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Energy transition: Connotations, mechanisms and effects

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ABSTRACT

Currently, the research agenda of energy transition is gaining momentum. This paper conducts a comprehensive review of this body of research by presenting a framework that describes the connotations, mechanisms, and effects of energy transitions. The study concludes that the energy transition will lead to the reconstruction of energy system elements beyond the energy sector, with the dual connotations of explicit transition and implicit transition. The explicit transition is usually captured by statistic data and information, for instance, energy utilization type, structure, form, transportation mode, and spatial pattern. The implicit transition involves shifts in energy security, geopolitical structure, energy power, energy justice, and energy governance, which receives relatively less attention in current literature. The energy transition is a highly socialized process, driven by many intertwined factors such as technological innovation, market mechanisms, policy arrangements, and sociocultural factors, triggering profound socio-economic and ecological effects. Looking ahead, it is urgent to pay attention to the multi-scale effects of energy transition, avoid the risks brought by energy transition, and ultimately achieve just energy transition. This paper provides a novel perspective and contributes to the literature on theoretical understanding and advancement of energy transition.

1. Introduction

The transition to zero carbon, aiming to achieve global carbon neutrality, poses a significant challenge for human society. Against this background, the energy sector is one of the major stakeholders called upon to address this challenge [1]. To achieve net-zero emission targets and limit global warming to 1.5 °C by 2050, a sustainable, efficient, competitive, and secure energy system needs to be developed [2,3]. Benefiting from improved cost competitiveness and widespread support for low-carbon energy policies, renewable energy, particularly wind and solar, has experienced unprecedented growth in the last decade, consistently surpassing expectations. According to data released by the International Renewable Energy Agency (IRENA), by the end of 2021, the global installed capacity of renewable energy reached 3.064 billion kilowatts, accounting for 38.3 % of the total installed power supply. Meanwhile, according to the IEA's stated policy scenarios, renewables are projected to contribute 80 % to the incremental installed electricity globally by 2030 [4–6]. In the long run, shifting from fossil fuels to renewable energy sources is an important energy strategy to achieve net-zero emission targets, and has been identified as a fundamental action framework among policy-making circles around the world [7,8].

Historically, an energy transition refers to the shift from one dominant energy resource—or set of resources—to another, switching from low-efficient energy sources towards high-efficient ones [9]. Referring back to history, human society has experienced two energy transitions from the firewood era to the coal era and eventually to oil [10]. The latest phase of energy transition, which is at the center of discussions in this paper, is marked by a shift from carbon-based energy, most significantly coal and oil, to lower-carbon energy resources such as gas, wind, solar, and hydropower. Since the global oil crisis in the 1970s, many countries have started to advance energy transition strategies that seek alternative energy solutions [11]. Researchers from the German Institute of Applied Ecology believed that economic growth could be achieved with less energy consumption under the conditions of turning to renewable energy and improving energy efficiency. In 1982, the Institute published the book "Energy Transition, Growth and Prosperity without Oil and Uranium", which first proposed the notion of "Energiewende" [12], pointing out that the dominant energy in the future

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should shift from oil and nuclear energy to renewable energy, which can be regarded as an embryonic form of the concept of renewable energy transition.

Overall, energy transition is an issue of tremendous academic, policy, and practical importance. Over the past few decades, energy transitions have unfolded at an unprecedented pace, resulting in the emergence of a substantial body of literature dedicated to this subject (Table 1) [13–17]. For example, Podobnik defines energy transition as a process in which a new primary energy source is widely used for human consumption through the invention of new technologies or the discovery of new types of energy [18]. Smil defines energy transition as a process of changing from a specific energy combination to another and points out that if the proportion of new energy in the energy consumption structure reaches 5 %, it can be regarded as signaling the beginning of energy transition, and if the proportion exceeds half, it can be regarded as indicating the completion of transition [19]. "The Global Energy Transition" report, jointly issued by the World Energy Council and Kearney, defines energy transition as a fundamental change in a country's energy mix, such as an increase in the proportion of renewable energy, an improvement in energy efficiency, and the phasing out of fossil fuels [20]. These studies have undertaken an intricate exploration of the concept of energy transition, particularly with regard to the various facets encompassing types, forms, and structures of energy consumption. Nevertheless, these definitions may be considered somewhat cursory, as they do not comprehensively encompass the complex transformations occurring within energy policies, infrastructure landscapes, socio-technical systems, and societal practices that underlie the process of energy transition.

Table 1
Existing definitions of energy transition.

Division	Definition	Ref.
Types, forms and structures of energy consumption	A structural shift toward a world energy system that is mainly based on renewable energy.	[21]
	The shift from one dominant energy resource—or set of resources—to another.	[22]
	The time that elapses between the introduction of a new primary energy source, or prime mover, and its rise to claiming a substantial share of the overall market.	[23]
	A shift in the nature or pattern of how energy is utilized within a system.	[14]
	A transition was from 5 % to 80 % (or the peak, if it did not reach 80 %) of the energy consumption for a particular service in a specific sector.	[24]
	A change in fuels (e.g. from wood to coal or coal to oil) and their associated technologies (e.g. from steam engines to internal combustion engines).	[25]
	Shifts in the fuel source for energy production and the technologies used to exploit that fuel.	[26]
	A single energy source, or group of related sources, dominated the market during a particular period or era, eventually to be challenged and then replaced by another major source or sources.	[27]
Socioeconomic ramifications	The switch from an economic system dependent on one or a series of energy sources and technologies to another.	[28]
	Pervasive changes in an energy system that affect multiple energy resources, carriers, sectors, and end-use applications, often associated with the diffusion of "general purpose" technologies (e.g. steam engines or electricity).	[29]
	A particularly significant set of changes to the patterns of energy use in a society, potentially affecting resources, carriers, converters, and services.	[30]
	Energy transition is a new direction that pertains to both the socio-technical landscape and the socio-political-technical regime that maintains it.	[16]
	Long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption.	[31]
	Energy transition is fundamentally a geographical process that involves reconfiguring current spatial patterns of economic and social activity.	[32]
	A shift toward a high-efficiency energy system that is well-managed to balance environmental and social costs, risks, and benefits such that the shift is deemed to be sustainable.	[33]

