicated in **Table 1**, existing literature has extensively explored the impact of traditional financial development on the general technological innovation of enterprises, and the theoretical views obtained from the research mainly include three categories: 1) Commercial bank credit and commercial bank competition can make a positive impact on the quantity and quality of corporate innovation by alleviating financing constraints (Zhang et al., 2019); 2) The development of the credit market has no significant impact on corporate innovation investment (Brown et al., 2013); 3) The credit market will have a negative impact on innovative activities in high-tech industries that rely on external financing (Hsu et al., 2020). How the stock market, as a direct financing channel, affects corporate innovation has also attracted scholars' attention. How the stock market as a direct financing channel affects corporate innovation has also attracted scholars' attention. Most of the existing studies believe that the stock market has a more positive impact on enterprise innovation through the risk redistribution function, the pricing function and the unsecured feature (Levine and Schmukler, 2006; Brown et al., 2009; Brown et al., 2013; Zhong and Wang, 2017). Moshirian et al. (2021) and Luong et al. (2017) proposed that the mechanism of stock market liberalization to promote innovation may include financing channels, risk channels and corporate governance channels. There is little literature on how traditional financial markets affect continuous technological innovation. Gan and Ma (2021) suggest that strengthen credit support for SMEs, reduce financial discrimination in the credit market, and ensure that small and micro enterprises (SMEs) have a fair and favorable competitive environment, thereby promoting continuous technological innovation of SMEs.

As for digital finance, existing literature has not discussed whether it will affect the continuous technological innovation of enterprises. At present, it is only analyzed whether the development of digital finance can empower the general technological innovation, and the results are divergent. Some studies believe that the development of digital finance is conducive to promoting corporate innovation. Zhang and Chi (2018) believe that digital finance can significantly promote the innovation input and innovation frequency of SMEs. Psarrakis and Kaili (2019) found that digital finance can enhance the willingness of companies to initiate cutting-edge technology projects. Liang and Zhang (2019) found that digital finance can promote the innovation output of SMEs. Li et al. (2020) found that digital financial inclusion can significantly promote the innovation of Chinese companies from the perspective of inclusiveness. Tang et al. (2020) found that the development of digital finance has a better and more stable effect on the technological innovation of enterprises, and this promotion effect is universal, especially has a significant impact on the technological innovation of enterprises in areas with weak traditional financial development. Yao et al. (2021) find that digital inclusive finance contributes to innovation, reflected in the number of patents. However, some studies have pointed out that digital finance is difficult to make a significant impact on innovation activities (Gomber et al., 2018). With the deepening of research, the mechanism by which the digital finance affects enterprise innovation is also an important topic that academic try to discuss. Existing literature reveals that digital finance can stimulate enterprise innovation through financing channels including financing constraint mitigation and financing cost reduction. Specifically, Liang and Zhang (2019) found that the development of digital inclusive finance can reduce the cost of debt financing and ease external financing constraints for SMEs, which in turn boosts firms' innovation output. Li et al. (2020) finds that digital finance can significantly promote corporate innovation by alleviating financing constraints and increasing the amount of tax rebates. Chen and Yoon (2021) demonstrate that digital finance can help stimulate innovation by easing financing constraints and reducing debt financing costs.

2.2 Research Hypothesis

Existing literature indicates that risk-taking is an important driving factor for stimulating the enthusiasm of corporate innovation. R&D and innovation investment has a high degree of risk and uncertainty and is different from general scale investment. The typical feature of risk-taking is the willingness to venture into unknown areas for exploration, which coincides with the high risk and high uncertainty of R&D and innovation projects (Guo and Jiang, 2020). The willingness to take risks will increase the possibility of the creation and implementation of creative ideas (Salvi and Bowden, 2020). Therefore, raising the level of risk-taking is important to stimulate the enthusiasm of corporate innovation. Guo and Jiang (2020) found that companies with high risk-taking levels will respond to market changes with a positive attitude through a study of Chinese manufacturing companies. They are more willing to take action to find new technology and market opportunities in the external environment, and then invest resources into the long-term risky projects with high returns and high probability of failure. Games and Rendi (2019) analyzed the data of 165 small business owners in Indonesia's creative industry and found that risk-taking is an important driving factor affecting the innovation of small and medium companies, which also plays an important role in reducing negative innovation behaviors. Cai et al. (2015) researched 235 new companies in China and found that risk-taking positively regulates the relationship between market orientation and innovation radicalness, and risk-taking has a positive impact on radical innovation of new companies. In addition, risk-taking can also bring more resource support for companies. Hilary and Hui (2009) found that risk-taking companies are more likely to be favored by funds, and R&D and innovation activities can be better funded, which will further strengthen corporate innovation. On the other hand, Castillo-Vergaraa and García-Pérez-de-Lemab (2021) found that risk-taking helps small and medium-sized companies to transform creativity into product innovation based on the study of 139 small and medium-sized industrial companies in Chile. Nguyen and Dang (2019) found that risk-taking is an intermediary variable for bond liquidity to affect corporate innovation, and the increase in risk-taking level can promote the increase of corporate innovation output. It can be seen that risk-taking also has a positive impact on corporate innovation performance.

