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# Exploring the synergy of blockchain technology and low-carbon innovation for enterprise sustainability for unlocking a sustainable energy

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Along with further implementation of the policy strategy of carbon peaking and carbon neutralization in our country, the development idea of realizing the "dual carbon" goal with emphasis on environmental protection and low-carbon technology development has been preliminary established. At present, Chinese energy enterprises urgently need to break the dilemma between system and efficiency through technological innovation, so as to achieve the goal of sustainable development. Based on the legitimacy theory and stakeholder theory, this paper discusses the internal mechanism and boundary conditions of low-carbon technology innovation affecting the sustainable development of energy enterprises. Based on the data of listed Chinese energy companies from 2015 to 2021, the empirical study found that the level of low-carbon technology innovation of energy enterprises has an inverted U-shaped positive impact on their sustainable development performance, and the dual legitimacy (political legitimacy, market legitimacy) plays a part of the intermediary role. The degree of market competition positively moderates the relationship between low-carbon technology innovation and political legitimacy, and positively moderates the mediating effect of political legitimacy between low-carbon technology innovation and sustainable development performance. However, the degree of market competition has no significant moderating effect on the relationship between low-carbon technology innovation and market legitimacy, nor can it significantly regulate the mediating effect of market legitimacy. The constraint strength of "dual carbon" targets positively moderates the relationship between low-carbon technology innovation and political legitimacy, and positively moderates the mediating effect of market legitimacy between low-carbon technology innovation and sustainable development performance. On the contrary, the "dual carbon" target constraint intensity negatively moderates the relationship between low-carbon technology innovation and market legitimacy, and negatively moderates the mediating effect of market legitimacy. This article not only provides a new perspective for the integration of low-carbon innovation and legitimacy theory, but also provides theoretical reference and guidance for the practice of low-carbon technology innovation in energy enterprises.

KEYWORDS

**low-carbon technology innovation, political legitimacy, market legitimacy, sustainable development performance, the "dual carbon" goal**

# 1 Introduction

In 2020, China put forward the development goal of "striving to peak carbon dioxide emissions before 2030, and striving to achieve carbon neutrality before 2060" [hereinafter referred to as the "dual carbon" goal (Fang and Shao, 2022)]. On 22 September 2021, the "Opinions of the Central Committee of the Communist Party of China and the State Council on Completely and Accurately Implementing the New Development Concept and Doing a Good Job in Carbon Neutralization of Carbon Peaks" was announced. The document pointed out that the "dual carbon" goal should be integrated into the overall economic development of our country, and determined that economic growth should be transformed to a sustainable development route with the purpose of low-carbon transformation and the core of energy to green low-carbon transformation. As an important participant in the market, the implementation of sustainable development strategy by energy enterprises is not only to follow the inherent requirements of low-carbon economic development, but also to actively respond to the "dual carbon" target challenge (Xie and Zhu, 2021).

Lower sources of carbon emissions refer to activities, sectors, or practices that contribute relatively less to the overall carbon footprint. These sources are crucial to identify and address as they have the potential to significantly reduce greenhouse gas emissions and mitigate climate change. Conversely, the largest sources of low carbon energy encompass the sectors or technologies that provide substantial amounts of clean and renewable energy. These sources include solar power, wind energy, hydroelectricity, and nuclear power, among others. They play a vital role in transitioning away from fossil fuels and promoting a sustainable energy future. At present, it is widely recognized by stakeholders such as governments and consumers that low-carbon technology innovation is an important strategy to achieve the sustainable development goals of energy companies and build a modern energy system. However, as a typical feature of emerging economies, there are still many problems in the practice of low-carbon innovation strategy of China's energy enterprises due to the imperfect system and market. First of all, the acquisition of external resources (for example, government subsidies) depends on the "compliance" of enterprises to the government system, and to achieve the optimal allocation of innovation resources, enterprises need to have "subjective initiative" (Guo et al., 2018). Secondly, with the development of market economy, more and more attention has been paid to the guarantee of enterprises' implementation of green and low-carbon innovation (El-Kassar and Singh, 2019). However, due to the existence of moral irregularities, such as false innovation and patent fraud, energy enterprises are faced with challenges in low-carbon technological innovation. In this context, it is an urgent topic to explore how to effectively implement low-carbon innovation in China's energy enterprises to promote their sustainable development.

Reviewing the existing research results, most theoretical results on low-carbon innovation are discussed from the perspective of stakeholders under the traditional theoretical framework of "external pressure—technological innovation—corporate performance" (Hojnik and Ruzzier, 2016), or from the perspective of basic resource theory, the impact of environmental regulation and stakeholder pressure on corporate innovation behavior is discussed. To verify the effect of low-carbon innovation on economic performance (Xie et al., 2019) and environmental performance (Li et al., 2022a). However, financial performance or environmental performance alone cannot assess whether a business meets sustainability requirements. Therefore, this paper combines the ESG concept and the "triple bottom line" theory to build a sustainable development performance evaluation index system that includes four dimensions of economic, environmental, social and governance performance, and is used to evaluate the sustainable development performance of energy enterprises, so as to better reflect their performance in achieving long-term development. In recent years, although domestic and foreign scholars have gradually attached importance to the relationship between green and low-carbon innovation and sustainable development of enterprises (Fernando et al., 2019; Xie et al., 2019; Li et al., 2022a), these studies mostly focus on manufacturing enterprises, and rarely involve low-carbon innovation of energy enterprises with high pollution, high energy consumption and high carbon emission. The existing research results cannot well provide theoretical basis for the sustainable development of China's energy enterprises under the constraint of "dual carbon" target. The identified gap in the aforementioned work lies in the need to understand the internal mechanism and boundary conditions of low-carbon technology innovation that impact the sustainable development of Chinese energy enterprises, particularly in relation to the dual legitimacy (political and market) and the constraint strength of "dual carbon" targets. This study fills this gap by providing empirical evidence and insights into the inverted U-shaped positive impact of low-carbon technology innovation on sustainable development performance, the mediating role of dual legitimacy, and the moderating effects of market competition and target constraint intensity. According to this situation, this paper intends to explore the non-linear impact of low-carbon technology innovation on the sustainable development performance of enterprises under the theoretical framework of "innovation behaviors-firm performance," in order to enrich and improve the existing research on the sustainable development of enterprises. In addition, this paper also focuses on how low-carbon technology innovation affects the sustainable development performance of energy enterprises through internal mechanisms. From the perspective of signal transmission, in the context of the "dual carbon" goal, the low-carbon technology innovation of energy enterprises can not only build a clean energy system that meets the carbon emission reduction requirements of the government, but also meet the low-carbon needs of relevant stakeholders, and convey to the outside world the legal signal of actively responding to the national "dual carbon" goal and fulfilling environmental protection and social responsibility through low-carbon technology innovation. In turn, it is recognized and trusted by the government, partners, investors and consumers, which provides favorable conditions for enterprises to obtain core resources. In view of the diversity of the "audience" of legitimacy and the differences in the evaluation criteria of legitimacy, the mechanisms affecting the sustainable development of enterprises may be different (Fisher et al., 2016). Based on this, this paper identifies two main types of organizational legitimacy (political legitimacy and market legitimacy) according to different audience groups and interest

needs, which is used to interpret the internal mechanism of low-carbon technology innovation affecting the sustainable development performance of enterprises.

In addition, the mechanism of low-carbon technology innovation on corporate sustainability performance is context-dependent. Therefore, the third research question of this paper is to explore the boundary conditions that affect the relationship between low-carbon technology innovation and firm sustainable development performance. Although existing literature has expanded the boundary research of green low-carbon innovation based on resource-based view (Bossle et al., 2016), dynamic capability theory (Yu et al., 2017) and other perspectives, there are few situational studies based on legitimacy theory. From the perspective of social networks, the existence and development of organizations are closely related to social networks, which play different roles in different network systems. The operation of these network systems will have a significant impact on the organization, and the organization will take corresponding measures to adjust its operation mode according to these impacts. In particular, the dynamic institutional pressure will have a huge impact on the innovation behavior and consequences of energy enterprises. The logic of this is as follows: First, the combination of institutional structures such as economic development, geographical location, political culture and so on in different regions is different, resulting in obvious differences in regulatory pressures in different regions (Jin et al., 2022), which will force energy enterprises to comply with institutional changes to obtain legitimacy. Secondly, energy enterprises not only face the regulatory pressure of the government, but also the competitive pressure of enterprises in the same industry (Sun, 2022) and the change of consumers' demand for environmental protection (Tang et al., 2022) and other factors will have a significant impact on the innovation activities and sustainable development of energy enterprises. This paper aims to explore two dimensions under institutional pressure (namely, regulation pressure and imitation pressure), and take "dual carbon" target constraint strength and market competition degree as their manifestations respectively to investigate their impact on the relationship between low-carbon innovation activities and performance of energy enterprises, so as to expand the context of low-carbon innovation theory. Improve the theoretical extension of the process of low-carbon innovation's impact on enterprise performance.