Notably, and with specific relevance to this essay, certain scholars have expanded their purview beyond the mere consideration of energy consumption and, instead, have directed their attention to the broader socio-economic implications of energy transition. They define energy transition as the interplay between the energy system and the socio-economic system (Table 1). For instance, Child and Breyer suggest that the concept of energy transition also refers to a complex development of economic, social, and political regimes associated with shifts in technologies [16]. Bridge et al. note that energy transition is fundamentally a geographical process that involves reconfiguring current spatial patterns of economic and social activities [32]. Chen et al. and Mohammad et al. believe that an energy transition foresees a well-managed, high-efficiency energy system that can balance environmental, social, and economic costs, risks, and benefits [33,34]. In essence, an energy transition represents a multifaceted, enduring, and structural evolution within energy systems [15,35–38]. Mainstream research has predominantly concentrated on two key heuristic approaches to comprehending energy transition. The first pertains to the alteration of energy usage, suggesting that the widespread adoption of a particular type of new energy signifies the onset of a transition [10]. The second heuristic underscores the modification of energy mixes, emphasizing that the process of energy transition encompasses a succession of transformations in the structures of energy production and consumption [28,39,40]. Overall, prior research has offered descriptions of epistemic variances within the realm of energy transition but has yet to furnish compelling evidence substantiating the existence of such divisions.

Fundamental transitions incurred by the energy transition not only involve a deeper transformation in energy technologies and economics, but also physical and human geographies, social meanings, and the political organization of energy production, distribution, and consumption [26]. In the interim, it is imperative to recognize that an energy transition will not materialize spontaneously, whether at the local, regional, national, or international scale [41,42]. Instead, it gives rise to a profoundly intricate, contentious, and heterogeneous social process driven by a multitude of interconnected factors. With the growing scholarly and public interest in energy transition, it becomes imperative to develop a more systematic epistemological framework to better understand the driving forces and consequences of this process. Specifically, energy transition brings about extensive and profound social and economic changes, highlighting the increasingly co-constitutive relationships between the socioeconomic system and the ecosystem. Unfortunately, although the term "energy transition" is now widely used, there is yet to be a systematic cognition of, and analytical framework on, energy transition [15]. To fill this research gap and to ensure that the ongoing and future energy transitions articulate well with local needs and socioeconomic contingencies across varying contexts, it is necessary to (1) further nuance the connotation of energy transition; (2) explicate the driving mechanisms; and (3) reflect on its multi-dimensional ramifications.

This paper contributes to the literature on energy transitions by presenting an analytical framework that describes the connotations, important driving mechanisms, and effects of the process (Fig. 1). This analytical framework provides a novel perspective that attempts to illustrate how energy transitions can be studied through more conventional explicit and underrepresented implicit analyses, as well as identifying the intertwined mechanisms of energy transition and multidimensional ramifications.

2. Nuancing the connotation of energy transition

There have been three energy transitions in human society so far (Fig. 2): the first is the replacement of firewood by coal; the second is the replacement of coal by oil; and the third (and on-going) transition is the replacement of fossil energy represented by oil and coal by clean and renewable energy. By nature, the current wave of low-carbon energy transition foresees a pattern of energy production and consumption dominated by clean electricity to achieve net-zero emission by 2050.

Energy transition is essentially a process of fundamental transformations of the main elements of the energy system towards a new configuration of energy service embodied in a prolonged chain and complex system that involves energy production, storage, transmission and consumption, energy technologies, management, and practices related to energy security, geopolitics, and energy governance. Therein, this paper elaborates on the connotations of energy transition from multiple dimensions such as energy type, structure, form, transportation, spatial pattern, technology, benefit, management mode, energy security, geo-structure, geo-energy power, and energy governance. Specifically, the connotations of energy transition are elaborated as both having an explicit and implicit dimension (Fig. 2).

2.1. Explicit connotations

The explicit connotations of energy transition are usually captured by statistical data and information, through the analysis of, for instance, energy utilization type, structure, form, transportation mode and spatial pattern in the midst of transformation. Signaling energy transition, the energy type will change from fossil energy to renewable energy; electricity will become the main conduit of energy; and emissions resulting from energy utilization will change from carbon-intensive to low carbon, or even zero carbon [43–45]. The energy structure will be more diversified, showing a transition process in which the quantity of fossil energy consumption and its proportion to the whole mix gradually decrease, while the quantity of renewable energy consumption and its proportion increase [46,47].

The energy form refers to a transition process from solid (coal) and liquid (oil) to gaseous (natural gas) and ionic (electricity) forms [48]. With the transition of energy form, the energy transportation mode will also change from energy transportation channel and pipeline network to power grid, and cross-regional energy grid will play an essential role in the transportation of renewable energy. In addition, fossil fuels are not evenly distributed throughout the globe, the broad-spectrum of renewable energy will change the uneven spatial distribution pattern and enhance spatial justice of the transition from unbalanced distribution to relatively balanced distribution [49].

2.2. Implicit connotations

Implicit energy transition refers to the transition of more latent and intangible transitions co-constituted by the explicit processes of energy transition, such as energy technology, benefit, management mode, energy security, geopolitics, energy power, energy justice, and energy governance.

First of all, energy transition will alter the dependence of the energy industry on fossil energy and extracted resources to form a sustainable energy system that involves fundamental technological changes. With the progress of low-carbon technology, the energy sector in the renewable energy era will be technology-oriented, which will liberate the energy system from the traditional ‘lock-ins’ to carbon-heavy energy [50]. The energy transition will depart from the development paradigm that prioritizes economic benefits while neglecting the social and ecological aspects prevalent in the fossil energy era. Instead, it will strive to achieve synergistic benefits encompassing the realms of economy, society, and ecology, thereby enhancing the capacity for sustainable development.

Second, energy transition is expected to create decentralised energy geographies [31], through the de-monopolization and de-centralization of energy production, consumption, and distribution [51], where a diversity of producers and consumers, such as residents, community energy organizations, and participants in social movements play increasingly critical roles [52,53]. The decentralization and intermittency of renewable energy necessitate a shift in its development, utilization, and management towards a distributed and intelligent approach. This departure from the monopoly and centralization of fossil fuels will enable the maximization of flexibility in renewable energy utilization and management, while also facilitating “energy democracy” [54].

Third, energy transition will shift the notion of energy security from energy supply security to systematic security [55]. In the fossil-fuel scenario, the focus of energy security lies in energy supply security and price stability, and there is a limited diversity of energy sources.