Finance is a core component of the corporate innovation environment. Its development helps to improve the external financing environment, ease financing constraints and optimize the allocation of financial resources by stimulating corporate risk-taking willingness (Chen, 2020; Li et al., 2013; Yan et al., 2019). Compared with traditional finance, digital finance has the advantages of lower cost, faster speed and wider services (Huang and Huang, 2018), which has a more positive impact on corporate risk-taking. First of all, digital finance relies on the Internet and big data technology to absorb social idle funds and turn them into effective financial supplies. It provides companies with diversified financing channel options in addition to traditional finance, broadening the sources of corporate funds and stabilizing the corporate capital chain. It helps to increase the level of corporate risk-taking from the financing supply side. Secondly, the inclusive characteristics of digital finance can reduce the cost and threshold for companies to obtain financial services (Guo and Jiang, 2020). At the same time, digital finance will also force the transformation and upgrading of traditional financial institutions, and optimize the products of traditional financial institutions. The structure provides more convenient and low-cost credit products for financing companies (Huang and Huang, 2018), which helps to increase the level of corporate risk-taking from the perspective of financing threshold and cost. Finally, digital finance relies on powerful information collection, information processing, information screening. Risk discrimination capabilities rely on big data technology to achieve rapid information matching between different entities. They usually implement more accurate risk assessments for companies (Huang, 2018). The information asymmetry in the process, the avoidance of adverse selection and moral hazard problems in the financial market (Demertzis et al., 2018), and the improvement of corporate risk management capabilities (Norden et al., 2014) can increase the level of corporate risk-taking.

Based on the above analysis, this research concludes that the digital finance development can promote the continuous technological innovation of energy companies. The risk-taking plays an intermediary role in the process of digital finance influencing the continuous technological innovation of companies. The digital finance development encourages companies to carry out continuous R&D and innovation activities more actively by increasing the level of corporate risk-taking.

3 RESEARCH DESIGN

3.1 Data Sources

The digital financial inclusion index is contained from 2011 to 2018, and we download the data from China's energy industry listed companies. This paper discusses the impact of digital finance development on the continuous technological innovation and its mechanism in China's energy companies by cross-level matching. We collect prefecture-level city-level digital financial inclusion index from the Digital Finance Research Center of Peking University; We gather continuous technological innovation, finance and corporate governance index from CSMAR database. In addition, we perform basic processing on some outliers in the sample, such as deleting samples values that cannot be obtained. After excluding ST enterprises, we finally collect 1,388 observations in enterprises-year level.

3.2 Variable Setting

3.2.1 Continuous Technological Innovation

Existing research mainly measures the continuous technological innovation of companies based on the perspective of input or output. Input indicators mainly include total R&D expenditure and R&D intensity (total R&D expenditure accounts for the proportion of operating income), etc. The output indicators mainly include patent applications or authorizations, and intangibles. The increase in assets accounts for the ratio of the company's total assets at the end of the period. Since innovation output can reflect a company's innovation capability, we mainly measure the continuous technological innovation of energy companies from the perspective of output. With reference to the research of Xu et al. (2020), this paper uses **Eq. 1** to measure the level of continuous technological innovation of Chinese energy companies.

$$CTI_t = \frac{OP_t + OP_{t-1}}{OP_{t-1} + OP_{t-2}} \times \frac{OP_t - OP_{t-1}}{2} \quad (1)$$

In **Eq. 1**, OP_t, OP_{t-1} and OP_{t-2} represent the number of invention patent applications of the sample companies in t, t-1 and t-2, respectively.

3.2.2 Digital Financial Development (*DFindex*)

At present, relevant studies mainly adopt two methods to measure the degree of digital finance development: one is to match the relevant keywords of digital finance (digital finance, internet finance, financial technology, equity crowdfunding financing, digital currency, blockchain, smart financial contracts and smart investment advisors, etc.) with the name of the region to obtain the search term of "digital financial keywords + region". The number of news items retrieved in Baidu News is used as the proxy variable of the regional digital financial development level (Li et al., 2020). The second is to use the Digital Finance Index released by the Digital Finance Research Center of Peking University to measure the level of regional digital finance development (Xie et al., 2018; Tang et al., 2020). In comparison, the Digital Financial Inclusive Index released by the Digital Finance Research Center of Peking University has the advantages of support by big data technology, which spans long-time and covers wide area (Guo and Jiang, 2020). Therefore, this study adopts the prefecture-level city-level digital financial inclusion index to measure the digital financial development environment.

3.2.3 Risk-Taking Level

On the basis of relevant studies, we use corporate risk-taking to analyze the willingness to invest in projects with uncertain returns (Zhou et al., 2019). Existing research shows that companies operating under higher investment risks have greater volatility in their return on investment (John et al., 2008). Therefore, at present, researchers generally use earnings volatility to measure the level of corporate risk-taking. This study refers to the measurement method of Boubakri et al. (2013), and uses the fluctuation range of the ratio of earnings before interest and taxes (EBIT) to total assets to measure the level of corporate risk taking. The calculation method is shown in **Eq. 2**:

$$Risktake_{it} = Max\left(\frac{EBIT_{it}}{Asset_{it}}\right) - Min\left(\frac{EBIT_{it}}{Asset_{it}}\right) \quad (2)$$

Among them: i is the company serial number, t is the year, $EBIT_{it}$ is the profit before interest and tax, and $Asset_{it}$ is the total assets at the end of the year. $EBIT_{it}$ does superposition calculations for four consecutive years, $Asset_{it}$ does not perform superposition calculations.

3.2.4 Control Variables

In this study, control variables include the size of the company (*Size*), main business income (*Mturnover*), proportion of independent directors (*Indratio*), corporate growth capability (*Growth*), merger of two positions (*Merge*), capital intensity (*Capital*), management shareholding ratio (*Msh*), company age (*Age*), corporate profitability (*Roa*), year (*Year*) and industry (*Ind*) (Zhang and Chi, 2018).

The definitions and descriptive statistics of the main variables in this paper are shown in **Table 2**.