# 2 Theoretical basis and research hypothesis

## 2.1 Low-carbon technology innovation and sustainable development performance

In order to realize the transformation from large-scale production to sustainable development, low-carbon technology innovation of energy enterprises reduces carbon dioxide emissions and increases energy efficiency by adopting renewable energy, optimizing production processes, implementing carbon recovery technologies, etc., so as to improve their environmental performance. Good environmental performance means that the production, emission, recycling and other processes of energy enterprises comply with relevant environmental regulations and are less likely to be punished for environmental pollution (Hojnik and Ruzzier, 2016; Jin et al., 2022), thus promoting the improvement of corporate profits and contributing to the improvement of sustainable development performance. With the establishment of the "dual carbon" goal, China's public society has gradually deepened its understanding of the low-carbon green concept. From the perspective of market and future development direction, energy enterprises need to follow the development trend through low-carbon technology innovation to establish a good green image and improve stakeholders' trust in corporate environmental performance, which is conducive to seizing the market in the low-carbon energy market. Improve the competitive advantage of enterprises (Zheng and Xu, 2022). In addition, in the context of the "dual carbon" goal, the government's low-carbon tax incentives, low-carbon innovation project support and technological innovation subsidies and other favorable policies can provide more support and incentives for energy enterprises to help them achieve greater development in the field of low-carbon technology. At the same time, the key breakthrough of low-carbon technology can not only help enterprises improve environmental efficiency, but also bring more business opportunities and markets, help enterprises to open up new business areas, achieve higher profits and returns, so as to enhance their own competitive advantage in the low-carbon technology industry chain. In addition, energy companies entering the mainstream low-carbon technology innovation market, access to more front-end technical information and other resources, can also bring immeasurable economic benefits for enterprises. To sum up, in the implementation of low-carbon technology innovation strategy, enterprises can not only achieve energy saving and consumption reduction in the production process through energy efficiency technology, fossil energy technology and new energy coupling technology, improve production efficiency, and achieve carbon emission reduction, but also create competitive environmental protection results by using new carbon technology, and establish an environmental protection corporate image. Further enhance its sustainable development advantages.

However, it must be pointed out that low-carbon technology innovation does not always promote the production and development of energy enterprises. On the contrary, it has a turning point, and if it exceeds the turning point, it will have a negative impact on the sustainable development performance of enterprises. The reasons are as follows: First, a high level of low-carbon technology innovation is not easy, requiring a large amount of research and development funds to upgrade and transform equipment, which will increase the cost of enterprises. Second, low-carbon innovation needs to invest resources, but excessive resource allocation will reduce marginal benefits, so that enterprises cannot fully use, absorb and digest these resources, and reduce the resource utilization rate of low-carbon technology innovation. At the same time, if an enterprise fails to effectively manage excessive innovation resources, it will lead to organizational redundancy, thus hindering the sustainable development of the enterprise (Soetanto and Sarah, 2018). Third, in terms of both human and financial resources, if energy enterprises only pay attention to investment in low-carbon innovation, other investments will be ignored, which will lead to unreasonable

business structure (Huang et al., 2017), thus hindering the overall development of enterprises and ultimately affecting their sustainable development performance. Finally, the current preferential policies for energy enterprises will not increase without limit with the degree of low-carbon technology innovation, and the public will also have an "inherent impression" on the low-carbon technology innovation behavior of enterprises and raise expectations, and the marginal social and economic performance of enterprises will be reduced, unable to promote the further growth of their sustainable development performance. A lower amount of carbon emissions has significant benefits for the environment, health, energy security, and industrial competitiveness. By reducing carbon emissions, we can mitigate the impacts of climate change and protect the environment for future generations. In terms of the environment, lowering carbon emissions helps mitigate global warming and reduce the severity of climate-related events such as extreme weather conditions, rising sea levels, and ecosystem disruptions. By transitioning to low carbon technologies and renewable energy sources, we can decrease reliance on fossil fuels and decrease the release of greenhouse gases into the atmosphere. This contributes to the preservation of biodiversity, ecosystems, and natural resources. From a health perspective, reducing carbon emissions leads to improved air quality. Fossil fuel combustion releases pollutants and particulate matter that contribute to air pollution and various respiratory and cardiovascular diseases. By adopting low carbon practices and cleaner energy sources, we can minimize air pollution and create healthier living environments for communities. Energy security is another benefit of lower carbon emissions. Dependence on fossil fuels from foreign sources can pose geopolitical risks and economic vulnerabilities. Investing in low carbon technologies and diversifying energy sources, such as renewable energy, enhances energy security by reducing reliance on finite and imported resources. It promotes energy independence, resilience, and stability in the face of volatile energy markets. Furthermore, embracing low carbon development enhances industrial competitiveness. As nations worldwide transition towards a low carbon economy, industries that adapt and innovate in clean technologies gain a competitive edge. Companies that invest in energy-efficient practices, renewable energy, and sustainable production methods are better positioned to meet evolving market demands, comply with stringent regulations, and attract environmentally conscious consumers. Low carbon development fosters innovation, promotes green jobs, and drives economic growth in sectors such as renewable energy, energy-efficient technologies, and sustainable manufacturing. Based on the above analysis, it can be concluded that energy enterprises cannot always improve their sustainable development performance by simply improving the level of low-carbon innovation. When low-carbon innovation reaches a certain threshold, the cost of innovation will rise significantly, even exceeding the various benefits brought by low-carbon innovation. As a result, the resource constraints faced by energy companies will become more serious and the implementation efficiency and effect of low-carbon innovation activities will decline. It has a negative impact on the sustainable development performance of enterprises. Therefore, this paper proposes the following hypothesis:

**H1:** There is an inverted U-shaped relationship between low-carbon technology innovation and sustainable development performance of energy enterprises.

## 2.2 The mediating effect based on legitimacy theory

The concept of legitimacy is the core concept of the school of organizational system theory, and it belongs to the school of organizational system theory. It is helpful for an organization to obtain and maintain legitimacy and comply with social expectations, which will help it obtain more social resources and support from stakeholders (Wang, 2017). Suchman (1995) defined legitimacy as "the general perception and assumption that an entity's behavior is desirable, appropriate, and appropriate within a social system constructed by norms, values, beliefs, and definitions" (Suchman, 1995). Domestic and foreign academic circles mainly interpret the impact of legitimacy on corporate behavior from two perspectives: strategic perspective and institutional perspective. From the strategic perspective, legitimacy itself is regarded as a resource of the enterprise, which can leverage other resources for the enterprise (Suchman, 1995). According to the resource-based theory, valuable, scarce, imitable and irreplaceable resources owned by enterprises are the source of sustainable competitive advantage (Barbey, 1991). In institutional theory, legitimacy is regarded as a standard and code of conduct established by the society. As a member of the society, if an enterprise wants to obtain legitimacy, it needs to act in accordance with the standard and take actions in line with social expectations (Tornikoski and Newbert, 2007), so as to relieve external pressure and maintain operation and development. The differences between the strategic perspective and the institutional perspective in the interpretation of organizational legitimacy are reflected in two aspects: First, from the efficiency logic, the strategic perspective emphasizes that enterprises obtain unique competitive advantages through optimal resource selection and allocation; From the institutional perspective, efficiency logic is conditional, and the selection and use of resources embedded in institutional environment must conform to social standards and judgments (Guo et al., 2018). Second, the strategic perspective emphasizes "empowerment," believing that organizations with high legitimacy have resource advantages and are more capable of adopting innovative behaviors to maintain competitive advantages. From the perspective of system, however, the emphasis is more on "limitation," believing that legitimacy is the prerequisite for the survival of organizations, and organizations must comply with social and institutional norms to reduce the impact of uncertainty risks (Rosário et al., 2022). Therefore, in different research perspectives, organizational legitimacy has different effects on the innovation activities and results of enterprises. In view of the fact that innovation efficiency and institutional pressure are often considered comprehensively when making innovation strategy decisions, the integration of the two perspectives helps to better understand the complex impact of organizational legitimacy on firm development.

On the basis of considering the connotations of "institutional constraints" and "resource acquisition" of legitimacy, this paper divides legitimacy into political legitimacy and market legitimacy according to audience groups and interest demands at different stages (Nugroho et al., 2022). The evaluation subject of political legitimacy is the government and its agencies. Having political legitimacy indicates that an enterprise has complied with the relevant laws, regulations and standards set by the government, realized the specific requirements of the government on the enterprise, and obtained the recognition of the government (Tornikoski and Newbert, 2007). The evaluation subject of market legitimacy is a large number of market participants (business partners, other enterprises of the same type, customers, the public and industry associations, etc.). Having market legitimacy indicates that an enterprise has complied with the code of conduct shared by all parties in the market and has been recognized by all market participants, which also indicates that an enterprise has market competitiveness (Zimmerman and Zeitz, 2002).