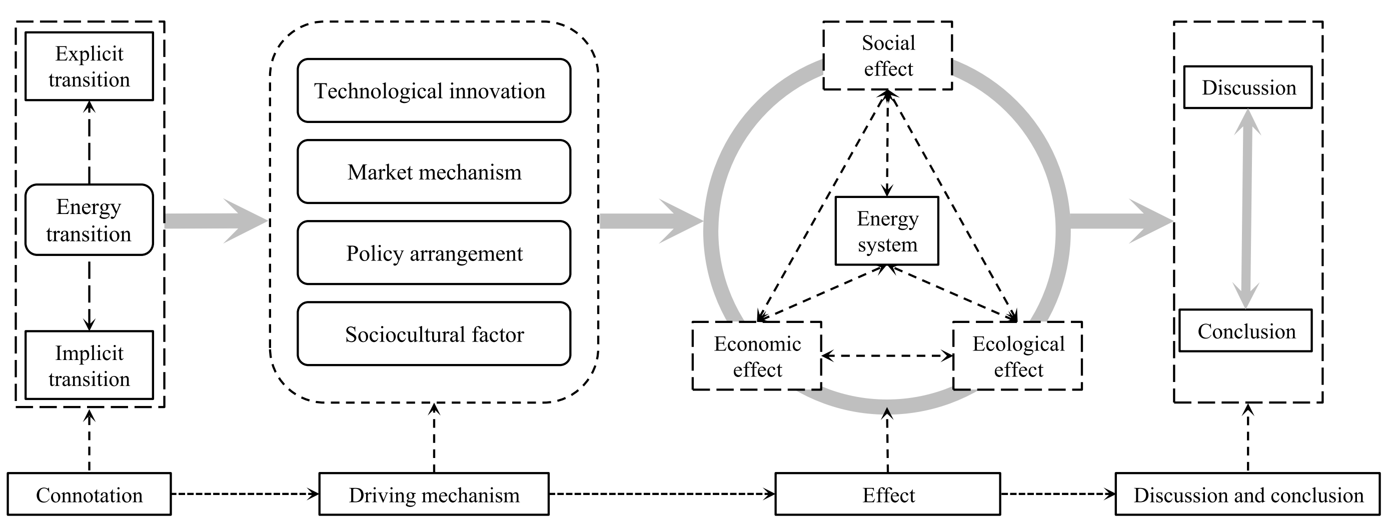

Fig. 1. Energy transition analytical framework.

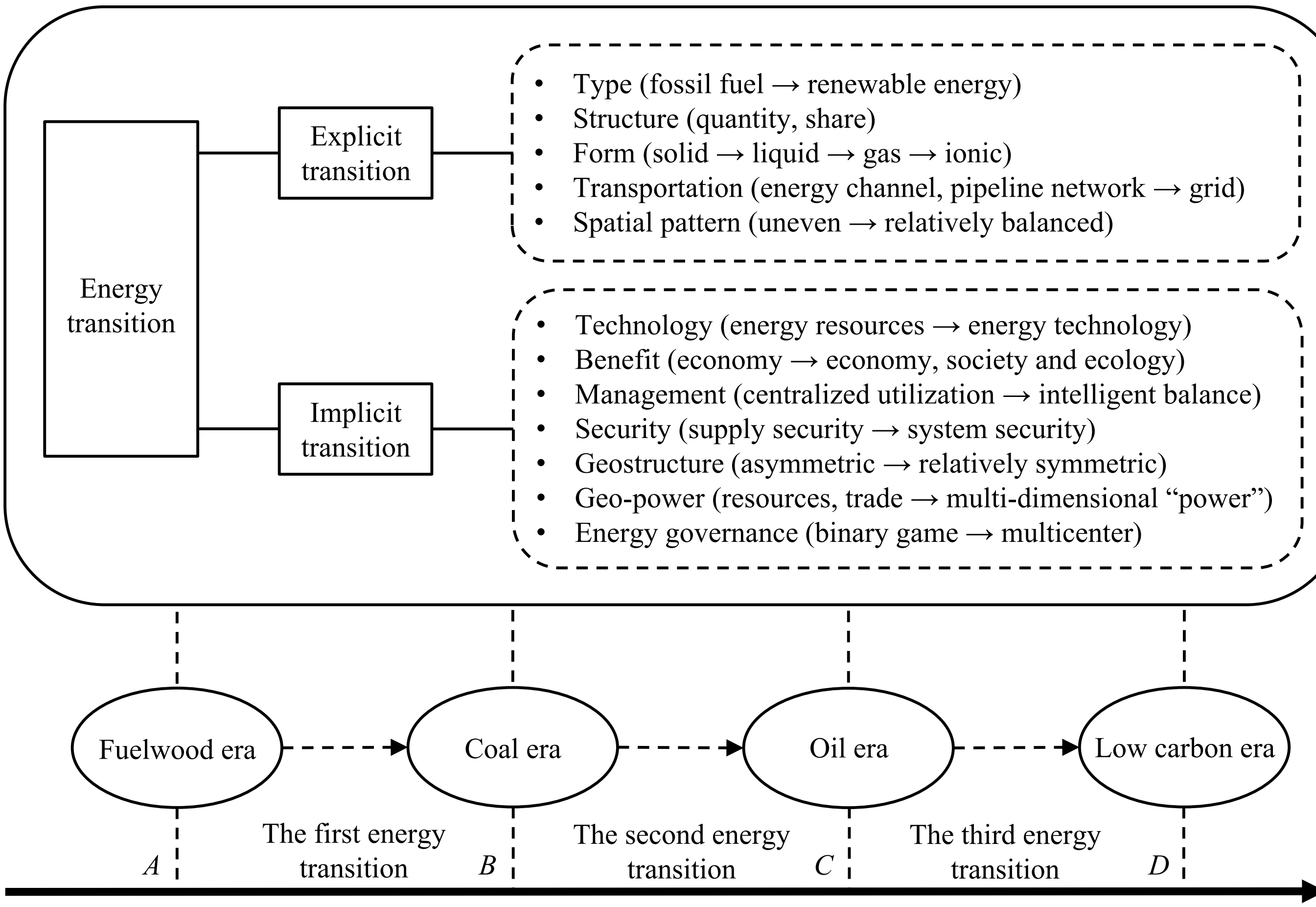

Fig. 2. The connotation of energy transition.