3.3 Model Setting

3.3.1 The Test Model for the Impact of the Development of Digital Finance on the Continuous Technological Innovation

According to Gan and Xu (2019), the panel data fixed-effect approach is useful to exclude the influence from the unobserved and invariable enterprises' heterogeneity. This approach also alleviates the endogenous problems caused by missing variables, which could not be overcome by other methods such as dynamic GMM methodologies (Gan and Xu, 2019). The Hausman test was used to select a suitable estimation model, and the results showed that the fixed effect model was most reliable and valid. Specifically, we construct a panel data fixed-effect model as **Eq. 3** for estimating the impact of the development of digital finance on the continuous technological innovation of Chinese energy companies:

$$CTI_{it} = \alpha_0 + \alpha_1 DFindex_{jt} + \sum Controls_{it} + \sum Year + \sum Ind + \varepsilon_{it} \quad (3)$$

Where the subscripts i, j and t represent the serial number of the company, prefecture-level city and year, respectively. The dependent variable CTI_{it} represents the continuous technological innovation level of the company. The independent variable $DFindex_{jt}$ represents the level of digital finance development at the prefecture-level city level. $Controls_{it}$ represents a number of control variables defined in the previous section. *Year* and *Ind* represent year and industry effects, respectively. α_0, α_1, and α_2 represent parameters to be estimated. ε_{it} is a random error term. This study is mainly based on the estimation results of α_1 to determine the impact of the development of digital finance. When α_1 is significantly positive (negative), it means that digital finance development has the effect of promoting (inhibiting) the continuous technological innovation of Chinese energy companies; otherwise, the impact of digital finance development on the continuous technological innovation is not significant.

TABLE 2 | Descriptive statistics of variables.

Variable name	Measurement methods and units	Maximum	Minimum	Mean	References
CTI	$CTI_t = \frac{OP_t+OP_{t-1}}{OP_{t-1}+OP_{t-2}} \times \frac{OP_t-OP_{t-1}}{2}$	67.454	–18.309	2.237	Xu et al. (2020)
DFindex	Peking university digital inclusive Finance Index	177.143	76.000	266.000	Li et al. (2020)
Risktake	$Risktake_{it} = Max\left(\frac{EBIT_{it}}{Asset_{it}}\right) - Min\left(\frac{EBIT_{it}}{Asset_{it}}\right)$	0.026	0.000	0.057	Boubakri et al. (2013)
Size	Ln (Total assets)	22.767	20.989	23.936	Liang and Zhang (2019)
Mturnover	Ln (Total operating income–Other operating income)	22.420	20.294	23.738	Raymond and St-Pierre (2010)
Merge	The value is 1 if the Chairman is also the Managing Director, otherwise the value is 0	0.071	0.000	1.000	Tang et al. (2020)
Capital	Total assets/Main business income	1.485	0.887	2.581	Mao and Zhang (2018)
Indratio	The number of independent directors/The number of board members	0.338	0.333	0.364	Liang and Zhang (2019)
Growth	Growth rate of revenue from main business	0.323	–0.561	3.082	Zhang et al. (2018)
Msh	Number of shares held by management/Total share capital (%)	4.821	0.000	33.549	Zhang et al. (2018)
Age	Statistical year minus the year of incorporation (year)	14.000	10.000	18.000	Nguyen and Dang (2019)
Roa	Net profit/Total assets (%)	0.037	–0.026	0.187	Liang and Zhang (2019)

TABLE 3 | Estimation of the impact of digital finance development on the continuous technological innovation of Chinses energy companies.

Variables	Fixed-effect model	Fixed-effect model	Instrumental variable method: The first stage	Instrumental variable method: The second
	(1)	(2)	(3)	(4)
	CTI	*CTI*	*DFindex*	*CTI*
DFindex	0.004[a]	0.011[b]	—	0.012[a]
	(5.850)	(2.546)	—	(2.810)
Ipr	—	—	0.910[a]	—
	—	—	(47.435)	—
Size	—	0.605[a]	–1.655[a]	1.027[a]
	—	(3.607)	(–2.775)	(8.468)
Mturnover	—	–1.349[a]	2.447[a]	–1.535[a]
	—	(–8.526)	(4.572)	(–14.035)
Merge	—	–0.185	1.439[a]	0.146
	—	(–1.501)	(2.719)	(1.357)
Capital	—	0.258[a]	0.158[a]	0.245[a]
	—	(31.031)	(3.041)	(23.238)
Indratio	—	2.108[b]	0.166	1.961[b]
	—	(2.132)	(0.037)	(2.143)
Growth	—	0.017	–0.134	–0.001
	—	(0.839)	(–0.985)	(–0.052)
Msh	—	–0.007	0.049[a]	0.005[b]
	—	(–1.489)	(4.040)	(1.980)
Age	—	–0.130	0.028	–0.035[a]
	—	(–0.658)	(0.572)	(–3.480)
Roa	—	–2.158[a]	–3.056	2.948[a]
	—	(–2.780)	(–0.662)	(3.158)
Constant	3.264[a]	17.645[a]	6.025	10.740[a]
Year	No	Yes	Yes	Yes
Ind	No	Yes	Yes	Yes
Observations	1,388	1,388	1,204	1,204
R^2	0.010	0.318	0.934	0.395

[a]*Note: (1) significant at the 1% statistical levels.*
[b]*significant at the 5% statistical levels.*
[c]*significant at the 10% statistical levels.*
(2) t-values in parentheses.