### 2.2.1 The mediating effect of political legitimacy

Under the background of "dual carbon" goal, energy enterprises promote the integration of themselves and the government in the value orientation of environmental protection by adopting the research and development behavior of low carbon technology which is consistent with the sustainable development strategy of our country, so as to improve their competitiveness and obtain sustainable development performance. On the one hand, low-carbon technological innovation by energy companies can enhance their political legitimacy. The details are as follows: First, the coupled development technology of new energy and fossil energy and the alternative technology of new energy promote the transition from fossil energy to new energy, and curb waste and carbon dioxide generation from the source of environmental governance goals (Xie et al., 2016). Secondly, energy efficiency technology realizes clean production, improves energy efficiency and controls the release of carbon dioxide by means of process improvement and resource recycling, so as to prevent the occurrence of substandard greenhouse gas emissions (Shu et al., 2016). Thirdly, carbon dioxide capture, utilization and storage technology can effectively reduce carbon emission intensity, achieve the end of industrial exhaust emission reduction management, help enterprises to achieve waste gas recycling, create new profit growth points at the same time help the government to achieve the "dual carbon" goal. In general, energy enterprises can build a green low-carbon technology system from the three aspects of energy supply, process emission and end, so that enterprises can achieve environmental regulations and standards such as energy saving and carbon emission reduction, so as to obtain the government's recognition of enterprises' environmental behavior, thus improving the political legitimacy of enterprises.

On the other hand, political legitimacy helps energy companies achieve sustainable development performance. Based on the dominant position of our government in economic activities, political legitimacy can provide enterprises with a lot of scarce resources and preferential treatment to promote the development of the enterprise. Since the Chinese government has incorporated the "dual carbon" goal into the overall layout of economic and social development and ecological civilization construction, the establishment of a green, low-carbon, efficient renewable energy system is an important direction for the future development of the energy industry. This shows that in the important stage of Chinese energy industry to low-carbon sustainable development, energy enterprises to adopt environmental protection strategies in line with the local government's "dual carbon" strategy, will be conducive to its access to tax incentives, dual carbon special funds, green credit, industry access permits and other valuable government resources and corresponding technical support. In addition, there are still some defects in Chinese current carbon market mechanism. In this case, energy enterprises can win more power protection and exclusive recognition for themselves by adopting low-carbon innovation strategies in line with government orientation, so as to avoid excessive intervention in innovation activities, (Sheng et al., 2011), which helps to improve innovation efficiency. In summary, the government feedbacks political legitimacy to energy companies to show recognition of their low-carbon innovation behavior; enterprises with political legitimacy are more likely to obtain the resources needed for survival and development, and help improve the performance of sustainable development. Therefore, this paper argues that political legitimacy is the transmission intermediary in the process of low-carbon technology innovation on sustainable development performance. Accordingly, the following assumptions are made:

**H2a:** Political legitimacy plays an intermediary role in the relationship between low-carbon technological innovation and sustainable development performance of energy enterprises.

### 2.2.2 The mediating effect of market legitimacy

Energy enterprises are facing increasingly fierce competition in the low-carbon market. By actively carrying out low-carbon innovation activities, we can establish our own green brand and image, so as to achieve positive interaction with different subjects, so as to achieve coordinated integration and optimization of all resources, and improve our core competitiveness. On the one hand, low-carbon technological innovation helps energy companies achieve their strategic goals of energy conservation and carbon emission reduction. It can effectively avoid negative news reports on environmental pollution, establish a good green image (Xie et al., 2016), and improve the positive evaluation of business partners and the public on enterprises, so as to obtain market legitimacy. In addition, in view of the two guidelines of the Opinions and the Plan pointed out that the energy industry should promptly deploy low-carbon technology innovation research and achieve major breakthroughs in green and low-carbon technologies, we should accelerate the construction of a clean, low-carbon, safe and efficient energy system. In this context, the low-carbon innovation strategy of energy enterprises is consistent with industry norms and industry development, which helps to gain the recognition and trust of the industry or alliance, thus improving their legitimacy in the industry or alliance.

On the other hand, market legitimacy helps energy companies achieve sustainable development performance. First of all, energy companies with high market legitimacy mean that they have gained the trust of other players in the market, and it is easier to form long-term strategic alliances with other companies, thereby reducing transaction costs between the two sides, and at the same time,

they can jointly carry out low-carbon technology innovation, thereby reducing research and development costs. Second, higher market legitimacy helps energy companies build social networks, obtain diversified information and broader technology exchange (Sheng et al., 2011). Finally, enterprises with a high level of market legitimacy are more likely to be favored by investors and receive financial support due to their high evaluation by business partners and consumers (Modell, 2022), which can alleviate the inhibition of financing constraints on low-carbon technology innovation of energy enterprises to a certain extent. In summary, market players will use rich and efficient heterogeneous resources as a reasonable feedback to low-carbon innovation of enterprises, and promote sustainable performance improvement of enterprises. Therefore, this paper believes that market legitimacy is the transmission intermediary in the process of low-carbon technology innovation on sustainable development performance. Accordingly, the following assumptions are made:

**H2b:** Market legitimacy plays an intermediary role in the relationship between low-carbon technological innovation and sustainable development performance of energy enterprises.

## 2.3 The regulating effect of external market environment and institutional pressure

### 2.3.1 The role of the degree of market competition

China's energy development is in a critical period of transformation and reform, and the competition in the energy market is becoming increasingly fierce. In the competitive market, the continuous progress of technology and market changes make energy enterprises face unprecedented challenges (Tracey et al., 2018), so that enterprises must invest a lot of resources to seize market opportunities and achieve sustainable development. However, the positive effects of green and low-carbon technological innovation are often not immediately apparent, especially in terms of obtaining economic benefits. Therefore, when the market competition of energy enterprises is more intense, the cost of low-carbon technology innovation will increase correspondingly, thus reducing the profits of enterprises and reducing the budget for further low-carbon innovation, which makes many enterprises unwilling or lack resources to carry out low-carbon technology innovation (Al-Awlaqi and Aamer, 2022). At the same time, the strength and effect of legitimacy depends on the difficulty and cost of building it: if the process of building it is very difficult, and the enterprise needs to pay a lot of sincerity and effort to obtain it, then its strength and effect will be better. In addition, due to the high cost of constructing legitimacy, it is difficult for competitors to imitate it, so enterprises that obtain it are more likely to attract the attention and recognition of stakeholders. Similarly, in the face of the new competition pattern under the increasingly fierce low-carbon constraints, the political legitimacy and market legitimacy established by energy enterprises when they carry out low-carbon technology innovation are more significant, and it is easier to get the attention, recognition and support of the government and other market entities. In this case, legitimacy is a powerful criterion to measure whether the enterprise is competitive, which helps the enterprise to stand out from many competitors and achieve long-term sustainable development.

When the intensity of market competition is low, the enterprise has a large space for resource utilization, so it will be considered by stakeholders that it has sufficient resources to implement social responsibility behaviors such as green environmental protection and low-carbon innovation (Obradović and Stojanović, 2022). In this context, China's energy enterprises to carry out low-carbon innovation may be regarded as a matter of course by the government, the government will not give it special support and care, but if the enterprise ignores the government's requirements on environmental protection and green low-carbon development, it may face severe supervision and heavy penalties. Therefore, in the market with low competition intensity, the legitimacy of low-carbon technology innovation of energy enterprises will be weak. In addition, in the market with low competitive intensity, the competition of products, technologies and prices is very weak, and few of the same competitors can meet the needs of business partners, customers or investors, so other subjects in the market do not have much choice, so even enterprises without sufficient legitimacy are likely to obtain their preferences, thus obtaining innovative resources. In this way, the positive impact of legitimacy built through low-carbon innovation on sustainable development performance is weakened.

To sum up, in a highly competitive market, energy enterprises regard low-carbon technology innovation as their differentiation strategy, and the legitimacy obtained by it is more effective, and it will also attract the attention of more stakeholders, which will help enterprises to obtain competitive advantages. Therefore, this paper proposes that the intensity of market competition will affect the mediating effect of legitimacy on the relationship between low-carbon technology innovation and sustainable development performance. Accordingly, the following hypothesis is proposed in this paper:

**H3a:** The degree of market competition positively regulates the relationship between low-carbon technology innovation and political legitimacy of energy enterprises.

**H3b:** Compared with less competitive markets, when energy companies carry out low-carbon technology innovation in highly competitive markets, the effect of political legitimacy on sustainable performance is stronger.

**H3c:** The degree of market competition positively regulates the relationship between low-carbon technology innovation and market legitimacy of energy enterprises.

**H3d:** When energy companies carry out low-carbon technology innovation in a highly competitive market, the effect of market legitimacy on sustainable performance is stronger than that in a less competitive market.

### 2.3.2 The role of "dual carbon" target constraint

As an important external factor, government policy plays an irreplaceable role in the sustainable development of enterprises. In the context of the upgrading of the "dual carbon" policy to the national strategy, the energy industry, as an important field to achieve the "dual carbon" goal, the innovation activities and sustainable development path of enterprises will definitely be affected by the policy goal. The "dual carbon" target has an impact on the low-carbon technology innovation activities and

performance of energy enterprises by restricting their carbon emissions, and its constraint effect varies depending on the degree of emphasis placed on the target by different regions. This paper proposes that the relationship between low-carbon technology innovation and corporate political legitimacy will be affected by the constraint strength of the "dual carbon" goal.