Energy security in the era of transition would embrace broader social, economic, and environmental dimensions, such as energy availability, infrastructure resilience, energy prices, societal effects, environmental considerations, governance, and energy efficiency [55], with a more diversified energy mix. On the other hand, energy transition also introduces new security vulnerabilities and risks, including supply chain instability of critical minerals required for the manufacturing of renewable energy technologies and susceptibility to cyberattacks targeting energy infrastructure [56–61]. Supply chain security and cybersecurity have become pivotal aspects of energy security in the era of renewable energy.

Fourth, energy accessibility is inherently affected by geopolitical factors, as nations rich in energy resources often seek to safeguard their reserves [56,62]. The geographies of fossil fuels often leads to frequent geopolitical conflicts, characterized by "asymmetric" geopolitical structure [63]. However, the energy transition will change the geographic concentration and imbalance of hydrocarbon resources that traditional energy geopolitics relied upon, leading to the decentralization of renewable energy supply, a re-balancing of the spatial distribution of energy resources, the emergence of a relatively symmetrical geopolitical structure [49]. The geopolitics triggered by the energy transition will no longer be confined to the energy sector, but will extend to encompass renewable energy technologies and critical minerals. As the energy transition progresses, renewable energy technologies and critical minerals are evolving into significant variables, reshaping the global energy geopolitical landscape.

In addition, the energy transition will usher in a profound change in the role of power in energy geopolitics [64,65]. While the key source of power in the fossil energy era lies in the control of resources and trade routes, in the scenario of renewable energy, the focus will be shifted to the control of energy investment, technology, and the market. Energy no longer merely represents the interests of state entities or big energy corporations but is a process of ongoing power redistribution within the interweaving networks of global energy production, trade, consumption, and investment. Energy transition facilitates the broadening of energy authority across various multi-dimensional "energy power", such as energy supply, energy demand, energy technology, energy finance, carbon emission, and development [64,65].

Energy justice is the concept that every group should have access to energy that is affordable, safe, sustainable, and capable of supporting a decent quality of life. It also entails the opportunity to engage in energy-related decision-making processes and the right to bring about changes in this regard. A just energy transition puts social justice at the center of the transition. In essence, energy transition serves as a potent catalyst for democratization and justice, as renewable energy enables the decentralization of energy supply. This empowers citizens, local communities, and cities, ultimately facilitating the realization of both energy justice and energy democracy.

Lastly, energy transition will reconstruct the system of global energy governance. In the era of fossil energy, geopolitics related to energy governance is dominated by major producers and consumers of energy, exhibiting a typical "binary game" model [66,67]. As the energy transition progresses, various energy stakeholders, including international energy agencies, national governments, non-governmental organizations, and multinational energy companies, engage in interactions related to diverse energy domains, thereby contributing to the emergence of a "polycentric" system in global energy governance [68,69].

In summary, energy transition is not merely a straightforward substitution of one energy source for another. Instead, it signifies comprehensive and profound transformations within the energy system [70, 71]. It involves long-term, complex, and multi-dimensional reconfigurations of the energy system, encompassing technology, policy, infrastructure, scientific knowledge, and social culture to achieve the goal of combating climate change and advancing sustainable development.

3. The driving mechanisms of energy transition

The analysis of driving mechanisms constitutes an important component of both theoretical and practical research related to energy transition. Energy transition does not occur spontaneously; instead, it is a highly socialized process influenced by a multitude of factors with varying influences [41,42]. Currently, many policy-oriented energy researchers and climate models still adhere to disciplinary approaches that focus on singular facets of the energy transition, yet overlooking various socio-technical factors for accelerated transitions [72]. Socio-technical transitions theories can address the multi-dimensionality of the energy transition challenge and show how coevolutionary interactions between technologies and societal groups can accelerate energy transitions [73–75]. Inspired by this, we believe that the interrelated factors such as technology innovation, market mechanism, policy design, and sociocultural conditions are key to revealing the mechanisms underlying energy transition. This section elucidates the driving mechanisms of energy transition through four broader lenses, namely technology innovation, market dynamics, policy arrangements, and sociocultural influences (Fig. 3).

3.1. Technological innovation

Technological innovation of renewable energy is one of the most important factors leading to the success of energy transition [31,76,77]. The primary rationale behind technological innovation propelling the energy transition manifests itself in two key aspects. From the perspective of the action mode, technological progress has become the key driving force in the energy transition by promoting the innovation of energy production factors, changing the form and function of energy system elements, and making low-carbon technology highly integrated into the whole energy industry chain. From the perspective of the effect, on the one hand, technological innovation improves the structure of various factors within the energy system and optimizes the allocation of factors, improves the marginal output level of production factors and the efficiency of energy factors, so as to maintain the long-term competitiveness of renewable energy. On the other hand, renewable energy technology is increasingly integrated into a modern information and smart grid, constantly producing new products, patterns, and business models of energy utilization, which will greatly improve energy efficiency and promote low-carbon energy transition [78,79].

Furthermore, from the perspective of the relationship between supply and demand in the energy market and the mechanism of division of labor in the energy industry, technological innovation will change socio-economic factors, thereby promoting energy transition. On the one hand, low-carbon technological innovation drives the iterative upgrading of energy utilization, brings about the transition of energy consumption patterns, changes the supply-demand relationship in the international energy market, and then drives the process of energy transition. On the other hand, the advanced level of energy technology determines a country's position in the global energy industry and value chain, and technological evolution promotes the transition of global energy production structure and consumption structure, thus promoting the process of energy transition.

3.2. Market mechanism

Energy transition is largely influenced by the supply and demand dynamics of resources in a market economy [80]. Achieving net-zero emission targets will inevitably entail the phasing-out of fossil fuel capacity, which highlights the importance of market mechanisms in facilitating long-term energy transition [81]. With the decline in the market cost of low-carbon technology, the commercialization of renewables has become a main driving force of low-carbon energy transitions [82].