3.3.2 The Test Model for Risk-Taking Mechanism

Referring to the method proposed by Wen and Ye (2014), this paper constructs the models shown in **Eqs 4–6**, and tests the mediating effect of corporate risk-taking:

$$CTI_{it} = \alpha_0 + \alpha_1 DFindex_{jt} + \sum Controls_{it} + \sum Year + \sum Ind + \theta_{it} \tag{4}$$

$$Risktake_{it} = \beta_0 + \beta_1 DFindex_{jt} + \sum Controls_{it} + \sum Year + \sum Ind + \varphi_{it} \quad (5)$$

$$CTI_{it} = \gamma_0 + \gamma_1 DFindex_{jt} + \gamma_2 Risktake_{it} + \sum Controls_{it} + \sum Year + \sum Ind + \delta_{it} \quad (6)$$

The $Risktake_{it}$ represents the intermediate variable corporate risk-taking level. We construct Model (4) to explore the total impact of the digital finance development on the continuous technological innovation. The coefficient α_1 measures the size and significance of the total impact. The coefficient β_1 in model (5) reflects the influence of the development of digital finance on the level of corporate risk-taking. The coefficient γ_1 in model (6) reflects the direct effect of the development of digital finance on the continuous technological innovation, and $\beta_1 \times \gamma_1$ reflects the effect intensity of the development level of digital finance that affects the corporate continuous technological innovation through corporate risk-taking.

4 EMPIRICAL RESULTS AND ANALYSIS

4.1 Test Results of the Impact of the Development of Digital Finance on the Continuous Technological Innovation

Columns (1) and (2) of **Table 3** report the benchmark results of the impact of the development of digital finance on the continuous technological innovation of Chinese energy companies. The column (1) shows the estimation result without considering any control variables. The estimated coefficient of *DFindex* is 0.004 (t statistic is 5.850), which is highly significant at the 1% level. The column (2) shows the estimated results considering the control variables. The estimated coefficient of *DFindex* is 0.011 (t statistic is 2.546), which is significant at the 5% level. It can be seen that, regardless of whether the control variables are considered, the regression coefficients between *DFindex* and *CTI* are significantly positive, indicating that the development level of digital finance is significantly positively correlated with the continuous technological innovation intensity of Chinese energy companies. By comparing with the existing literature, it can be found that digital finance can make up for the deficiencies of traditional finance in supporting enterprise innovation to a certain extent. It has been argued that bank credit is biased towards supporting low-tech innovation (Zhang et al., 2018). Some studies even found that bank credit will hinder the technological innovation of enterprises (Zhang et al., 2019; Ling et al., 2020). However, our findings suggest that digital finance can well support the continuous innovation of Chinese energy companies. This shows that, with its advantages of “crossing time and space, low cost, and information visualization”, digital finance has broken through many limitations of traditional financial services and provided a new source of financing options for enterprises to continue scientific and technological innovation.

TABLE 4 | Estimations of the risk-taking mechanism.

Variables	(1)	(2)	(3)
	CTI	*Risktake*	*CTI*
DFindex	0.011[b]	0.001[a]	0.011[b]
	(2.546)	(2.932)	(2.493)
Risktake	—	—	0.378[b]
	—	—	(2.017)
Size	0.605[a]	−0.013[c]	0.610[a]
	(3.607)	(−1.691)	(3.635)
Mturnover	−1.349[a]	0.005	−1.351[a]
	(−8.526)	(0.625)	(−8.537)
Merge	−0.185	−0.006	−0.183
	(−1.501)	(−1.040)	(−1.483)
Capital	0.258[a]	0.000	0.258[a]
	(31.031)	(1.194)	(31.004)
Indratio	2.108[b]	0.107[b]	2.068[b]
	(2.132)	(2.339)	(2.090)
Growth	0.017	0.003[a]	0.016
	(0.839)	(2.746)	(0.790)
Msh	−0.007	−0.000	−0.007
	(−1.489)	(−1.331)	(−1.465)
Age	−0.130	−0.023[b]	−0.122
	(−0.658)	(−2.526)	(−0.613)
Roa	−2.158[a]	−0.347[a]	−2.027[b]
	(−2.780)	(−9.661)	(−2.576)
Constant	17.645[a]	0.437[a]	17.480[a]
	(4.925)	(2.639)	(4.874)
Year	Yes	Yes	Yes
Ind	Yes	Yes	Yes
Observations	1,388	1,388	1,388
R^2	0.318	0.146	0.319

Note: (1) [a]significant at the 1% statistical levels.
[b]significant at the 5% statistical levels.
[c]significant at the 10% statistical levels.
(2) t-values in parentheses.

We test the instrumental variable (IV) to exclude the effect of endogeneity. We select Internet penetration rate (*Ipr*) as an instrumental variable for digital financial development according to Xie et al. (2018). We also adopt 2SLS instrumental variable regression method to alleviate the endogenous problems that may exist in the empirical model. The two-stage estimation results based on the instrumental variable method are reported in columns (3) and (4) of **Table 3** respectively. In the first stage estimation results shown in column (3), the Internet penetration rate *Ipr* is highly correlated with the development level of digital finance *DFindex* (coefficient is 0.910, t statistic is 47.435). The empirical test result shows that the regression coefficient of the Internet penetration rate is significantly positive. According to the second-stage estimation results shown in column (4), the regression result shows that the regression coefficient of instrumental variable is significantly positive at the level of 1%. These results indicate that the results obtained from the previous tests are less affected by endogeneity problems.

The benchmark regression and instrumental variable regression test results show that the development of regional digital finance does have a significant positive effect on the continuous technological innovation of Chinese energy companies.

TABLE 5 | Estimations of the risk-taking mechanism: robustness test.