First of all, when the "dual carbon" target constraint intensity is large, the basic survival of energy enterprises is facing a greater threat. Considering the balanced relationship between regulatory losses and corporate sustainable development, enterprises are more motivated to invest in low-carbon technology innovation to satisfy political legitimacy. Secondly, the stricter the "dual carbon" target constraint, the local government will pay more attention to the various behaviors and consequences of enterprises' low-carbon innovation based on the pressure of regional carbon peak. In this case, energy enterprises will pay more attention to technological innovation capacity and efficiency, and enterprises will implement more substantive low-carbon innovation and reduce symbolic management strategies, which will help local governments achieve the environmental binding targets proposed by the central government, so as to obtain higher quality political legitimacy. Finally, a higher "dual carbon" target constraint strength can ensure energy enterprises' compliance with the government's work, and enterprises' low-carbon innovation can also serve as a compliance signal, helping enterprises to obtain positive evaluation from the government and gain more political legitimacy (Paeffgen, 2022). However, lower "dual carbon" target constraints cannot ensure that the actions of energy enterprises are consistent with national development strategies and values, and will reduce the government's positive evaluation of low-carbon innovation as a legitimacy signal, resulting in lower political legitimacy obtained by energy enterprises from low-carbon technology innovation.

**H4a:** The "dual carbon" target constraint strength positively regulates the relationship between low-carbon technology innovation and political legitimacy of energy enterprises.

**H4b:** The constraint strength of "dual carbon" targets enhances the mediating role of political legitimacy between low-carbon technology innovation and corporate sustainability performance.

The relationship between low-carbon technology innovation and the market legitimacy of energy enterprises will also be affected by the constraint strength of the "dual carbon "target. Most stakeholders believe that companies' efforts in environmental protection are due to external institutional pressure, rather than enterprises taking the initiative to assume social responsibility. Therefore, when the "dual carbon" target constraint pressure is greater, energy enterprises need to achieve a higher level of low-carbon technology innovation to meet the expectations of stakeholders, while the public, investors and other market players will reduce the positive evaluation of low-carbon technology innovation behavior of energy enterprises. Stakeholders are likely to take low-carbon technology innovation by energy companies as a matter of course in the context of the "dual carbon" goal, thereby reducing market legitimacy feedback. In addition, when the strict "dual carbon" target constraint continues for a long time, energy enterprises will focus on low-carbon innovation in order to build new competitive advantages, and excessive pursuit of low-carbon technology innovation level will lead to low innovation efficiency of energy enterprises and lead to high costs, resulting in market players' distrust and lack of support for their innovation activities, which may offset the benefits of market legitimacy. On the contrary, the low constraint strength of the "dual carbon" target means that the supporting carbon quota, carbon trading market and low-carbon innovation system are not perfect or cannot be effectively implemented, weakening the external institutional factors for the implementation of low-carbon technology innovation in energy enterprises, and reducing the expectations of stakeholders on enterprises' low-carbon innovation behavior (Claasen and Roloff, 2012). In this case, low-carbon technology innovation of energy enterprises has become an obvious clue and signal for market entities to make legitimate judgments, and a higher positive evaluation will be given to low-carbon technology innovation of energy enterprises at the same level (Park et al., 2014), and the market legitimacy status of enterprises has been significantly improved. Therefore, the following hypothesis can be obtained:

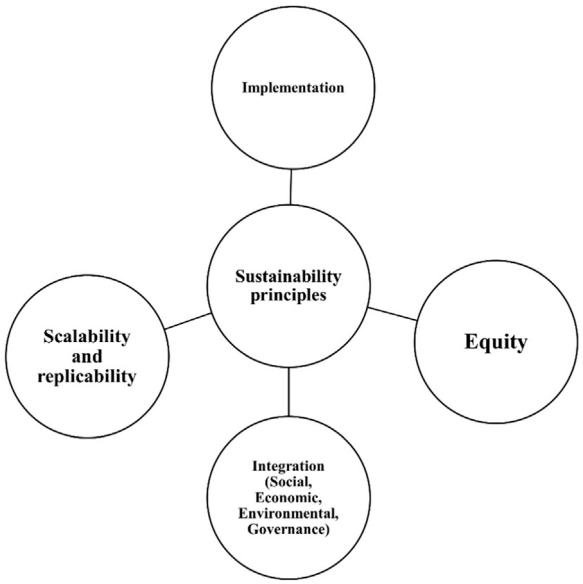


FIGURE 1
Theoretical model.

**H4c:** "dual carbon" target constraint intensity negatively regulates the relationship between low-carbon technology innovation and market legitimacy of energy enterprises.

**H4d:** "dual carbon" target constraint strength weakens the mediating role of market legitimacy between low-carbon technology innovation and firm sustainability performance. In conclusion, the theoretical model of this paper is constructed, as shown in Figure 1.

Figure 1 illustrates the sustainability principles that underpin the concept of sustainable development. These principles are key considerations in achieving a balance between economic growth, social wellbeing, environmental protection, and good governance.

**TABLE 1 Variable definitions and data sources.**

| Variable | Variable name | Variable definitions | Data sources |
|---|---|---|---|
| Type Explained | (Sustainable Development Performance, SDP) | Economic performance Vuță et al. (2022): includes four secondary indicators such as profitability, operating ability, debt repayment ability, and development ability (emphasizing the competitive behavior and financial performance of energy companies) | A sustainable performance evaluation system for energy companies constructed using principal component analysis-entropy method; the original data comes from the Wind database and environmental and social responsibility reports of energy companies |
| | | Environmental performance Vuță et al. (2022): includes four secondary indicators of environmental protection system and mechanism, resource utilization effectiveness, and pollution reduction effectiveness (emphasizing the active commitment and efforts of energy companies in environmental management) | |
| | | Social performance Lim (2023): including three secondary indicators of employee development, social contribution, and social damage (to examine the social contribution of energy companies and the performance of improving employee capabilities) | |
| | | Governance performance Lim (2023): includes two secondary indicators such as organizational structure, compliance and internal control, and information disclosure (the performance of corporate governance, supply chain governance, and information disclosure of energy companies) | |
| Variable | (LowC_Tech) | The natural logarithm of the number of utility model and invention patent applications related to "low carbon" plus one | Intellectual Property Network Patent Database (CNIPA) |
| Intermediary variable | (Political legitimacy) | Number of environmental information disclosure projects | 2015–2021 Environmental and Social Responsibility Report of Energy Enterprises The |
| | (Market legitimacy) | Logarithm of the number of investors | CSMAR |
| Adjust Variable moderating variables | "Double carbon" goal | Constraint strength of "double carbon" target constructed by text analysis method | government working report |
| | Constraint strength (DC) | Use the operating income of a single enterprise to calculate its industry market share | Wind database |
| | Degree of market competition | The natural logarithm of the total assets of the enterprise | |
| | (HHI) | The number of years from the year of listing to the year when energy companies report on low-carbon technology innovation reports | |
| | Enterprise size | Operating income growth of the current year/ Total operating income of the previous year | |
| | (Size) | The ratio of operating profit to total operating income | |
| | Enterprise listed years | R&D expenses/Main business income | |

# 3 Research design

## 3.1 Data sources

This paper uses Wind ESG rating database to select traditional energy enterprises listed in Shanghai and Shenzhen as research objects. Since most listed energy companies have only officially disclosed their environmental data since 2015, the sample period of this paper is 2015–2021. In the process of data screening, samples of undisclosed corporate environmental data, abnormal financial status (ST, * ST) and listed companies during the study period were excluded. In order to eliminate the influence of extreme values, all continuous variables are winterized at the level of 1% above and below. The following data reports are based on the processed data results. To reduce the possibility of multidisciplinary between variables, all variables are centralized. After the above screening of the data, a total of 521 sample observations were obtained.

## 3.2 Variable selection and measurement

Low Carbon Technology innovation (LowC_Tech). Based on the text analysis method of Ren Sheng Gang (Gomes Junior and Schramm, 2022), this paper uses the sum of the number of low carbon invention patents and low carbon utility model patents applied by energy enterprises to measure the degree of low carbon technology innovation. The specific approach is to search the full text of the patent by keywords (including low carbon, carbon emissions, greenhouse gases, energy conservation and emission reduction, renewable energy, clean energy and other six keywords) to determine the number of invention and utility model patent applications related to low-carbon technological innovation. In this paper, the natural logarithm of explanatory variables is taken. In order to prevent the enterprises from obtaining relevant patents in the current period, which will lead to meaningless log-taking, the number of patents obtained is increased by 1.

### 3.2.1 Explained variable

Sustainable Development Performance (SDP). Corporate Sustainability performance is a measure of the level of corporate sustainability. This paper integrates the concept of ESG (environment, society and corporate governance) with the Triple Bottom Line theory (economy, environment and society) adopted by most scholars, and constructs a set of sustainable development performance evaluation index system of energy enterprises that includes four indicators: economy, society, environment and governance. Specific measurement indicators are shown in Table 1.

### 3.2.2 Mediating variable

Political Legitimacy (PL). Referring to the research of Guo Li and Dong Qingduo (Jin et al., 2022), this paper selects the number of environmental information disclosure items as a variable to measure the legitimacy of regulations. Market Legitimacy (ML). Based on the research of Xu and Xie (Li et al., 2022b), this paper uses the logarithm of the number of investors to measure the market legitimacy.