The logic of energy transition driven by market mechanism is mainly reflected in the following three aspects: First, from the perspective of

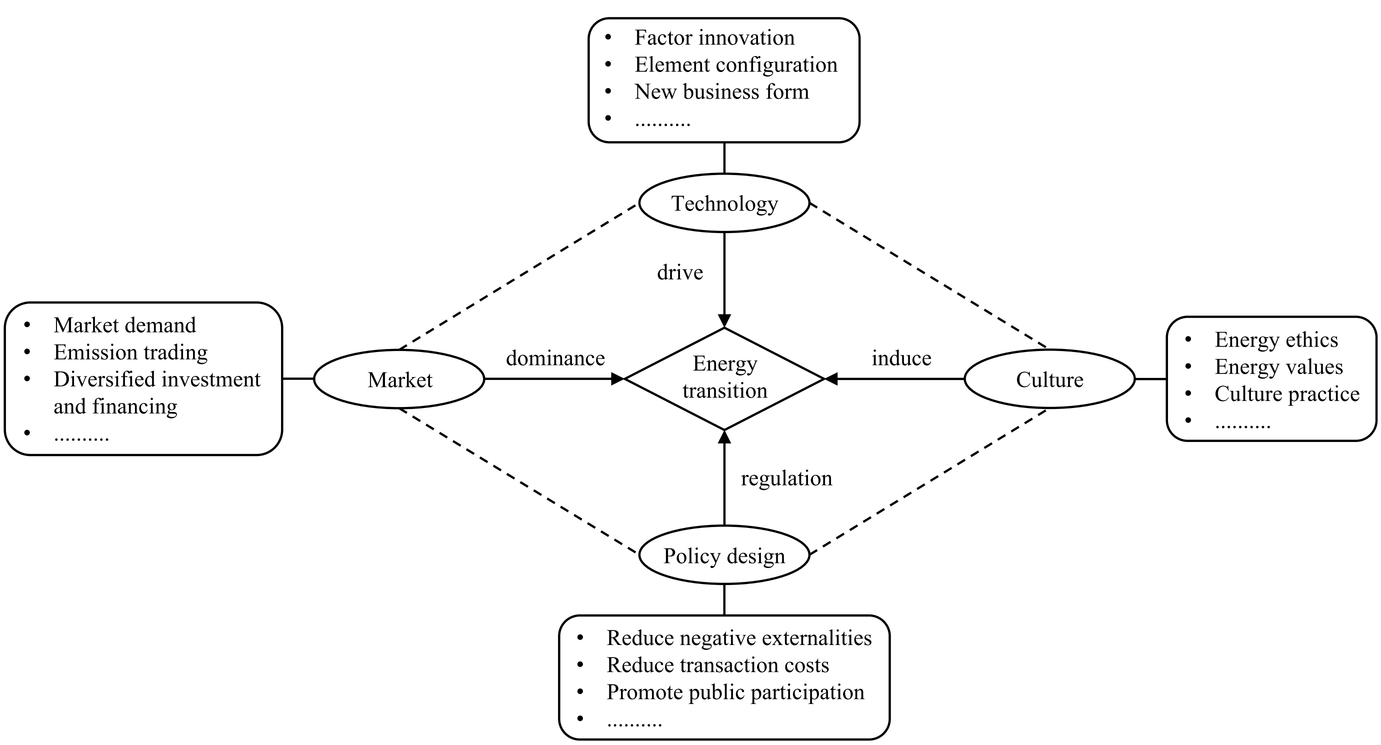

Fig. 3. The framework of energy transition mechanisms.

supply and demand, market demand plays an irreplaceable regulatory role in energy supply because the orientation of market demand often shapes the patterns of supply. The energy consumption demand in line with the concept of sustainable development will effectively promote the energy transition under the condition of adapting to the market demand of energy consumers. Second, as a market-based environmental economic policy [83], emission trading, especially carbon trading, is essentially a market incentive to allocate resources by market mechanisms, which can effectively internalize the environmental costs of energy utilization, increase the environmental cost of using fossil energy, and promote technological innovation of clean energy. Market emission trading promotes the development of renewable energy by improving the use of green and low-carbon energy and reducing the demand for emissions allowances, creating economic incentives to promote energy transition [84]. In addition, the diversified investment and financing mechanisms of the market promote energy transition. By means of incentives, subsidies, and loan discounts, all kinds of social capital are encouraged to participate in the investment, construction, and operation related to renewable energy, so as to promote the diversification of investors in the renewable energy market and drive energy transition.

3.3. Policy arrangement

Effective policy design could regulate energy transitions, and play a key role in initiating, accelerating, or supporting energy transitions, providing a supportive framework for the energy transition [31,77,85,86]. On the one hand, effective policy arrangements could improve the benefits of policy innovations related to energy transition and reduce the negative externalities of renewable energy sources [87]. On the other hand, by setting and implementing legally binding climate and energy transition targets and related policies, the state steers enterprises to carry out renewable energy-related R&D activities and production, thus promoting energy transition [88]. In addition, policy innovation also establishes the basic rules for people to participate in the production, exchange and benefit distribution of products and services related to energy transition, and reduces the uncertainty and information asymmetry in the emerging energy market [89]. Through the institutional arrangements of formulating codes of conduct, arbitration and enforcement rules, the transaction costs in the market can be effectively reduced, and ultimately the energy transition can be promoted [90]. Energy transition is a highly complex social process that requires close collaboration between diverse stakeholders such as international energy organizations, regional and national governments, energy companies and utilities, research institutions, advocacy groups, and local communities. Through policy innovation, not only the environmental awareness of these stakeholders is translated into actions, but the coordination among different stakeholders' interests is also promoted [87].

3.4. Cultural factors

Sociocultural factors, such as education level, gender roles, family structures, food preferences, cooking habits, rituals, house materials, and ethnobotanical knowledge, often reflect local energy consumption habits and their socio-technical manifestations, and are important in influencing fuel choices and catalyzing efforts to promote the energy transition [91–95]. Energy culture, including energy ethics and energy values, is often embedded in social and economic contexts as an informal system established through negotiation of meanings and ethical codes during actual usage, and can manifest itself at multiple scales and in many spheres of social life. This adds another layer of complexity to the energy transition [96–98]. In addition, cultural factors affect the formation of the routines and patterns of energy consumption in a country or region. Specifically, a regional culture that emphasizes the economic attributes of energy while neglecting its social and ethical attributes often perpetuates a system devoted to the one-sided pursuit of the commodity output growth of energy. The growing demand for commodity production contributes to the escalating scarcity of energy, often directed towards the function with the highest marginal output. This pursuit prioritizes the maximization of the economic benefits from energy utilization, sometimes at the expense of sustainable energy use, thereby impeding progress in energy transition.

On the contrary, regional cultures that encompass economic, social, and environmental considerations in their approach to energy foster a cultural perspective that emphasizes the pursuit of sustainable energy use and the attainment of economic, social, and ecological benefits, thereby promoting low-carbon and sustainable energy transitions. From the viewpoint of social practice theory, energy practices, involving the formation and perpetuation of local culture, play a pivotal role in energy transition. This includes local religious customs, norms, beliefs, national identity, and family practices, all of which can exert influence on the energy transition process [91,99].