	(1)	(2)	(3)
Variables	*CTI*	*Risk*	*CTI*
DFindex	0.011[b]	0.000[a]	0.011[b]
	(2.546)	(2.632)	(2.500)
Risk	—	—	0.654[b]
	—	—	(2.000)
Size	0.605[a]	−0.007	0.610[a]
	(3.607)	(−1.638)	(3.634)
Mturnover	−1.349[a]	0.001	−1.350[a]
	(−8.526)	(0.309)	(−8.532)
Merge	−0.185	−0.002	−0.184
	(−1.501)	(−0.586)	(−1.491)
Capital	0.258[a]	0.000	0.258[a]
	(31.031)	(1.151)	(31.005)
Indratio	2.108[b]	0.062[b]	2.068[b]
	(2.132)	(2.376)	(2.090)
Growth	0.017	0.001[a]	0.016
	(0.839)	(2.748)	(0.791)
Msh	−0.007	−0.000	−0.007
	(−1.489)	(−0.737)	(−1.476)
Age	−0.130	−0.013[b]	−0.122
	(−0.658)	(−2.439)	(−0.616)
Roa	−2.158[a]	−0.186[a]	−2.036[a]
	(−2.780)	(−9.105)	(−2.592)
Constant	17.645[a]	0.276[a]	17.465[a]
	(4.925)	(2.933)	(4.868)
Ind	Yes	Yes	Yes
Year	Yes	Yes	Yes
Observations	1,383	1,388	1,383
R^2	0.318	0.143	0.319

[a]*Note: (1)significant at the 1% statistical levels.*
[b]*significant at the 5% statistical levels.*
[c]*significant at the 10% statistical levels.*
(2) t-values in parentheses.

4.2 Test Results of Risk-Taking Mechanism

In this paper, we use the stepwise regression model of **Eqs 4–6** to further empirically test whether digital finance affects the continuous innovation of Chinese energy companies through corporate risk-taking, and the test results are reported in **Table 4**. According to the test procedure of the mediation effect, the first step is to test the total impact of the development of digital finance on continuous technological innovation. The test results in the column (1) of **Table 4** show that the estimated coefficient of *DFindex* (α1 = 0.011, t = 2.546) is significantly positive, indicating that the total impact effect of digital finance development on continuous technological innovation is significantly positive. The second step is to examine the impact of digital finance development on mediator—risk-taking levels. The test results in column (2) of **Table 4** show that the estimated coefficient of *DFindex* (β1 = 0.001, t = 2.932) is highly significantly positive at the 1% level, indicating that the development of digital finance helps to increase the level of corporate risk-taking. The third step is to test whether risk-taking plays a mediating effect in the process of digital financial development affecting continuous technological innovation of Chinese energy companies. The test results in column (3) of **Table 4** show that the estimated coefficients ($\gamma1$, $\gamma2$) of *DFindex* and *Risktake* are 0.011 and 0.378, respectively, and both of them are significant at the statistical levels of 5%, indicating that risk-taking plays a significant mediating effect in the process of digital financial development affecting the continuous technological innovation of Chinese energy companies.

Existing literature proposes that the development of traditional financial markets such as stock market liberalization spurs innovation through encouraging firms' risk-taking activities (Moshirian et al., 2021). Our findings are consistent with their conclusion that the digital finance also encourages risk-taking and incentivize enterprises to innovate continuously. Some recent literature finds that digital finance can stimulate corporate innovation through financing channels such as ease of financing constraints and lower financing costs (Li et al., 2020; Chen and Yoon, 2021). This paper finds that the development of digital finance has the effect of encouraging firms' risk-taking activities, and thus discovers a new mechanism for the impact of digital finance on continuous innovation.

Referring to the measurement of John et al. (2008) and Boubakri et al. (2013), this paper uses **Eq. 7** to make an alternative measurement of the level of corporate risk-taking:

$$Risktake_{it} = \sqrt{\frac{1}{T-1}\sum_{t=1}^{T}\left(\frac{EBIT_{it}}{Asset_{it}} - \frac{1}{T}\sum_{t=1}^{T}\frac{EBIT_{it}}{Asset_{it}}\right)^2} \Bigg| T = 4 \quad (7)$$

In order to further test the reliability of the research results, we select alternative variables and put them into the model for the regression analysis again. The test results are shown in **Table 5**. From the test results shown in **Table 5**, we can see that the regression results are consistent with the original results. Therefore, the risk-taking mechanism is robustness.

5 FURTHER RESEARCH

In order to explore the specific conditions and boundaries for the digital finance development on the continuous technological innovation of energy companies through risk-taking, we further examine the impact of situational factors such as the nature of ownership, scale, and external financing dependence based on the corporate dimension.

5.1 Analysis of the Moderating Effect of Property Rights

According to the nature of property rights, our research sample is divided into two groups: state-owned energy companies and non-state-owned energy companies, and then the grouping test is carried out. The results of the grouping test are shown in **Table 6**. According to the results reported in columns (1)–(3) of **Table 6**, the estimated coefficient of *DFindex* to *Risktake* is 0.001, which is significant at the 5% level. However, the estimated coefficient of *DFindex* to *CTI* is −0.004 and not significant. This result shows that the digital finance development can increase the level of risk-taking of state-owned energy companies, but the impact of digital finance

TABLE 6 | Estimations of the moderating effect of property rights.