### 3.2.3 Adjusting variables

Market competition degree. The Herfindahl index is usually used to measure the degree of market monopoly. The larger the index, the higher the degree of market monopoly and the smaller the degree of market competition. In this paper, the Herfindahl (HHI) index of enterprise income is used to measure the degree of market competition, and the inverse of it is turned into a positive indicator in the regression analysis, that is, the greater the index is, the fiercer the market competition is. "dual carbon" target constraint strength. Drawing on the researchers (Kobylińska and Ryciuk, 2022), this paper uses the space of carbon-related text in the annual work reports of prefecture-level cities to measure local governments' attention to the policy of "dual Carbon," which indirectly represents the constraint strength of "dual carbon" goal. The specific method is to use text analysis method to select the sentences related to "carbon peak," "carbon neutral," low carbon, carbon emission trading, double control of energy consumption, etc. Then, measure the proportion of the total words of the local government to the "dual carbon" target, the higher the "dual carbon" target constraint of local energy enterprises.

### 3.2.4 Control variables

In view of the fact that the sustainable development performance of enterprises is affected by many factors, this paper selects enterprise Size (Size), Age (Age), R&D investment intensity (R&D), Growth (Growth) and sales profit margin (ROS) as control variables. The specific measurement of each variable is shown in Table 1.

### 3.2.5 Model building

Based on the above theoretical analysis, this paper holds that there is an inverted U-shaped relationship between low-carbon technology innovation and sustainable development performance of energy enterprises. Based on this, this paper first builds the following benchmark model:

$$\begin{aligned}\mathrm{SDP}_{it} =& \beta_0 + \beta_1 \mathrm{LowC\_Tech}_{it} + \beta_2 \mathrm{LowC\_Tech}_{it}^{\ 2} + \beta_3 \mathrm{Size}_{it} + \beta_4 \mathrm{Age}_{it} \\ &+ \beta_5 \mathrm{Growth}_{it} + \beta_6 ROS_{it} + \beta_7 R\&D_{it} + \beta_8 IND + \beta_9 Y + \varepsilon_{it}\end{aligned} \tag{1}$$

In order to test the mediating effect of political legitimacy and market legitimacy on the performance of low-carbon technology innovation and sustainable development of energy enterprises, based on model (Eq. 1), the stepwise regression method was adopted to test the mediating effect:

$$\begin{aligned}\mathrm{Mediator}_{it} =& \alpha_0 + \alpha_1 \mathrm{LowC\_Tech}_{it} + \alpha_2 \mathrm{LowC\_Tech}_{it}^{\ 2} + \alpha_3 \mathrm{Size}_{it} + \alpha_4 \mathrm{Age}_{it} \\ &+ \alpha_5 \mathrm{Growth}_{it} + \alpha_6 \mathrm{ROS}_{it} + \alpha_7 \mathrm{R\&D}_{it} + \alpha_8 \mathrm{IND} + \alpha_9 \mathrm{Y} + \mu_{it}\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{SDP}_{it} =& \delta_0 + \delta_1 \mathrm{LowC\_Tech}_{it} + \delta_2 \mathrm{LowC\_Tech}_{it}^{\ 2} + \delta_3 \mathrm{Mediator}_{it} \\ &+ \delta_4 \mathrm{Size}_{it} + \delta_5 \mathrm{Age}_{it} + \delta_6 \mathrm{Growth}_{it} + \delta_7 \mathrm{ROS}_{it} + \delta_8 \mathrm{R\&D}_{it} \\ &+ \delta_9 \mathrm{IND} + \delta_{10} \mathrm{Y} + \tau_{it}\end{aligned} \tag{3}$$

In order to test the regulatory effects of the degree of market competition and the "dual carbon" target constraint strength on the low-carbon technology innovation and political/market legitimacy of energy enterprises, the following model is constructed on the basis of model (Eq. 2):

$$\begin{aligned}\mathrm{Mediator}_{it} =& \chi_0 + \chi_1 \mathrm{LowC\_Tech}_{it} + \chi_2 \mathrm{Moderator}_{it} \\ &+ \chi_3 \mathrm{LowC\_Tech}_{it} * \mathrm{Moderator}_{it} + \chi_4 \mathrm{Size}_{it} \\ &+ \chi_5 \mathrm{Age}_{it} + \chi_6 \mathrm{Growth}_{it} \\ &+ \chi_7 \mathrm{ROS}_{it} + \chi_8 \mathrm{R\&D}_{it} + \chi_9 \mathrm{IND} + \chi_{10} \mathrm{Y} + \vartheta_{it}\end{aligned} \tag{4}$$

Based on Bootstrap method, the moderated mediating effect is tested through the difference of mediating effect, which involves the following models:

$$\begin{aligned}\mathrm{Sustainability}_{it} =& \varphi_0 + \varphi_1 \mathrm{LowC\_Tech}_{it} + \varphi_2 \mathrm{LowC\_Tech}_{it}^{\ 2} + \varphi_3 \mathrm{Moderator}_{it} \\ &+ \varphi_4 \mathrm{Mediator}_{it} + \varphi_5 \mathrm{Moderator} * \mathrm{Mediator}_{it} + \varphi_6 \mathrm{Size} \\ &+ \varphi_7 \mathrm{Age}_{it} + \varphi_8 \mathrm{Growth}_{it} + \varphi_9 \mathrm{ROS}_{it} + \varphi_{10} \mathrm{R\&D}_{it} \\ &+ \varphi_{11} \mathrm{IND} + \varphi_{12} \mathrm{Y} + \upsilon_{it}\end{aligned} \tag{5}$$

Among them, Mediator it is the intermediary variable, including political legitimacy (PL) and market legitimacy (ML); Moderator it is the regulating variable, including the degree of market competition (HHI) and "dual carbon" target constraint strength (DC); IND and Y tables represent the fixed effects of industry and year.

**TABLE 2 Descriptive statistics and correlation analysis.**

| Variable | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1) SDP | 1.000 | | | | | | | | | | |
| 2) LowC_Tech | 0.415*** | 1.000 | | | | | | | | | |
| 3) Age | 0.055* | −0.026* | 1.000 | | | | | | | | |
| 4) Size | 0.182*** | 0.361*** | 0.195*** | 1.000 | | | | | | | |
| 5) ROS | 0.146*** | −0.016*** | −0.064* | −0.025 | 1.000 | | | | | | |
| 6) Growth | 0.037** | 0.051 | −0.105* | 0.053** | 0.255*** | 1.000 | | | | | |
| 7) R&D | 0.029* | 0.035*** | −0.224*** | −0.138** | 0.111** | 0.047** | 1.000 | | | | |
| 8) HHI | 0.083*** | 0.015 | 0.135** | 0.163* | −0.121*** | 0.063 | −0.080*** | 1.000 | | | |
| 9) PL | 0.324*** | 0.186*** | −0.094*** | 0.032 | 0.038 | 0.046 | 0.042 | 0.144 | 1.000 | | |
| 10) ML | 0.429*** | 0.244*** | 0.021 | 0.157*** | 0.034 | 0.002 | 0.065** | 0.117* | 0.514*** | 1.000 | |
| 11) DC | −0.198** | 0.439*** | −0.064 | 0.619*** | 0.201* | 0.085 | 0.106 | 0.047*** | −0.490* | −0.062** | 1.000 |
| | 38.11 | 1.504 | 22.12 | 24.18 | 0.068 | 0.104 | 0.029 | 0.101 | 2.339 | 3.314 | 4.159 |
| | 3.168 | 1.508 | 4.272 | 1.307 | 0.188 | 0.230 | 0.015 | 0.066 | 1.698 | 0.506 | 1.891 |

# 4 Empirical analysis

## 4.1 Descriptive statistics and correlation analysis

Table 2 shows that most of the control variables are significantly correlated with the explained variables, indicating that the control of these variables in this paper is reasonable. In general, the correlation coefficient among explanatory variables is small, and the variance inflation factor test results show that the VIF value is far less than 10, indicating that there is no serious multidisciplinary problem in the data.

## 4.2. Baseline regression result

In view of the fact that the Hausman test results of all models reject the null hypothesis at the level of 1%, the fixed effect model is adopted in this paper, and the model calculation adopts Stata.16. The baseline regression results are shown in Table 3, where only control variables are added to column (1), and the primary and secondary terms of low-carbon technology innovation are added to column (2). The results show that the regression coefficients of the first and second low-carbon technology innovation items and enterprise sustainable development performance are 1.034 and −0.841, respectively, and both are significant at the level of 1%. The Utest test results pass the significance test at the level of 1%, and the extremum points are included in the sample interval, indicating that there is an inverted U-shaped relationship between low-carbon technology innovation and enterprise sustainable development performance, and hypothesis H1 is supported.

## 4.3 Intermediate effect test

The regression results of the mediating effect of political legitimacy on the relationship between low-carbon technology innovation and sustainable development performance of energy enterprises are shown in Table 3 and Table 4. Columns (1)–(3) in Table 4 report the impact of low-carbon technological innovation on the political legitimacy of energy companies. Column (2) is to test whether enterprises' low-carbon technology innovation has a nonlinear impact on political legitimacy. Based on column (1) (including only control variables), the quadratic term of enterprises' low-carbon technology innovation is added for testing. The regression result is not significant, indicating that China's energy enterprises' low-carbon technology innovation does not have a significant nonlinear impact on political legitimacy at this stage. In column (3), on the basis of the control variable (Column 1), an item of enterprise low-carbon technology innovation is added. The results show that the path effect of "low-carbon technology innovation—political legitimacy" is significantly positive at the 10% level. Table 3 (3) Introduces the political legitimacy variable on the basis of Table 3 (2), and the results show that compared with Table 3 (2), the path of "low-carbon technology innovation—corporate sustainable development performance" is significantly weakened, while the path of "political legitimacy—corporate curriculum development performance" is significantly positive at the 10% level. Therefore, political legitimacy plays a partial mediating role between low-carbon technology innovation and sustainable development performance of energy firms, assuming that H2a is supported. Similarly, market legitimacy also plays a partial mediating role between low-carbon technology innovation and energy firms' sustainability performance, assuming H2b is supported.