4. Ramifications of energy transition

The energy system is not isolated, but always related to social, economic, and ecological systems (Fig. 4). It is widely anticipated that the energy transition will lead to a reconstruction of the socio-economic system and ecological system that were originally based on fossil energy, resulting in a broad spectrum of socio-economic and ecological effects [100]. This section provides a comprehensive review of how energy transitions impact social equity, economic development, and ecological environment.

4.1. Social effects

Energy transition will trigger a wide range of social effects, bringing about changes in areas such as energy accessibility, employment access, and public health. In the era of low-carbon energy transition, there are increasing concerns about the intensification of energy poverty [101]. Energy poverty is not only manifested in the high dependence on traditional biomass energy or other fossil fuels, but also in the difficulty of paying and obtaining electricity or other clean energy services [102,103]. This paper identifies two main groups of perspectives on this issue: the "increased energy poverty" approach and the "reduced energy poverty" approach. The former believes that energy transition is likely to increase energy poverty, and the latter believes that greater self-sufficiency will reduce energy poverty.

The first camp argues that energy transition will increase the cost of energy use, such as heating, cooking, and refrigeration to a certain extent and impose an additional burden on low-income households and thus aggravate energy poverty. Their research shows that subsidies and various other incentives for low-carbon technologies disproportionately increase the percentage of household income spent on energy by marginalized groups, which leads to increased energy poverty [104,105]. The energy transition not only increases household expenses on fuel, but also related financial burden by increasing the share of fuel expenses in household total expenditure and total income and leads to energy poverty [106]. In the process of energy transition, rural households' energy expenditure will increase disproportionately to urban households, and they face higher clean energy transition costs. Therefore, forcibly promoting energy transition may face great resistance, and even cause energy poverty in rural households [107].

By contrast, the reduced energy poverty camp believes that affordable, reliable, and sustainable energy is readily available in a world that has renewables as its main source of energy, and transitions to clean energy can increase access to electricity in impoverished areas, benefit households who suffer from energy poverty, and reduce energy poverty as a whole [108–110]. This group of scholars emphasizes that compared to fossil fuels, renewable energies are widely distributed, and every country has one or more types of renewable energy sources [111]. The renewable energy transition therefore will promote decentralization of energy supply, lead to greater energy self-sufficiency, and reduce energy

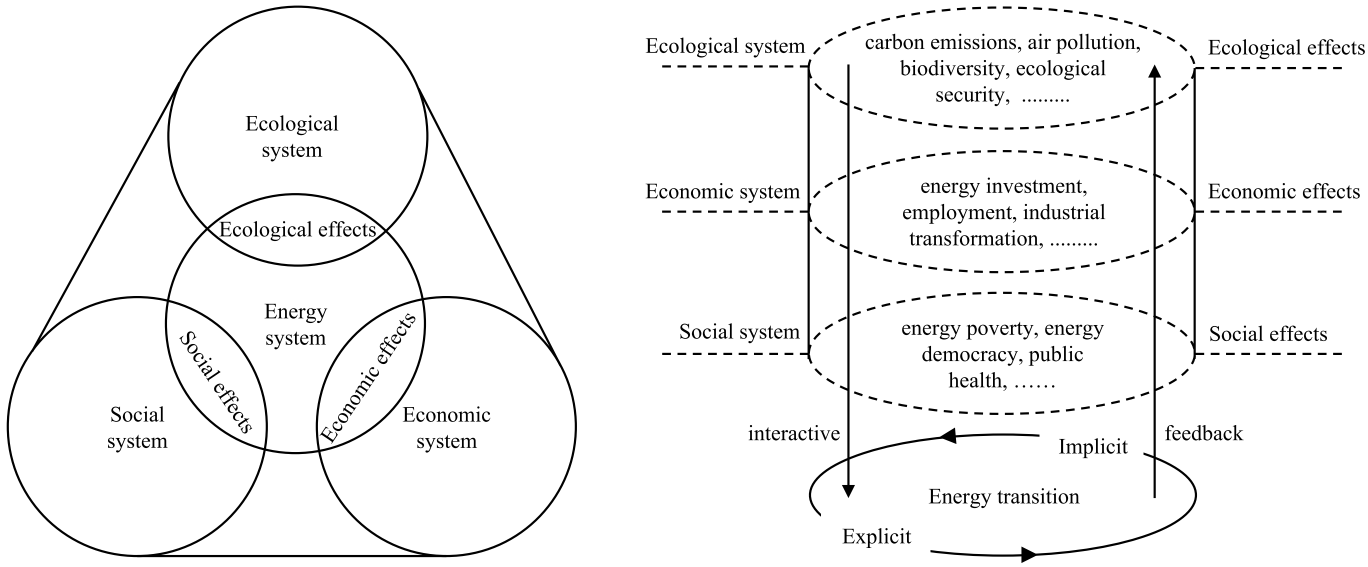

Fig. 4. Research framework of energy transition effects.

poverty. It might shift the focus of energy consumption from external to internal supply, creating a broader horizon of actions for reducing energy poverty. A number of studies have been published, highlighting that the promotion of energy transition can improve energy independence at the national or community level, achieve energy democracy and diversification of energy supply, and therefore help get rid of energy poverty [100,112,113].

As regard to public health, it is an indisputable fact that solid fuel combustion puts public health at risk. Long-term exposure to air pollution can easily lead to respiratory diseases such as lower respiratory tract infection, chronic obstructive pulmonary disease, bronchitis, and lung cancer, which seriously threaten public health. These health problems also directly affect people's study, life, and work [114–116]. Air pollution from solid-fuel stoves contributes to an estimated 2.8 million premature deaths annually and influences regional and global air quality and public health [116,117]. Low-carbon energy transitions are thus necessary to safeguard public health from air pollution [118]. Increasing evidence supports that the transition to renewable and clean energy will reduce the emissions of pollutants such as CO_2 and $PM_{2.5}$, improve air quality, and bring synergistic benefits to health and climate [119–121]. For example, A study conducted by Zhang et al. shows that urban residential energy switching from coal to clean energy in China between 1980 and 2014 effectively improved the health of residents and prevented 2.2 million premature deaths [122]. In addition, with the scenarios that included ambitious energy transition plans and met international climate goals to limit global warming to 1.5 °C and 2 °C, there were substantial decreases in China's $PM_{2.5}$-related deaths compared with NDC goals in 2050, and age-standardized death rates decreased by 10.2–14.2 deaths per 100 000 population per year [116].

