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A Literature Review on Addressing the Energy Trilemma in the Context of Carbon Peaking and Carbon Neutrality

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Abstract: Against the backdrop of carbon peaking and carbon neutrality, this paper reviews the literature on improving the energy trilemma. It first elaborates on the background and significance of carbon peaking and carbon neutrality, and then discusses in detail the theoretical research on the energy trilemma, energy security and the energy trilemma, energy transition and the energy trilemma, the evolution of the energy trilemma across different regions, measures for improving the energy trilemma, the role of the energy trilemma, and future development directions. Finally, it concludes that the "impossible triangle" of fossil energy can be transformed into an "achievable triangle" under a new energy system, and further develop into a "sustainable triangle" for the green energy transition revolution, thereby providing theoretical support and a practical pathway for achieving the goals of carbon peaking and carbon neutrality.

Keywords: Carbon peaking and carbon neutrality; Energy trilemma; Energy transition.

1. Introduction

With the acceleration of industrialization, excessive emissions of greenhouse gases such as carbon dioxide in recent years have driven up global temperatures and triggered a series of extreme climate events, such as sea-level rise, threatening human survival and development. To address this challenge, the international community has reached a consensus through instruments such as the United Nations Framework Convention on Climate Change and the Paris Agreement, requiring all countries to control their carbon emissions. In September 2020, at the 75th session of the United Nations General Assembly, General Secretary Xi Jinping announced: "China will scale up its nationally determined contributions, strive to peak carbon dioxide emissions before 2030, and work hard to achieve carbon neutrality before 2060." Carbon peaking refers to the historical inflection point at which total carbon dioxide emissions reach their peak and then shift from rising to falling; carbon neutrality refers to absorbing and neutralizing the carbon dioxide emitted by human activities through various means—such as afforestation, energy conservation and emission reduction, and industrial restructuring—so as to achieve "net-zero" carbon dioxide emissions. Carbon peaking and carbon neutrality are an inherent requirement of addressing global climate change, and achieving them is an international responsibility that China has voluntarily assumed. This commitment reflects China's sense of responsibility as a major country and constitutes an important practice in building a community with a shared future for mankind; it is an intrinsic requirement for implementing the new development philosophy, fostering a new development paradigm, and promoting high-quality development, and it is a major strategic decision made by the CPC Central Committee in coordinating the domestic and international situations.

It is widely recognized in the industry that a traditional energy system dominated by fossil fuels can hardly meet the three important goals of being green and low-carbon, economically viable, and safe and reliable at the same time—a situation commonly referred to as the "energy impossible triangle". However, green and low-carbon development is the fundamental direction of energy transition, economic viability is an important consideration for social acceptance, and safety and reliability are the basic requirements of an energy system. Achieving the "dual carbon" goals requires that the future new energy system gradually meet all three goals simultaneously, mitigating the energy trilemma and turning it into an "energy possible triangle". The practical significance of the "energy impossible triangle" is more important than ever before: any successful and lasting energy transition must address all three elements of the "energy impossible triangle". Therefore, under the "dual carbon" goals, transforming China's traditional energy system from an "impossible triangle" into a "possible triangle" is both necessary and urgent [1].

2. The Energy Trilemma: Conceptual Definition and Research Methods

2.1. Conceptual Definition of the Energy Trilemma

The concept of the energy trilemma first originated from the "impossible trinity" in the financial field, which specifically refers to the fact that a country cannot simultaneously achieve the three goals of free capital mobility, independent monetary policy, and exchange rate stability—at most two of them can be realized at the same time. On this basis, the World Energy Council later proposed the concept of the energy trilemma, also known as the "energy impossible triangle" [2]. In this framework, energy security and reliability, greenness, and economic viability constitute the three vertices of the impossible triangle, and likewise, at the current stage, at most two of the three goals can be achieved simultaneously. In the initial stage of research, scholars believed that the three vertices of the energy "impossible triangle"—energy security,

greenness, and economic viability—were equally important and could be achieved at the same time. However, with the continuous development of energy policies and technologies, scholars found that treating the three elements as equally important and simultaneously achievable was unrealistic, and they came to recognize that the priorities within the energy trilemma may vary according to region, level of economic development, and policy framework. Under such circumstances, the rigid balance among the three vertices may shift, with certain elements gaining priority in line with local needs and strategic priorities. It is generally held that once a modern energy economic system has been established, no room for Pareto improvement will remain among the three major development directions of security, economic viability, and greenness: the optimization of any one direction will correspondingly worsen the others. In the triangular game of the energy sector, safety and reliability are the basic requirements of an energy system, yet economic viability must also be satisfied for society to develop. The coordination and simultaneous realization of these three major development goals is what is meant by optimizing the energy "impossible triangle", or optimizing the energy trilemma.