Variables	State-owned companies			Non-state-owned companies		
	(1)	(2)	(3)	(4)	(5)	(6)
	CTI	*Risk*	*CTI*	*CTI*	*Risk*	*CTI*
DFindex	−0.004	0.001[b]	−0.004	0.019[b]	0.001[b]	0.019[b]
	(−0.534)	(2.190)	(−0.607)	(2.012)	(2.178)	(1.986)
Risk	—	—	0.674	—	—	0.237[b]
	—	—	(1.111)	—	—	(2.521)
Size	1.126[a]	−0.041[a]	1.154[a]	0.640[a]	−0.008	0.642[a]
	(4.512)	(−3.258)	(4.601)	(2.817)	(−0.734)	(2.824)
Mturnover	−1.365[a]	0.015	−1.375[a]	−1.754[a]	0.005	−1.755[a]
	(−6.013)	(1.336)	(−6.054)	(−8.063)	(0.544)	(−8.067)
Merge	0.044	0.007	0.039	−0.251	−0.011	−0.248
	(0.362)	(1.103)	(0.324)	(−1.466)	(−1.374)	(−1.450)
Capital	−0.031	0.007[b]	−0.036	0.256[a]	0.000	0.256[a]
	(−0.475)	(2.072)	(−0.544)	(26.288)	(1.049)	(26.266)
Indratio	0.410	−0.035	0.433	2.918[b]	0.175[a]	2.877[b]
	(0.452)	(−0.756)	(0.478)	(2.073)	(2.704)	(2.040)
Growth	−0.036	0.006[a]	−0.040	0.034	0.002[b]	0.034
	(−0.968)	(3.130)	(−1.070)	(1.384)	(2.023)	(1.360)
Msh	−0.004	0.001	−0.004	−0.004	−0.000	−0.004
	(−0.291)	(1.569)	(−0.345)	(−0.760)	(−1.205)	(−0.746)
Age	0.149	−0.018[c]	0.161	−0.289	−0.024[c]	−0.284
	(0.736)	(−1.799)	(0.796)	(−1.074)	(−1.914)	(−1.053)
Roa	0.704	−0.148[a]	0.803	−3.180[a]	−0.423[a]	−3.080[a]
	(0.922)	(−3.830)	(1.045)	(−2.951)	(−8.556)	(−2.813)
Constant	5.204	0.859[a]	4.626	26.633[a]	0.254	26.572[a]
	(1.498)	(4.894)	(1.317)	(5.627)	(1.170)	(5.611)
Ind	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	430	430	430	958	958	958
R^2	0.121	0.065	0.122	0.345	0.166	0.345

Note: (1) [a]significant at the 1% statistical levels.
[b]significant at the 5% statistical levels.
[c]significant at the 10% statistical levels.
(2) t-values in parentheses.

development on the continuous technological innovation intensity of state-owned energy companies is not significant. Therefore, the risk-taking mechanism does not work in state-owned energy companies. According to the results shown in columns (4)–(6) of **Table 6**, the coefficients of *DFindex* and *Risktake* are all significantly positive (α_1 = 0.019, t = 2.012; β_1 = 0.001, t = 2.178; γ_1 = 0.019, t = 1.986; γ_2 = 0.237, t = 2.521), indicating that the risk-taking mechanism works in non-state-owned energy companies. This result is consistent with Tang et al. (2020). The reasons why risk-taking mechanism works in non-state-owned energy companies can be summarized into three aspects: 1) State-owned companies have natural advantages in obtaining financial resources (Norden et al., 2014), their demand for digital finance is relatively low; 2) State-owned companies usually receive special care and protection from the government, and they have an asymmetric advantage in competition with non-state-owned companies, leading to “innovation inertia” in state-owned companies (Li et al., 2018); 3)State-owned companies cannot solve the problem of innovation incentives for managers, which leads to insufficient enthusiasm for continuous technological innovation of state-owned companies (Wu, 2012).

5.2 Analysis of the Moderating Effect of Company Scale

This study uses the median of corporate size (measured by year-end total assets) as a benchmark, and divides the research sample into two groups: large and small energy companies, and examines the moderating effect of company scale. According to the results shown in columns (1) and (4) of **Table 7**, the regression coefficients of *DFindex* estimated by using small and large energy companies are 0.009 and 0.019, respectively, but only the former is significant. It can be seen that the development of digital finance has a significant role in promoting the continuous technology innovation of small energy companies, but the impact on the continuous technology innovation of large energy companies is not significant. The results reported in columns (2) and (5) of **Table 7** show that the estimated coefficients of *DFindex* are 0.002 and 0.000, respectively, but only the former is significant. These results show that the development of digital finance has a positive impact on the risk-taking level of small energy companies, but has no significant impact on the risk-taking of large energy companies. Finally, according to the results reported in columns (3) and (6) of **Table 7**, it can be seen that the estimated coefficients of *DFindex* are all positive, but the latter is

TABLE 7 | Estimations of the moderating effect of company scale.