4.2. Economic effects

Energy consumption contributes to economic growth, but energy from renewable sources is preferable to fossil fuels. The transition from fossil energy to renewable energy ushers in new patterns of global green and low-carbon development, and promotes systematic changes such as the adjustment of energy industrial structure, the transition of production organization mode, and technological breakthroughs, exerting a far-reaching impact on economic development [123]. First, energy transition has a significant positive impact on economic growth by promoting the diversification of energy supply and reducing the impact of volatile fossil energy prices on the economy. Second, energy transition can enhance the sustainability of economic development by reducing the constraints of balance of payments and the negative externalities of fossil energy on the environment.

Energy transition would produce varying positive impacts on the macro-economy, achieving varying extent of double dividend effects [124]. Studies have shown that economic growth and renewable energy are positively correlated both in the short and long term, which testifies to a valid feedback hypothesis [125]. Large-scale renewable energy development would not incur a significant macroeconomic cost. On the contrary, it would have significant green growth effects that benefit the growth of upstream industries, reshape the energy structure, and bring substantial economic co-benefits [126]. However, the economy cannot avoid a temporary energy lock-in when the level of technological sophistication required for energy transition is not attained. In such circumstances, the transition from non-renewable energy to renewable energy may induce a shock and then degrowth [127]. Thus, unsurprisingly, some studies have pointed out that the transition to renewable energy does not seem to be economically feasible in the short term, but over time, renewable energy consumption will have a positive impact on economic growth [128].

The impact of the global energy transition on employment is of critical importance for the social viability of achieving net-zero emission targets. As the electric power industry is a basic industry of the national economy, the low-carbon transition of electric power characterized by the large-scale development of renewable electricity will inevitably lead to changes in the size of employment and the mix of skills required for jobs in the energy sector [129–131]. An increasing number of studies have looked at the impacts of energy transition on employment [132–134]. Among them, "green jobs" as a synergistic benefit of energy transition has attracted more and more attention from policymakers and researchers [130,135,136]. It is widely believed that energy transition will have a positive impact on employment, that is, the new green jobs created in the renewable energy sectors will compensate for the jobs lost in the fossil fuel sectors [132,137]. According to the International Labour Organization (ILO), measures to mitigate climate change, such as implementing cleaner energy, improving the efficiency of energy systems and buildings, and adopting electric vehicles, could generate 24 million new jobs, while only about 6 million jobs could be lost due to the scaling back of carbon-intensive industries (ILO 2018) [138].

However, some scholars pointed out the mismatch of employment distribution related to the energy transition [135,139], that is, new green jobs generated in the clean energy transitions may not be located in areas where fossil-fuels-based jobs are lost. If a particular location is only going to experience negative labor impacts, it may undermine societal support for energy transition in those areas. Therefore, from the perspective of justice, alternative training and employment opportunities or compensation must be provided for those who are likely to lose their livelihood due to the energy transition. In addition, "green jobs" do not necessarily exist, but depend on multiple factors such as the type of renewable electricity, the way of subsidies, and the measurement of employment impact [130]. Hence, policymakers should fully understand the complexity and systematicness of the impact of energy transformation on employment, and avoid policy bias caused by over-optimistic attitude.

4.3. Ecological effects

Global efforts to promote energy transitions are central to mitigating climate change and preclude the strong negative impacts of projected climate change on the ecological environment. An energy system dominated by fossil fuels has been found to be highly problematic from the environmental and health perspective. These problems include toxic gas emissions, depletion of natural resources, air pollution, endangered wildlife, etc., which are closely related to global climate change [140–142]. Achieving low-carbon energy transition can minimize the devastating impacts on the environment, which is essential for improving the environment and tackling climate change [143–145]. Climate change policies that promote a transition to renewable energy sources have the potential to achieve environmental benefits, such as reducing air pollutants, and carbon dioxide emissions and improving air quality [146]. In the long run, low carbon transition is essential to mitigate climate change and build an eco-friendly society [147].

Although it is widely acknowledged that increasing the proportion of renewable energy can reduce carbon dioxide emissions, many studies have shown that the prospect of renewable energy to reduce emissions depends on the size of the national economy and the level of income inequality [148–151]. In addition, In the process of energy transition, the large-scale development and utilization of wind power and solar energy resources will also bring new environmental hazards. First, there is a conflict between the site selection of renewable energy development and land use, and improper site selection may cause ecological damage. Some studies have pointed out that the deployment of renewable energy infrastructure poses a threat to biodiversity conservation [152,153]. For example, the construction of renewable energy will change land use, surface functions, and local ecosystems [154,155]. Globally threatened large scavengers and other unique and rare soaring birds are paying a heavy toll for the approximately 20 000 existing turbines, with demographic consequences for some threatened populations [156–158]. Careful strategic planning is therefore urgently required to ensure that the threats to biodiversity caused by renewable energy transition do not bypass public and policy attention simply due to the problems averted by efforts to slow fossil fuel extraction and use [159]. Second, the manufacture of new energy equipment relies on a large number of mineral resources, and over-exploitation of mineral resources will have a negative impact on the environment [159–161]. However, a recent study shows that although conservation scientists warn that renewable energy infrastructure poses a threat to area-based conservation, the current and near-term overlap of the two land uses need not be as severe as previously suggested. If appropriate policies are adopted and the deployment of renewable energy infrastructure is properly planned and managed, it will be possible to achieve climate goals while avoiding significant negative impacts on biodiversity conservation [162].

5. Discussion and conclusion

5.1. Discussion

(1) Fossil fuels have significantly shaped the current energy system, and coupled with the uncertainties surrounding the costs, technologies, and policies of energy transition, transitioning to renewable energy becomes a formidable challenge [100,163]. This ongoing energy transition is not merely a shift from one set of fuels to another, but also a highly complex social process, in which a wide array of actors are engaged in the multi-scalar and multi-dimensional transition process [11,100,164–166]. Meanwhile, energy transitions consist of fundamental and systemic changes across multiple domains (for example, economic, technological, social, institutional, cultural, political, and ecological) [31,167]. Transitions of this nature necessitate strong collaboration among regional and national governments, energy companies and utilities, research institutions, advocacy groups, and local communities [168]. As pointed out by IEA. (2020), "no one indicator can grasp the complexity of the world's transition to clean energy" [169]. In addition, energy transition is fundamentally a very complex spatio-temporal process "that involves reconfiguring current spatial patterns of economic and social activity" [32]. Therein, the effects induced by energy transition at different spatio-temporal scales exhibit strong heterogeneity. Looking ahead, it is necessary to further explore the geographical contours, evolutionary patterns, and driving mechanisms of energy transition under the background of multi-scale transition, and strengthen the research on the effects of energy transition at different spatial and temporal scales.