2.2. Research Methods for the Energy Trilemma

Coupling coordination degree model. Coupling refers to the process in which, during development, numerous elements or systems become closely interconnected through mutual promotion and influence. In physics, coupling coordination generally denotes a measure of the degree of mutual dependence between two or more objects. From a systems perspective, all things in nature are invariably interconnected, and coupling coordination can thus be defined as the phenomenon in which systems interact with and influence one another. The realization of the "possible triangle" in the energy sector hinges on whether short-term safety and stability, medium-term economic viability, and long-term low-carbon environmental performance are mutually dependent and mutually reinforcing. The coupling coordination degree model is widely applied in analyzing the interactions between two or more systems. By constructing a composite index and calculating the coupling coordination degree, the model evaluates the coupling coordination level of the energy system according to the grading criteria for the coupling coordination degree. The measurement results are regarded as the degree to which the energy trilemma is mitigated.

Exploratory spatial data analysis (ESDA). ESDA explores the distributional characteristics of spatial objects by analyzing the correlation among spatial sample values and its magnitude, including global and local autocorrelation analysis. The Global Moran's I coefficient and the local indicator of spatial association (LISA) statistic are used to analyze the spatial correlation of the energy trilemma at the provincial level.

Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT). The STIRPAT model is an extension of the environmental pressure (IPAT) model. It takes population size, affluence, and technology level as the drivers of environmental variables to assess the extent of human impacts on the environment, and it is commonly used as a theoretical model in environmental research.

Econometric models. Econometric models are used to examine the economic relationships among macro variables, including multidimensional panel fixed effects models and geographically weighted regression models. Building on the traditional panel model, the multidimensional panel fixed effects model can be specified with interactive (cross) fixed effects. The geographically weighted regression model is an extension of the traditional regression model and is used to observe the spatial characteristics of data while accounting for spatial differences.

3. Theoretical Research on the Energy Trilemma

3.1. Energy Security and the Energy Trilemma

Energy security is an overarching and strategic issue that bears on a country's economic and social development, and it is crucial to national prosperity, the improvement of people's living standards, and long-term social stability. Energy systems can be divided into single-energy systems, multi-energy systems, and super energy systems. China has put forward a new energy security strategy featuring the "Four Revolutions and One Cooperation", which points the way for high-quality energy development in the new era. China's current energy structure is characterized by the "three highs and one low": a relatively high carbon content, relatively high carbon emissions from energy use, and a relatively high degree of dependence on imported oil and gas, together with a relatively low level of production and utilization of new energy. China's present energy insecurity is mainly the insecurity caused by its high dependence on imported oil and gas, which calls for the underground gasification of coal and coal-rock gas and a shale oil and gas revolution; its future energy insecurity will mainly be the insecurity caused by a high volume of imports of critical minerals for new energy, which calls for stepping up the development of critical minerals. To safeguard China's energy security now and in the future, it is necessary to proceed from the "four systems perspectives"—the whole-coal system (surface and underground), the whole oil and gas system (conventional and unconventional), the whole energy system (fossil and new energy), and the whole carbon cycle system (carbon emissions and carbon utilization and storage)—and to plan for clean coal utilization, the cost-effective development of unconventional oil and gas, the accelerated development of new energy, and the steady realization of carbon neutrality, thereby making a great contribution to the global response to climate change, the achievement of the "carbon neutrality" goal, and the green energy transition [3].

3.2. Energy Transition and the Energy Trilemma

"Green energy transition" refers to the process of shifting the energy mix toward clean and low-carbon development through green energy technology innovation, so that energy production and consumption become safe, efficient, and smartly integrated across multiple energy sources, carbon emissions are significantly reduced and carbon is utilized and stored, thereby supporting the realization of carbon neutrality, energy independence, and green and sustainable development. As ecological security is a key factor constraining the development of clean energy, exploring the coordination and synergy mechanism between ecological security and energy security has become an urgent issue in the transformation of the energy industry [4]. During the 14th Five-Year Plan period, the energy industry has adhered to the new energy security

strategy, accelerated the new process of "re-electrification", and fostered new business forms of energy transition and new energy development with Chinese characteristics [5]. The green and low-carbon energy transition consists in phasing out outdated and inefficient capacity while releasing high-quality and efficient capacity in such industries as coal, coal-fired power, and petrochemicals, while at the same time accelerating the clean utilization of energy so as to ensure environmentally sustainable development under a secure energy supply [6]. Guided by the carbon neutrality goal, China should build a new energy system along three dimensions—cleaner fossil energy, scaled-up renewable energy, and smarter integrated energy—and comprehensively coordinate the intrinsic relationship between energy security and energy transition [7].