Variables	Small companies			Large companies		
	(1)	(2)	(3)	(4)	(5)	(6)
	CTI	*Risk*	*CTI*	*CTI*	*Risk*	*CTI*
DFindex	0.009[b]	0.002[a]	0.010[b]	0.019	0.000	0.019
	(2.034)	(2.722)	(2.062)	(1.616)	(1.338)	(1.633)
Risk	—	—	2.354[a]	—	—	−0.165
	—	—	(3.068)	—	—	(−0.311)
Size	−0.203	−0.013	−0.172	−3.579[a]	−0.038[c]	−3.586[a]
	(−0.621)	(−1.267)	(−0.526)	(−7.874)	(−1.727)	(−7.878)
Mturnover	−0.384	0.008	−0.402	2.815[a]	0.014	2.817[a]
	(−1.319)	(0.802)	(−1.383)	(6.193)	(0.640)	(6.195)
Merge	−0.649[a]	−0.004	−0.639[a]	0.176	−0.007	0.175
	(−3.895)	(−0.788)	(−3.844)	(0.921)	(−0.803)	(0.914)
Capital	0.331[a]	0.001	0.330[a]	2.033[a]	0.009	2.035[a]
	(4.102)	(0.225)	(4.096)	(15.548)	(1.388)	(15.545)
Indratio	2.606[b]	0.084[b]	2.409[c]	0.935	0.073	0.947
	(2.061)	(2.035)	(1.908)	(0.586)	(0.945)	(0.593)
Growth	0.013	0.000	0.012	−0.036	0.023[a]	−0.032
	(0.273)	(0.054)	(0.269)	(−0.342)	(4.623)	(−0.303)
Msh	−0.033[a]	−0.001[b]	−0.032[a]	0.011	0.000	0.011
	(−4.454)	(−2.274)	(−4.284)	(1.508)	(0.100)	(1.508)
Age	−0.059	0.005	−0.071	−0.379	−0.036[b]	−0.385
	(−0.236)	(0.600)	(−0.282)	(−1.174)	(−2.290)	(−1.190)
Roa	−0.179	−0.165[a]	0.210	−4.045[a]	−0.435[a]	−4.117[a]
	(−0.153)	(−4.331)	(0.178)	(−3.688)	(−8.160)	(−3.672)
Constant	15.475[a]	0.030	15.406[a]	18.112[a]	0.962[a]	18.271[a]
	(2.972)	(0.175)	(2.967)	(3.059)	(3.337)	(3.073)
Ind	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	694	694	694	694	694	694
R^2	0.099	0.045	0.104	0.229	0.305	0.229

[a]*Note: (1)significant at the 1% statistical levels.*
[b]*significant at the 5% statistical levels.*
[c]*significant at the 10% statistical levels.*
(2) t-values in parentheses.

not significant. In summary, it can be seen that the risk-taking mechanism only works in small energy companies, indicating that the development of digital finance has broadened the financing channels for small energy companies, enriched the sources of innovative funds for small energy companies, stabilized small companies' capital chain, and reduced the cost and threshold of financial services for small companies. This all can provide more innovation capital guarantees for small companies, thereby increasing the level of risk-taking by small companies and ultimately having a positive impact on the continuous technological innovation of small energy companies. It is not difficult to see that the above research results are consistent with the existing literature such as Liang and Zhang (2019), revealing that the inclusive nature of digital finance is effective in supporting the innovation activities of small, medium and micro enterprises.

5.3 Analysis of Heterogeneity Based on the Dependence of External Funds

According to Maskus et al. (2012), financial development is more important for companies that are highly dependent on external funds. Therefore, whether the digital finance development would still continue this heterogeneous characteristic remains a problem. To answer this question, this study refers to the practice of Rajan and Zingales (1996) and adopts " (Capital Expenditure-Operating Cash Flow)/Capital Expenditure" to measure the company's external capital dependence. Taking the median of external financing dependence as a benchmark, the research sample is divided into two groups: high external financing dependence and low external financing dependence. This paper discusses the mechanism of digital finance development on the continuous technological innovation in China's energy companies. The specific results are shown in **Table 8**.

Table 8 shows the result that for energy companies that are highly dependent on external funds. The risk-taking mechanism plays a significant role, and the digital finance development promotes its continuous technological innovation level by increasing the level of risk-taking. However, for energy companies with low dependence on external funds, the overall effect of the digital finance development on continuous technological innovation is significantly negative, and the intermediary effect of risk-taking is not significant. The investment cycle of innovation projects is long, the future cash flow is uncertain, and the huge and continuous technological funding needs to become a barrier to the continuous technological innovation of energy companies. According to the theory of orderly financing, endogenous financing has the advantages of lower cost and less restrictive conditions compared with exogenous financing. For energy companies with low dependence on external financing, their innovation funds mainly come from internal financing. It is naturally difficult for digital finance development to play a role in such companies through risk-taking mechanisms. Seeking external funds has become the only way for their innovation process, as using internal funds to support the continuous development of their R&D and innovation activities is not enough. Risk-taking behaviors such as R&D and innovation are resource-consuming activities, which are highly resource-dependent (Lu et al., 2013). The digital finance development can help ease financing constraints and reduce financing costs, which coincides with the resource dependence needs of external financing-dependent companies. Therefore, the development of digital finance can increase the risk-taking level of external financing-dependent energy companies and conduct innovation incentive effects.

6 RESEARCH CONCLUSIONS AND POLICY IMPLICATIONS

The continuous technological innovation of energy companies is an important foundation and source of energy transformation and real economic growth. This study matches the Peking University Digital Financial Inclusive Index with the data of Chinese listed energy companies from 2011–2018, empirically test the impact of digital financial development on the continuous technological innovation and its risk-taking mechanism. The research conclusions mainly include: First, the development of

TABLE 8 | Heterogeneity analysis results based on external capital dependence.