(2) The energy system exhibits strong transition inertia [170], embedded in the fossil-fuel-dependent energy system, the built infrastructure, and institutional legacies. That is to say, the energy system dominated by fossil energy shows strong path dependence, sometimes even 'carbon locking', making rapid transformation unattainable [170–172]. One of the core issues of energy transition is to understand the relationship between stability and risk. In order to realize the sustainable transformation of the energy system, the crucial factor lies in comprehending how renewable energy can evolve, disrupt, and potentially overhaul the established fossil energy-based system. This entails finding ways to deviate from the deep institutionalization within the existing fossil energy system and forge a new and innovative pathway toward a sustainable energy system. Currently, renewables alone cannot meet power demands, and global energy consumption is still dominated by fossil fuels, especially in developing regions that are heavily dependent on fossil fuels [173]. Statistics in 2020 show that 90.47 % of African energy consumption came from fossil fuels, and fossil fuel consumption in Algeria, Egypt, and South Africa accounted for more than 94 % of their total primary energy consumption [174]. Development projects such as roads, schools, and housing still operate on fossil fuels in these countries [173], if the transition from fossil fuel-based energy to renewables occurs under conditions of continuing high-energy demand, it will inevitably bring about energy supply shocks and may lead to energy security vulnerabilities [175]. Global fossil energy and power prices soared in 2021, resulting in fuel crises of differing degrees in nearly 30 countries and regions, such as the power and gas shortage in Europe and Brazil, the coal shortage in India, and the national power outage in Lebanon. These crises all signal energy system vulnerabilities. Therefore, countries must recognize that energy transition is a long-term process, and promoting the sustainable, stable, and just transition of the energy system needs to cope with the climate and economic risks.

(3) In advancing the energy transition, a critical subject that warrants thorough examination is how to secure fairness and justice throughout the transition process. Research on just energy transition emphasizes not only how costs and benefits are distributed during energy transitions, but also the importance of procedural justice and recognition justice [176,177]. The main argument is that justice issues need to be accounted for carefully in an energy transition, so as to prevent the generation of new, or the reinforcement of old, inequalities [11,178,179]. Furthermore, the shift towards lower-carbon energy sources is highly likely to result in inequities among various societal groups and between developing and developed countries on the global stage [22,180]. For example, energy transition heightens the issue of gender-blindness, that is women are hardly visible in energy transition, and their social roles and differentiated needs are generally relegated to the margins [181,182]. Therefore, during the low-carbon energy transition, it is crucial to focus on safeguarding the interests of vulnerable groups to ultimately attain a fair transition [101]. Neglecting this aspect could jeopardize meaningful climate change mitigation efforts. The international community needs to grapple with the challenge of upholding principles of fairness and equality to realize energy justice.

(4) One of the key contributions of this paper lies in the introduction of a theoretical framework with potential applicability. This analytical framework provides a novel perspective to illustrate the connotation of energy transition from explicit transition and implicit transition, as well as the intertwined mechanisms of energy transition and multi-dimensional ramifications. It will aid researchers, scientists, and policymakers in gaining in-depth and systematic understanding of the intricacies involved in the energy transition. However, it is important to clarify that our objective is not to establish a universal paradigm for energy transition applicable to all countries. Such an ambition is unrealistic, given the significant disparities that exist in energy transitions among nations (Table 2). These distinctions encompass not only social, economic, technological, and cultural facets but also extend to energy infrastructure, encompassing power grids and distribution networks. For example, developed economies typically boast well-established centralized power generation and distribution systems, while emerging economies exhibit distinct characteristics in energy generation, distribution, and connectivity. The paper does not assess whether the theoretical framework proves more effective in the context of developed or emerging economies. Therefore, the practical feasibility of the theoretical framework constructed in this paper in different countries has yet to be verified.

5.2. Conclusion

This paper presents both the explicit connotations and the implicit connotations of energy transitions. The process of explicit energy transition is usually captured through statistical data or information, encompassing changes in energy utilization types, structures, forms, transportation modes, and spatial patterns. Implicit energy transition, on the other hand, pertains to the transition of more latent and intangible attributes derived from the explicit processes of an energy transition, such as energy technology, benefit, management mode, energy security, geopolitical structure, energy power, and energy governance. The energy system is not isolated but always related to social, economic, and ecological systems. The shift toward renewable energy sources entails a profound transition of the entire energy system, with significant social, economic, and ecological consequences that extend far beyond the energy sector. In future research, it is urgent to explore the multiscalar effects of energy transition, mitigate the risks associated with this process, and ultimately achieve a “just and sustainable” energy transition.

Table 2
Energy transition pathways in major countries and regions.

Country/region	Energy transition pathways
United States	Promote the clean-up of the energy system on the premise of achieving “energy independence” by increasing the proportion of clean energy (including nuclear power, renewable energy, natural gas and clean coal, etc.), with a primary focus on supporting the research and development of advanced energy technologies.
German	The three primary objectives of energy policy encompass energy security, economic efficiency, and environmental sustainability. The path of energy transition primarily involves reducing energy consumption, enhancing energy efficiency, phasing out nuclear energy, and expanding the utilization of renewable energy.
Japan	The development of energy technology is a strategic measure to ensure energy security, stabilize energy supply, optimize energy structure, and improve industrial competitiveness. The energy transition is characterized by the large-scale utilization of hydrogen energy, with the proposal for the construction of a “hydrogen society”.
Middle Eastern countries	Middle Eastern countries, abundant in solar, wind and geothermal resources, have witnessed some of the most significant reductions in the global cost of renewable energy in recent years. The development and increased share of renewable energy are regarded as pivotal strategies in the region’s energy transition.
China	Promote the clean, low-carbon, safe and efficient utilization of energy, accelerate the digital and intelligent development of the energy industry, promote the integrated development of the gas and electricity industry along with renewable energy, establish new energy systems with net-zero emissions, and strengthen international energy cooperation under the “Belt and Road” initiative.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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