3.3. The Evolution of the Energy Trilemma across Regions

China's energy development faces problems such as an imbalance between energy supply and demand, negative externalities of energy, distorted energy prices, and threats to energy security. Over the past decade, however, China's energy development has played a huge role in the process of building a moderately prosperous society in all respects: energy supply has been closely linked with economic development, major energy-related matters have ensured supply and stabilized prices, energy has empowered regional development, and notable progress has been made in the energy revolution [8]. Among these regions, the Yangtze River Economic Belt, as a major national development strategy and a core economic zone, still faces persistent and potential crises in energy supply, economic development, and sustainability. In the Belt, the lagging interconnection of oil and gas pipeline networks and the insufficient inter-provincial power transmission facilities threaten supply security. Hidden barriers in regional electricity markets and unsound trading mechanisms have called energy accessibility into question. The construction of clean energy infrastructure will seriously undermine the sustainability of the ecological environment [9], and the region thus faces a multi-agent energy trilemma. Chen et al. found that the contribution of the energy storage industry to green development within the energy trilemma is significantly higher in northern China than in southern China [10]. Li et al. used balanced panel data covering 276 Chinese cities from 2008 to 2021 as a sample, constructed a framework for calculating a city-level energy dilemma index, and applied K-means clustering to classify the cities of that period into three types: stable energy dilemma, progressive energy dilemma, and potential energy dilemma. They pointed out that Chinese cities are currently dominated by the potential energy dilemma type, and that the cities performing better are mainly regional economic centers [11].

4. The Energy Trilemma: Mitigation Measures and Its Role

4.1. Measures to Mitigate the Energy Trilemma

Stempien et al. proposed a new tool for addressing the energy trilemma based on an improved Markowitz mean-variance portfolio optimization theory; the tool can also be used in conjunction with more complex and more resource-intensive approaches, such as integrated assessment modeling, general equilibrium modeling, or technology roadmaps [12]. Barazza et al. used the BRAIN-Energy model to show that improving the energy trilemma requires taking into account the interactions between policies and market participants, and that improvement requires the collaboration of different market policies and participants [13]. Taking Xiamen, a coastal city in China, as a case study, Jing et al. proposed a bottom-up multi-objective energy transition (ET) optimization framework that can optimize a 20-year long-term energy portfolio as well as short-term hourly dispatch strategies that account for the demand-side flexibility of energy storage, thus forming an effective ET solution [14]. Wu et al. studied the design of active distribution networks under the energy trilemma and found that the trade-offs among trilemma objectives are nonlinear, that economic viability and greenness do not always conflict, and that efficient solutions exist for optimizing all trilemma objectives simultaneously; the introduction of distributed energy resources can achieve efficient trade-offs within the energy trilemma [15]. Gibellato et al. conducted a regression analysis of data from 118 countries and found that a longer school life expectancy is more conducive to raising the overall level of education in society, and that a larger number of people receiving higher education helps enterprises achieve green development, thereby improving the energy trilemma through social factors [16]. Based on a nonlinear system dynamics approach, Fang et al. constructed a four-dimensional coupled dynamic system comprising new energy, the economy, carbon emissions, and energy storage, and pointed out that the development of new energy faces the energy trilemma; they further noted that market mechanisms and energy regulation are crucial to resolving the energy trilemma [17]. Cen et al. constructed a "double triangle" theoretical framework consisting of the "energy impossible triangle" and the "sustainable development triangle", examined the coupling and synergy between the two triangles, and identified a preferred pathway for power system reconfiguration—namely, allowing security and greenness to develop in stages so as to dynamically mitigate the challenges of the energy "impossible triangle" [18]. Lu et al. employed a double machine learning model based on the random forest algorithm and a spatial Durbin difference-in-differences model to study China's regional industrial chains, and found that innovation and reform policies targeting regional industrial chains can effectively enhance their resilience, thereby promoting the coupled and coordinated development of the energy impossible triangle within the region and thus improving the energy trilemma [19]. Using data from 275 Chinese cities, Chen et al. concluded that the development of the energy storage industry can drive green technological innovation and the growth of the new energy industry, thereby promoting green economic development and improving the energy trilemma [10]. Matthias et al. refined the security dimension of the energy "impossible triangle" into five levels, providing a clear and measurable method for assessing energy security and enabling a clearer view of the trade-offs among security, economic viability, and greenness within the "impossible triangle" [20].

4.2. The Role of the Energy Trilemma

Khan et al. used principal component analysis (PCA) to create an index as a proxy variable for the energy trilemma and analyzed the top ten countries in WETI 2020, finding that the energy trilemma is positively correlated with economic growth and that the energy trilemma and population growth

affect economic growth only in the long run [21]. Zhao et al. pointed out that eliminating the energy trilemma helps significantly reduce China's CO_2 emissions, among which the improvement in economic viability is the most critical factor in curbing CO_2 emissions. The study also demonstrated that dual environmental regulation (DER) has a significant moderating effect on the energy trilemma and CO_2 emissions, altering the dynamic relationship between the energy dilemma and CO_2 [22].