Variables	High dependence on external funds			Low dependence on external funds		
	(1)	(2)	(3)	(4)	(5)	(6)
	CTI	*Risk*	*CTI*	*CTI*	*Risk*	*CTI*
DFindex	0.026[b]	0.000[b]	0.026[b]	0.000	0.000	−0.001
	(2.359)	(1.924)	(2.360)	(0.029)	(1.231)	(−0.063)
Risk	—	—	4.211[a]	—	—	−0.081
	—	—	(3.632)	—	—	(−0.098)
Size	−0.203	−0.003	−0.190	−4.167[a]	−0.035[b]	−4.170[a]
	(−0.765)	(−0.509)	(−0.718)	(−9.483)	(−2.415)	(−9.466)
Mturnover	−0.732[a]	0.004	−0.747[a]	3.577[a]	0.019	3.578[a]
	(−3.027)	(0.620)	(−3.102)	(8.288)	(1.348)	(8.283)
Merge	−0.170	−0.004	−0.154	−0.167	−0.003	−0.167
	(−0.880)	(−0.856)	(−0.798)	(−0.852)	(−0.495)	(−0.853)
Capital	0.263[a]	0.000	0.263[a]	2.367[a]	0.005	2.367[a]
	(26.422)	(0.180)	(26.525)	(17.567)	(1.082)	(17.555)
Indratio	2.849[c]	0.057	2.608	0.024	0.023	0.026
	(1.753)	(1.490)	(1.611)	(0.016)	(0.476)	(0.017)
Growth	0.018	0.002[c]	0.008	−0.017	0.002[b]	−0.017
	(0.327)	(1.900)	(0.139)	(−0.675)	(2.486)	(−0.666)
Msh	−0.021[b]	−0.000[b]	−0.019[b]	−0.005	−0.000	−0.005
	(−2.487)	(−2.028)	(−2.293)	(−0.633)	(−0.831)	(−0.635)
Age	0.140	−0.007	0.169	−0.539[c]	−0.005	−0.539[c]
	(0.447)	(−0.912)	(0.539)	(−1.775)	(−0.491)	(−1.776)
Roa	−4.042[a]	−0.592[a]	−1.549	−0.766	−0.151[a]	−0.778
	(−3.179)	(−19.735)	(−1.076)	(−0.639)	(−3.851)	(−0.646)
Constant	21.967[a]	0.256[a]	20.890[a]	19.338[a]	0.355[c]	19.367[a]
	(4.031)	(1.989)	(3.845)	(3.350)	(1.878)	(3.349)
Ind	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,054	1,054	1,054	334	334	334
R^2	0.418	0.809	0.424	0.259	0.057	0.259

[a]*Note: (1)significant at the 1% statistical levels.*
[b]*significant at the 5% statistical levels.*
[c]*significant at the 10% statistical levels.*
(2) t-values in parentheses.

digital finance has a positive impact on the continuous technological innovation of listed companies in China's energy industry. The digital finance shows its financial innovation side, forms a useful supplement to the traditional financial market, and plays the essential financial function of empowering the development of the real economy based on the important dimension of innovation incentives. Secondly, risk-taking plays a mediating effect in the process of the development of digital finance affecting the continuous technological innovation of Chinese energy companies. To a certain extent, the development of digital finance has alleviated the pain points of traditional financial market, such as "difficult financing and expensive financing", and provided new solutions for the financing of corporate risk-taking behaviors, thereby inspiring corporate risk-taking behaviors and encouraging companies to strengthen their continuous technological innovation. Finally, the nature of property rights, firm scale and external financing dependence have significant moderating effects on the risk-taking mechanism. Since non-state-owned enterprises and small, medium and micro enterprises have long been discriminated and treated differently by the traditional financial market, and the enterprises with low external financing dependence mainly rely on internal financing, the risk-taking mechanism is only applicable to non-state-owned enterprises, small enterprises and high external financing dependence energy companies.

Although the COVID-19 epidemic has had a great impact on the economies of countries around the world, it may provide an opportunity for the development of digital finance. First, the COVID-19 epidemic has boosted the wider rollout of the digital economy around the world. After the epidemic, the digital divide will be further bridged, and the consensus of the whole society on digital development will be further improved. Second, most retail businesses in banking, insurance, wealth management, securities and other fields require offline signatures and interviews. These businesses have been at a standstill throughout the epidemic and may be at risk of a slow recovery in the post-epidemic period. Facing the turbulent external environment, the online demand of enterprises will become more prominent. This will prompt regulators, enterprises and individuals to pay more attention to the digital construction of the economy in the future, and will also provide a new starting point for the development of digital finance. Third, the epidemic may accelerate the transformation of traditional finance to digital finance. Traditional financial institutions such as banks will accelerate innovation under the pressure of the epidemic. With the help of new digital and information technologies, they will follow customers from offline to online, and use big data to control risk to meet customers' financial needs.

Based on the above research findings, this study puts forward the following policy recommendations. First, during the critical period when the economy is transforming from high-rate growth to high-quality development, China should actively follow the trend of rapid technological development and give sufficient policy support to the development of digital finance to facilitate its development. In terms of policy implementation, the government should promote the construction of a diversified financial services industry, realize the precise match between finance and SMEs, thus lowering the service threshold of finance, promoting the majority of enterprises to obtain financial services at a lower cost and in a more convenient way, and better play the role of digital finance development in driving innovation, enhancing the efficiency of economic growth and leading to the release of new dynamic energy for economic growth.

Secondly, Chinese energy companies should be guided and encouraged to use digital finance to encourage their level of risk-taking and thus promote continuous technological innovation. In the process of financial services, the advantages of artificial intelligence and other technologies should be fully linked to financial products so as to provide comprehensive financial services with added value for enterprises and to empower their continuous technological innovation activities; in the process of risk control afterwards, the advantages of big data analytics should be considered as well. In the post-event risk control process, the advantages of data technology should be leveraged to build a dynamic early warning risk control system.

Finally, the COVID-19 epidemic continues to spread, and the shortage of funds is the main obstacle hindering the continuous innovation of energy companies, especially small and medium-sized energy companies. In terms of financial support policies, it is recommended to open up re-lending to digital financial companies with technological capabilities to help them more accurately target non-state-owned and small, medium and micro energy companies. Government departments and financial institutions should make full use of digital financial technology, through big data analysis and machine learning and other financial technologies, to accurately grasp the operating conditions, credit records and future prospects of energy companies, solve loan risk control problems, and accurately match financial resources to energy companies with continuous innovation potential.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

ZG: Conceptualization, writing the original manuscript and revising. YP: Methodology development, model design, writing the original manuscript and revising. YP: data analysis, results discussion and language polish.

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