**TABLE 3 Test results of mediating effect of baseline regression and legitimacy.**

| Variable | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Explanatory variables | | | | |
| LowC_Tech | | 1.034*** | 0.988*** | 0.964*** |
| | | (6.263) | (5.142) | (5.070) |
| LowC_Tech$^2$ | | −0.841*** | −0.795*** | −0.778*** |
| | | (−4.881) | (−4.063) | (−4.418) |
| Mediator variable | | | | |
| PL | | | 0.282* | |
| | | | (1.721) | |
| ML | | | | 0.376*** |
| | | | | (3.243) |
| control variable | | | | |
| Growth | 0.572** | 0.614*** | 0.596** | 0.621*** |
| | (2.625) | (2.618) | (2.528) | (2.835) |
| R&D | 4.454*** | 4.185** | 4.334** | 4.733*** |
| | (2.600) | (2.476) | (2.558) | (2.607) |
| ROS | 5.293*** | 5.359*** | 5.461*** | 5.294*** |
| | (3.264) | (3.550) | (3.836) | (3.266) |
| Age | −0.018* | 0.109 | 0.406 | 0.583* |
| | (−1.705) | (1.412) | (1.536) | (1.719) |
| Size | 0.061** | 0.037** | −0.079 | −0.128 |
| | (2.556) | (2.342) | (−1.534) | (−1.501) |
| _Cons | 5.483*** | 5.476*** | 4.707*** | 4.992*** |
| | (14.859) | (15.223) | (13.273) | (12.711) |
| Year | Yes | Yes | Yes | Yes |
| Industry | Yes | Yes | Yes | Yes |
| N | 521 | 521 | 521 | 521 |
| $R^2$ | 0.388 | 0.410 | 0.416 | 0.413 |

## 4.4 Adjustment effect test adjustment effect test

The regulating effect of market competition degree. Table 4 column (4) test the degree of market competition for energy enterprise low carbon technology innovation and political legitimacy of regulating effect, the enterprise low carbon technology innovation and the degree of market competition interaction coefficient of 0.053, and under the 5% level, it shows that in the fierce market competition situation, energy enterprises for low carbon technology innovation can get more significant political legitimacy, assuming H3a support. The results of column (9) show that the interaction term coefficient of enterprise low-carbon technology innovation and market competition degree is positive but not significant, that is, assuming that H3c is not supported. As can be seen from Figure 2, compared with when the degree of market competition is low, when the degree of market competition is high, low-carbon technology innovation has a stronger role in the promotion of the political legitimacy of energy enterprises.

The regulation of the "dual carbon" target constraint strength. Table 4 column (5) test the "dual carbon" target constraint strength of low carbon technology innovation and the adjustment effect of political legitimacy, including enterprise low carbon technology innovation and "dual carbon" target constraint interaction coefficient of 0.039, and at the level of 5% significantly, it shows that the higher "dual carbon" target constraint strength situation, enterprise low carbon technology innovation and political legitimacy of the positive relationship is stronger, assuming H4a support. As can be seen from Figure 3A, compared with the "dual carbon" target constraint intensity is low, when the "dual carbon" target constraint is strict, low-carbon technology innovation has a stronger promotion effect on the political legitimacy of energy enterprises.

The results of Table 4 (10) show that the interaction term coefficient of enterprise low-carbon technology innovation and "double-carbon" target constraint strength is −0.045, which is significant at the 1% level, which indicates that the "dual carbon" target constraint strength weakens the relationship between enterprise low-carbon technology innovation and market legitimacy, that is, assuming H4c is supported. As can be seen from Figure 3B, compared with when the "double-carbon" target constraint intensity is high, when the "dual carbon" target constraint is relatively loose, low-carbon technological innovation has a stronger promoting effect on the improvement of the market legitimacy of energy enterprises.

## 4.5 Mediated effects are regulated

This paper adopts the test method of "conditional indirect effect" proposed by Preacher. For the test of mediated effect, the results are shown in Table 5. For the mediating path of political legitimacy, the mediating effect index of market competition degree and "dual carbon" target constraint strength adjustment are 0.061 and 0.108, respectively, with confidence intervals [0.114, 0.134] and [0.013, 0.200], both excluding 0. It shows that both the degree of market competition and the constraint strength of the "dual carbon" target significantly positively regulate the mediating role of political legitimacy between low-carbon technology innovation and the sustainable development performance of energy enterprises, that is, H3b and H4b are assumed to be supported. In order to further describe the moderated mediating effect, Bootstrap took the mean value of the above two moderating variables and added and subtraction one standard deviation to form three levels of medium, high and low, so as to test the difference of mediating effect under different levels of moderating variables, presenting the results of conditional mediating effect test. As can be seen from Table 5, the confidence intervals of the mediating effect of political legitimacy are [0.112, 0.255], [0.179, 0.348] and [0.241, 0.464] respectively at different levels of market competition: low, medium and high, and none of them contain 0. Moreover, the effect coefficient gradually increases, indicating that when market competition becomes more intense, the confidence interval of

**TABLE 4 Test results of regulatory effects of market competition and "dual carbon "target constraints.**

| Variable | Political legitimacy | | | | | Market legitimacy | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Explanatory variables | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| LowC_Tech | | 0.586* | 0.067** | 0.060** | 0.063** | | 0.763* | 0.179** | 0.175** | 0.178** |
| | | (1.861) | (1.993) | (1.986) | (1.970) | | (1.854) | (2.098) | (2.035) | (2.041) |
| LowC_Tech$^2$ | | −0.317 | | | | | −0.485 | | | |
| | | (−1.552) | | | | | (−1.406) | | | |
| Moderator | | | | | | | | | | |
| HHI | | | | 0.015* | | | | | 0.033 | |
| | | | | (1.776) | | | | | (1.612) | |
| DC | | | | | −0.055 | | | | | −0.082* |
| | | | | | (−1.293) | | | | | (−1.686) |
| interaction term | | | | | | | | | | |
| LowC_Tech*HHI | | | | 0.053** | | | | | 0.071 | |
| | | | | (2.497) | | | | | (1.598) | |
| LowC_Tech*DC | | | | | 0.039** | | | | | −0.045*** |
| | | | | | (2.170) | | | | | (−2.673) |
| control variable | | | | | | | | | | |
| Growth | 0.037 | 0.052 | 0.048 | 0.058 | 0.050 | −0.006 | 0.029 | 0.029 | 0.028 | 0.030 |
| | (0.891) | (0.903) | (0.901) | (0.903) | (0.900) | (−1.120) | (1.055) | (1.054) | (1.108) | (1.087) |
| R&D | −0.292* | 0.099 | 0.099 | 0.088 | 0.096 | 0.453* | 0.868* | 0.866* | 0.940* | 0.882* |
| | (−1.914) | (1.530) | (1.537) | (1.543) | (1.542) | (1.694) | (1.700) | (1.703) | (1.782) | (1.754) |
| ROS | −0.187* | −0.146* | −0.143* | −0.148* | −0.145* | −0.049 | 0.025 | 0.023 | 0.015 | 0.020 |
| | (−1.785) | (−1.823) | (−1.926) | (−1.926) | (−1.920) | (−1.569) | (1.023) | (1.021) | (1.095) | (1.087) |
| Age | −0.377*** | −0.362*** | −0.360*** | −0.369*** | −0.364*** | −0.755*** | −0.731*** | −0.725*** | −0.737*** | −0.733*** |
| | (−3.362) | (−2.904) | (−2.902) | (−2.908) | (−2.900) | (−3.028) | (−2.885) | (−2.885) | (−2.904) | (−2.890) |
| Size | 0.191*** | 0.160** | 0.158** | 0.157** | 0.161** | 0.321*** | 0.254** | 0.250** | 0.264** | 0.267** |
| | (2.717) | (2.005) | (2.005) | (2.012) | (2.009) | (2.708) | (2.486) | (2.480) | (2.461) | (2.476) |
| _Cons | 1.932** | 2.347 | 2.472 | 2.194 | 2.226 | 7.069* | 7.137* | 7.186* | 7.214* | 7.259* |
| | (1.994) | (1.625) | (1.613) | (1.621) | (1.616) | (1.883) | (1.705) | (1.697) | (1.862) | (1.788) |
| Year | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Industry | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 521 | 521 | 521 | 521 | 521 | 521 | 521 | 521 | 521 | 521 |
| $R^2$ | 0.009 | 0.136 | 0.127 | 0.131 | 0.139 | 0.098 | 0.151 | 0.158 | 0.163 | 0.160 |

Note: *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively, and the t values are in brackets.

political legitimacy does not contain 0. Political legitimacy plays a stronger mediating role between low-carbon technology innovation and sustainable development performance of energy enterprises. Under the constraints of low, medium and high "dual carbon" goals, the confidence intervals of the mediating effect of political legitimacy are [0.052, 0.285], [0.056, 0.374] and [0.121, 0.487], respectively, and the effect coefficient gradually increases. It shows that the implementation of stricter "dual carbon" target constraints will strengthen the mediating role of political legitimacy between low-carbon technology innovation and sustainable development performance of energy enterprises.