5. Research Conclusions and Future Prospects

5.1. Research Conclusions

This paper reviews the literature on mitigating the energy trilemma in the context of carbon peaking and carbon neutrality, and draws the following conclusions.

First, the energy trilemma is conceptually rooted in the "impossible trinity" of the financial sector and was later extended by the World Energy Council to the energy domain, where security and reliability, greenness, and economic viability form its three vertices. The literature generally agrees that these three goals cannot be fully and simultaneously achieved at the current stage, and that their relative priority varies with regional endowments, stages of economic development, and policy frameworks. The trilemma should therefore be understood as a dynamic constraint rather than a fixed trade-off, one whose rigid balance may shift as policies and technologies evolve.

Second, methodological progress has provided a diversified toolkit for studying the trilemma. The coupling coordination degree model captures the degree of interdependence among the three dimensions and translates it into a measurable level of trilemma mitigation; exploratory spatial data analysis reveals spatial correlation and clustering at the provincial level; the STIRPAT model identifies population, affluence, and technology as driving factors; and econometric models, including multidimensional panel fixed effects and geographically weighted regression, support the identification of causal relationships and spatial heterogeneity. These approaches are complementary, and their combined use offers a more robust basis for measurement and inference than any single method.

Third, theoretical research has concentrated on two pillars—energy security and energy transition—and has increasingly recognized pronounced regional heterogeneity. Evidence at the provincial and city levels shows that China's energy development still faces supply-demand imbalances, negative externalities, price distortions, and security threats, and that regions such as the Yangtze River Economic Belt confront a multi-agent trilemma in which supply security, market accessibility, and ecological sustainability are difficult to reconcile. At the same time, the empirical literature indicates that trilemma performance is closely associated with economic growth, and that improving the economic dimension is the most critical channel through which trilemma mitigation reduces CO_2 emissions.

Fourth, mitigation measures operate through multiple channels: portfolio optimization and market design, multi-objective energy transition planning, active distribution networks and distributed energy resources, energy storage and green technological innovation, industrial chain resilience, environmental regulation, and social factors such as education. These measures do not act independently; their effectiveness depends on the coordination of policies, market participants, and regulatory institutions.

In summary, under the "dual carbon" goals, the "impossible triangle" of a fossil-fuel-dominated energy system can be transformed into a "possible triangle" and further into a "sustainable triangle" for the green energy transition revolution. Achieving this transformation requires not only technological innovation and industrial upgrading, but also institutional arrangements that reconcile security, equity, and efficiency across regions and over time.

Future research could proceed in four directions: developing a unified and cross-scale measurement framework for the trilemma; incorporating the three dimensions into dynamic coupled or general equilibrium frameworks to capture long-run interactions; examining how specific policy instruments—subsidies, carbon pricing, and differentiated environmental regulation—interact with multi-agent behavior; and extending the analysis to county-level and firm-level data so as to identify more micro-level mechanisms. Comparative studies across countries and energy systems would also help test the generality of the "impossible–possible–sustainable" triangle proposition.

5.2. Future Prospects

China is the world's largest country in terms of energy production, energy consumption, and energy imports, so its energy resource endowment needs to be reappraised: it should be described as "more coal, less oil and gas, and boundless wind and solar". Relative to global recoverable coal reserves and the reserve-to-production ratio, China's coal resources are not abundant; as both a major coal producer and a major coal consumer, China is not "coal-rich" but rather has "relatively more coal", whether compared with the rest of the world or judged by its own consumption. China is a major producer of oil and gas as well as a major global consumer of them, so it is not "poor in oil and gas" but rather has "relatively less oil and gas". China's wind and solar resources are enormous, domestically located, and renewable, and exploiting less than 30% of them would suffice to achieve China's energy independence. The endowment of "more coal and less oil and gas" means that China is weak in fossil energy resources, with a high degree of dependence on imported oil, gas, and other fossil fuels, and that its current energy supply is insecure. The solution to China's energy security problem lies in vigorously developing new energy. Any product or commodity can be "embargoed" and any company can be sanctioned; oil and gas can be embargoed, but no one can block the sunshine, and no one can sanction the wind. China is rich in new energy resources; new energy is an important guarantee of China's energy security and a realistic path for China to become an energy power and achieve energy independence. Under the "dual carbon" goals, building a "super energy system" that coordinates multiple forms of energy production and consumption with carbon neutrality is a strategic pivot. Underground carbon-based traditional energy, above-ground zero-carbon new energy, CCUS/CCS, and carbon sinks will be synergistically integrated, intelligently managed, and innovatively allocated to form a carbon-neutral "super energy system", develop new quality productive forces, build a new energy system, lead and promote the realization of the "dual carbon" goals, and provide green impetus for human development [3].

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