For the mediation path of market legitimacy, the confidence interval of the mediation effect of the degree of market competition regulation [−0.003,0.044], including 0, indicating that the mediation effect of regulation is not significant, i.e., assuming H3d is not supported. However, the confidence interval of the mediation effect

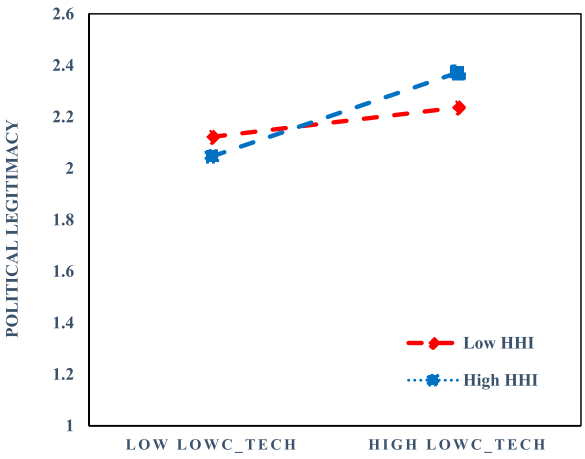


FIGURE 2
Moderating effect of market competition degree.

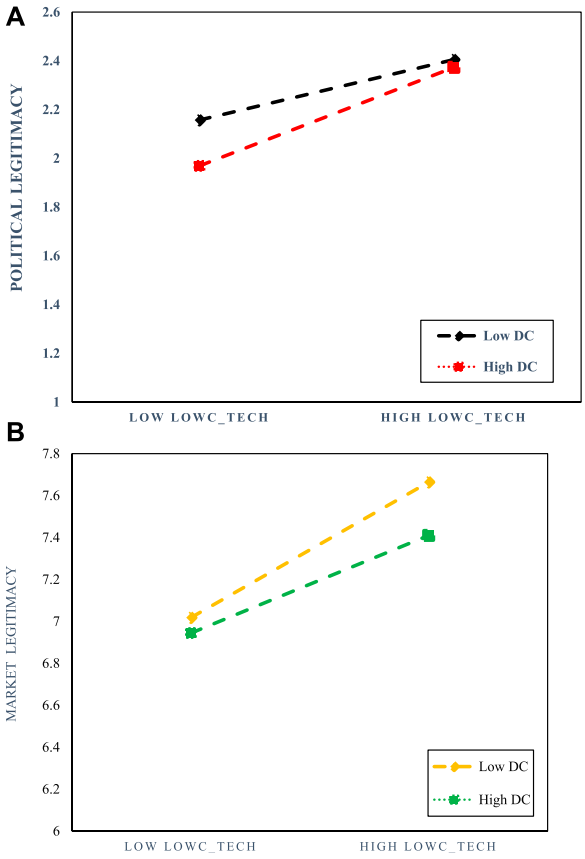


FIGURE 3
**(A)** The moderating effect of the intensity of "dual carbon "target constraint (political legitimacy). **(B)** The moderating effect of "dual carbon" target constraint intensity (market legitimacy).

of the "dual carbon" target constraint intensity regulation [−0.088, −0.003], which does not include 0, indicating that the mediation effect of the regulation is significant, i.e., assuming H4d is supported. Similarly, from Table 6, in low, medium and high different "dual carbon" target constraint strength, the legitimacy of market mediation confidence interval does not contain 0, and the effect coefficient gradually smaller, this shows that compared with the "dual carbon" target constraint strength is higher, when the "dual carbon" target constraint strength is low, the market legitimacy in low carbon technology innovation and energy enterprise sustainable development performance mediation between stronger.

# 5 Endogeneity and robustness test

## 5.1 Reverse causality test

There may be mutual causality between the independent variable and the dependent variable in this paper. Low-carbon technology innovation will have a certain impact on the sustainable development performance of energy enterprises, but it may also be that with the increase of the sustainable development performance of enterprises, enterprises will increase their investment in low-carbon technology innovation. To solve this problem, this paper takes the enterprise sustainable development performance as the explanatory variable, and the low-carbon technology innovation as the explanatory variable. The test results found that the above relationship did not have a significant linear relationship, indicating that the possibility of mutual causal effect is small.

## 5.2 Robustness test

In order to verify the reliability of the conclusion, this paper adopts two methods to test the robustness. First, the robustness of the main effect and the intermediate effect was tested by changing the measurement method of explanatory variables. The relative number of low-carbon patents of energy enterprises in the current year is used as a substitute variable for low-carbon technology innovation, and the ratio of the number of low-carbon patents granted by energy enterprises in the current year to all the licenses granted in the current year is measured. Second, the analysis of the regulated mediation effect is conducted based on the sequential method test. The regression results obtained by the above two methods are consistent with the conclusions obtained above, indicating that the research conclusions drawn in this paper are still valid.

The future prospects of low carbon technological innovation in the field of sustainable development for energy enterprises are promising, but they also come with certain challenges that need to be addressed. One of the key prospects is the potential for significant advancements in low carbon technologies. Rapid developments in renewable energy sources, energy storage systems, smart grids, and energy efficiency solutions present opportunities for energy enterprises to adopt and integrate these technologies into their operations. This can lead to reduced carbon emissions, increased energy efficiency, and enhanced overall sustainability performance. The continuous innovation and improvement of these technologies will play a crucial role in

**TABLE 5 Political legitimacy under different degree of market competition and "dual carbon" target constraint strength.**

| Path and effect | | Effect | Boot | Boot CI | Boot CI | Result |
|---|---|---|---|---|---|---|
| Path 1: Low-carbon technology innovation→political legitimacy→sustainable development performance | Moderated mediating effect (Market competition degree M1) | 0.061 | 0.031 | 0.114 | 0.134 | Significantly |
| | Moderated mediating effect ("Double carbon" target constraint strength M2) | 0.108 | 0.049 | 0.013 | 0.200 | Significantly |
| conditional intermediary effect | M1−1SD | 0.117 | 0.036 | 0.112 | 0.255 | Significantly |
| | M1 | 0.161 | 0.043 | 0.179 | 0.348 | Significantly |
| | M1 + 1SD | 0.255 | 0.057 | 0.241 | 0.464 | Significantly |
| | M2−1SD | 0.107 | 0.083 | 0.052 | 0.285 | Significantly |
| | M2 | 0.193 | 0.078 | 0.056 | 0.374 | Significantly |
| | M2 + 1SD | 0.279 | 0.091 | 0.121 | 0.487 | Significantly |

**TABLE 6 The mediating effect of market legitimacy and the judgment index of moderated mediating effect under different "dual carbon" target constraints.**

| Path and effect | | Effect size | Standard error | Boot CI lower bound | Boot CI upper limit | Result |
|---|---|---|---|---|---|---|
| Path 1: Low-carbon technology innovation→market legitimacy→sustainable development performance | Moderated mediating effect (market competition degree M1) | 0.032 | 0.025 | −0.008 | 0.073 | Not obvious |
| | Moderated mediating effect ("double carbon" target constraint strength M2) | −0.045 | 0.028 | −0.088 | −0.003 | Significantly |
| conditional intermediary effect | M2−1SD | 0.148 | 0.026 | 0.100 | 0.202 | Significantly |
| | M2 | 0.119 | 0.018 | 0.084 | 0.157 | Significantly |
| | M2 + 1SD | 0.089 | 0.022 | 0.047 | 0.132 | Significantly |

achieving long-term sustainability goals. Another prospective area is the emergence of blockchain technology. As blockchain offers decentralized, transparent, and secure solutions, it holds the potential to revolutionize energy systems. By enabling peer-to-peer energy trading, optimizing energy distribution, and facilitating the integration of renewable energy sources, blockchain can contribute to the growth of low carbon innovation. Moreover, blockchain-based platforms can enhance traceability and accountability, making it easier for energy enterprises to track carbon emissions, validate renewable energy sources, and meet sustainability standards. However, along with these prospects, several challenges need to be addressed. One of the main challenges is the high upfront cost of deploying and scaling up low carbon technologies. While the costs of renewable energy sources have been declining, they still require significant investments. Energy enterprises need to overcome financial barriers and explore innovative financing mechanisms to make these technologies more accessible and economically viable. Another challenge is the need for supportive regulatory frameworks. Clear and consistent policies that promote low carbon innovation and provide incentives for sustainable practices are essential. Governments and regulatory bodies play a crucial role in creating an enabling environment that encourages energy enterprises to invest in and adopt low carbon technologies.

# 6 Conclusion

## 6.1 Research and finding

Taking listed energy enterprises as samples, this paper empirically tests the impact of low-carbon technology innovation on the sustainable development performance of enterprises, and discusses the mediating mechanism of legitimacy between the two and the moderating effect of market competition and "dual carbon" goal constraint.

The study revealed several key findings. Firstly, it identified a significant inverted U-shaped relationship between low-carbon technology innovation and the sustainable development performance of corporations. As the level of low-carbon technology innovation increases, so does the sustainable development performance. However, there is a point at which further improvement in low-carbon technology innovation leads to diminishing returns, causing a decline in sustainable development performance. Secondly, the study found that both political legitimacy and market legitimacy partially mediate the relationship between low-carbon technology innovation and the sustainable development performance of energy enterprises. This means that from an institutional theory perspective, energy enterprises face scrutiny and pressure from stakeholders during

the innovation process. Low-carbon technology innovation aligns with the objectives of economic low-carbon transformation and social green development. By enhancing the legitimacy of enterprises, it attracts innovative resources and social support from stakeholders, thereby promoting competitive advantages and facilitating sustainable development. Thirdly, the degree of market competition positively influences the relationship between low-carbon technology innovation and political legitimacy of energy enterprises. It also positively moderates the mediating effect of political legitimacy on the relationship between low-carbon technology innovation and sustainable development performance. In other words, in a more competitive market, low-carbon technology innovation enables energy enterprises to enhance their political legitimacy and achieve higher sustainable development performance. However, the study did not find support for the moderating effect of market competition on the relationship between low-carbon technology innovation and market legitimacy of energy enterprises. Lastly, the study found that the constraint intensity of the "dual carbon" goal positively regulates the relationship between low-carbon technology innovation and political legitimacy of enterprises. It also positively moderates the mediating effect of political legitimacy on the relationship between low-carbon technology innovation and sustainable development performance. This suggests that a higher constraint intensity in achieving "dual carbon" goals encourages energy enterprises to enhance their political legitimacy, leading to improved sustainable development performance. That is, when the government pays more attention to the "dual carbon" goal constraint, energy enterprises will obtain more significant political legitimacy for low-carbon technology innovation, thus improving their sustainable development performance.

Sustainability is a multidimensional concept that involves balancing social, ecological, and economic considerations. Low-carbon technology innovation is one way to promote sustainability. This involves the development and deployment of technologies that reduce greenhouse gas emissions and other environmental impacts. Renewable energy sources such as wind and solar power, electric vehicles, and energy-efficient buildings are all examples of low-carbon technologies. Duality legitimacy refers to the idea that companies and organizations must balance the demands of different stakeholders, including shareholders, employees, customers, and the broader community. This requires companies to take into account social and environmental concerns in addition to economic considerations. By doing so, companies can build trust and legitimacy with their stakeholders, which can lead to long-term success. Resource-based economies are those that rely heavily on the extraction and export of natural resources, such as oil, gas, and minerals, for their economic growth and development. Low-carbon technology innovation, duality legitimacy, and enterprise sustainable development are all relevant concepts in the context of resource-based economies. For example, low-carbon technology innovation can help resource-based economies reduce their environmental impact and diversify their economies beyond dependence on non-renewable resources. This can also help these economies mitigate the negative effects of climate change and reduce their greenhouse gas emissions. Duality legitimacy is also important in the context of resource-based economies, as these economies often face competing demands from different stakeholders. For example, there may be tensions between the need to protect the environment and the desire to promote economic growth and development. By balancing these demands, resource-based economies can build trust and legitimacy with their stakeholders and achieve long-term sustainability. Finally, enterprise sustainable development is critical for resource-based economies to manage their resources effectively and sustainably. This can involve setting sustainability targets, measuring and reporting on sustainability performance, and engaging with stakeholders to understand their sustainability concerns and priorities. By pursuing sustainable development, resource-based economies can create value for both themselves and society as a whole, while also ensuring the long-term health and viability of their natural resources.

## 6.2 Theoretical contribution and management enlightenment

1) Based on the "triple bottom line" theory and ESG concept, this paper systematically interprets the impact of low-carbon technological innovation on the sustainable development performance of energy enterprises, and further expands the research scope of the relationship between low-carbon technological innovation and enterprise performance. It is found that there is a significant inverted U-shaped relationship between low-carbon technology innovation and sustainable development performance of energy enterprises. According to the research conclusion, energy enterprises should make clear that they are the main body of low carbon innovation. First of all, enterprises should realize the significance of low-carbon innovation for future development, and attach importance to investment in low-carbon innovation, so that enterprises can establish a better green image, so as to enhance their competitiveness in the market, win greater benefits for enterprises, and promote the sustainable development of enterprises; secondly, enterprises need to pay attention to the rational allocation of resources and funds for low-carbon innovation, maintain low-carbon innovation at a "moderate" level, prevent resource redundancy and low resource utilization, and improve the company's ability to absorb, digest and transform technology, and prevent excessive investment in low-carbon innovation from adversely affecting other production and operation activities of the company. This paper puts forward the research framework of "low carbon innovation——dual legitimacy——enterprise performance," discusses the mechanism of low carbon technology innovation to improve sustainable development performance based on the legitimacy theory, and makes up for the limitation of the current research on the influence mechanism. Most of the existing low-carbon innovation research focuses on the low-carbon innovation driving effect of the legitimacy pressure on enterprises (Li et al., 2019), while there are few related studies on revealing the legitimacy of enterprises by enterprises through low-carbon innovation. From the perspective of stakeholders, this paper divides the legitimacy into political legitimacy and market legitimacy, and proposes that low-carbon technology

innovation by energy enterprises can help enterprises obtain political legitimacy and market legitimacy from the outside.

At the same time, the legitimacy status helps energy enterprises to obtain heterogeneous resources, reduce operating costs and enhance risk tolerance, so as to build competitive advantages and promote the sustainable development of enterprises. Thus, energy enterprises should fully understand the low carbon innovation, legitimacy and sustainable development at the same time into the enterprise performance management framework is scientific, and build with the interests of the government, the public stakeholders communication platform, efforts to identify social participants on the sustainable development of energy enterprise cognitive needs and expectations, thus combined with their own development status and strategic target of low carbon innovation support path of carbon emission reduction. The establishment of new institutional theory has made it clear that the establishment of legitimacy will vary due to the external environment of the enterprise (Obradović and Stojanović, 2022), but there is still a lack of in-depth theoretical and empirical research on how to affect the construction of organizational legitimacy and what is its mechanism of action. In view of this problem, this paper finds that the intermediary effect of binary legitimacy between low-carbon technology innovation and sustainable development performance is different due to the degree of market competition faced by enterprises and the intensity of the "dual carbon" target constraint. This shows that the energy enterprise managers should comprehensively analyze the changes of the external system and the market environment when determining the development strategy. From the perspective of market competition, energy enterprises actively low carbon technology innovation can create the legitimacy of the stakeholders, especially for those enterprises in the competitive market, through the implementation of low carbon innovation government legitimacy may be a good choice, can provide support for enterprise scarcity innovation information, help to improve its sustainable development performance. From the perspective of the role of "dual carbon" target constraint intensity, under the context of high "dual carbon" target constraint intensity, the low-carbon technology innovation level of energy enterprises must exceed the requirements of relevant regulations, so that enterprises can obtain the recognition of the government and the public. The improvement of the innovation level of low-carbon technology of energy enterprises has significantly improved the political legitimacy, but limited the improvement of the market legitimacy. Therefore, energy companies also need to invest in other ways to get positive reviews from social justice and from business partners. On the contrary, in the "dual carbon" target constraint intensity is low, energy enterprise low carbon technology innovation degree is low, the more positive for low carbon technology innovation, the more obvious, the market legitimacy and the political legitimacy is limited, the enterprise can through other political behavior to obtain political legitimacy status. In short, energy enterprises should adjust their low-carbon innovation strategies in time according to the changes in the external system and market environment, so as to maintain and repair the dual legitimacy, so as to obtain good sustainable development performance.

There are still some limitations in this paper, which need to be further discussed in future research. First of all, this paper only explores the impact of low-carbon technology innovation on the sustainable development performance of energy enterprises from the perspective of innovation output. On this basis, subsequent studies can study the differentiated impact on the sustainable development performance of enterprises from the perspectives of low-carbon input, hierarchy, service innovation, etc., to improve the research scope of this paper. Secondly, energy enterprises are not only affected by regulatory pressure or imitation pressure, but also face the comprehensive effect of various institutional pressures. It is also of great significance to study the interaction of the two on the impact of low-carbon innovation of energy enterprises. On the other hand, there are other conditional variables that may affect the performance of low-carbon technology innovation and sustainable development. Therefore, further research can explore other internal and external factors that affect the relationship between green innovation and sustainable development performance, such as ethical executives, corporate culture, employee training, etc., to further explore the boundary conditions for enterprises to achieve legitimacy and sustainable development through low-carbon innovation. Thirdly, this paper only focuses on energy enterprises to examine the practice of low-carbon technological innovation. In the case of the integration of enterprises and innovation ecosystem, the follow-up research can try to focus on the low-carbon innovation behavior of multiple subjects (such as upstream and downstream of supply chain, industrial alliance, etc.), so as to provide more comprehensive suggestions for the construction of low-carbon energy system in China.

## Data availability statement

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

## Author contributions

ZA: Conceptualization, Formal Analysis, Methodology, Writing–original draft, Writing–review and editing. XG: Conceptualization, Investigation, Methodology, Writing–original draft.

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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.

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