International Research Progress and Future Trends of Energy Transition Driven by Climate Change: A Review

Shuai Zhou, Xiaolong Yang, Tek Tjing Lie, Wanyu Zhao, Jieping Han, and Wendong Shao

Abstract—**In response to escalating climate challenges, the global energy system is undergoing a rapid and profound transformation. Governments worldwide are prioritizing emerging technologies and international trends to accelerate the shift toward a low-carbon energy framework. This study systematically reviews 2,936 publications on energy transition, using quantitative analysis to identify research hotspots shaped by climate imperatives. It explores the evolving roles of diverse energy sources, highlights key enabling technologies, and examines major transition pathways adopted across countries. Building on these findings, the study outlines critical directions for future research, emphasizing the need for innovation, policy alignment, and global collaboration. By mapping the comprehensive landscape of energy transition and its driving forces, this research offers valuable insights to guide policymakers, researchers, and industry stakeholders. As the transition accelerates, a systematic and inclusive perspective becomes essential to support this historic shift toward sustainable energy systems.**

Index Terms—**Climate change, energy transition, low-carbon technologies, energy transition pathways.**

I. INTRODUCTION

Energy is an important material foundation and source of power for economic and social development. Since the industrial revolution, the economic development of human society has been closely accompanied by large-scale energy consumption. Energy has become one of the production factors driving GDP growth in various countries. Human exploitation and utilization of fossil fuels have reached an unprecedented scale. Since the 3rd industrial revolution in 1970, 78% of global greenhouse gas emissions have been linked to the use of fossil fuels, according to the Intergovernmental Panel on Climate Change (IPCC). The latest report from the International Energy Agency (IEA) shows that global energy demand is expected to grow by 2.2% to nearly 650 exajoule in 2024, significantly faster than the average annual growth rate of 1.3% over the past decade.

Renewable energy accounts for the majority of the growth in global energy supply at 38%, natural gas at 28%, followed by coal and oil at 15% and 11% respectively. Fossil fuels, with a combined 54% share, still hold an important position in the global energy structure [1]. In 2024, total energy-related carbon dioxide emissions rose 0.8% year-on-year to a record high of 37.8 billion tons. This increase led to atmospheric carbon dioxide concentrations reaching a record 422.5 ppm, about 3 ppm higher than in 2023 and 50% higher than pre-industrial levels. This is far beyond the planetary boundary of the Earth system at 350 ppm [2], which has raised global temperatures by about 1.2°C compared to pre-industrial levels, posing a serious challenge to the sustainable development of human society. The sharp increase in greenhouse gas creates major risks and challenges such as deteriorating ecological environment, severe damage to biodiversity, depletion of natural resources, continuous decline in social well-being and increasing health risks [3]. Addressing climate change, which concerns the survival and development of humanity, has become a major global challenge.

To actively address the risks of climate change, the Paris Agreement calls on countries to take action to keep the global temperature increase within 2°C, many countries have made net-zero or carbon neutrality commitments, and all parties to the United Nations Framework Convention on Climate Change have enacted laws to address climate change. At present, the number of countries setting carbon neutrality targets has increased to 151. Among them, 120 countries have established the legal status of their targets in the form of laws or policy documents, and 86 countries have presented detailed carbon neutrality roadmaps [4]. References revealed that the NDC targets of developed economies generally fall at or even exceed the upper limit of their 2°C emission allowance range, while those of developing countries like China are largely positioned near the median of their allowances. This highlights the differing responsibilities among nations in enhancing the intensity of their emission reduction efforts [5,6].

The active development of clean energy and the promotion of a green, low-carbon transformation of the economy and society have become a global consensus in addressing climate change. However, the energy transition and the response to climate change is a complex system involving multiple areas such as social change, technological innovation, policy layout and economic development. The system is characterized by uncertainty, nonlinearity, multilayer and mutagenicity. With

Manuscript received 8 October, 2025; revised 30 October, 2025; accepted 2 November, 2025. *(Corresponding author: Wanyu Zhao, e-mail: clairez001@163.com)*

S. Zhou and T. Lie are with the Department of Electrical and Electronic Engineering, Auckland University of Technology, New Zealand.

X. Yang, W. Zhao, J. Han and W. Shao are with the School of Economics and Management, Northeast Electric Power University, P.R. China.

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the continuous changes and evolution of global energy transition policies and supporting technologies, the path to achieving energy transition is also undergoing significant changes accordingly.

Existing research on energy transition is relatively fragmented, which is not conducive to accurately grasping the complex evolution trends of the energy system driven by climate change, nor can it support the construction of a modern energy system. In other words, past research may be inadequate in guiding future research directions. Therefore, there is an urgent need to review the latest literature on energy transition to better guide future research directions in this field and serve global climate governance and sustainable development goals. Based on this context, this study aims to analyze the latest trends in energy transition in the context of global climate governance, explore diverse paths for energy transition, and provide coping strategies and practical guidance for achieving global climate governance and sustainable development goals.

2. BIBLIOMETRIC ANALYSES OF ENERGY TRANSITION

A. Data Sources

This study employed a combination of bibliometrics and traditional literature review methods. Based on scientific search, visual analysis, and literature screening, VOSviewer bibliometric analysis software was used to systematically and comprehensively review the relevant studies. To ensure the quality of the sample literature, the Web of Science Core Collection database was selected, and the subject terms were set as energy transition and energy system transition. Research Categories are set as Environmental Sciences or Green Sustainable Science Technology or Environmental Studies or Ecology. Set the language to English. After de-duplication processing, a total of 2,936 documents were retrieved and set as the initial sample for this study.

B. Analysis of Highly Cited Papers

The top 10 most frequently cited documents were extracted using the highly cited papers function in the Web of Science database, as presented in Table Ⅰ. In the context of intensifying global climate change, the transformation of energy systems towards low-carbon, efficient and sustainable has become a consensus in the international community. The energy transition is not just a technical issue, but a complex process involving multiple dimensions of economy, society and politics. The core of the energy transition is to move away from fossil fuels and towards an energy system dominated by hydrogen and renewable energy. Hydrogen, as a secondary energy carrier, is playing an increasingly important role in the energy transition, and its application in the energy system has been the focus of many studies. Reference [7] investigated hydrogen energy applications in power systems, including production, re-electrification, and storage, highlighting that a cost-competitive hydrogen economy depends on performance improvements, large-scale deployment, technological innovation, and supportive policies. Reference [8] examined the challenges and opportunities associated with green and blue hydrogen. A low-carbon hydrogen economy not only presents significant potential to mitigate climate change but also enhances energy security and supports the development of local industries in many countries.

Renewable energy is the core source of the energy transition, and research focuses on its integration paths and application challenges. Reference [9] provided an in-depth analysis of the process of integrating renewable energy resources (such as solar, wind, geothermal, hydro, ocean, and biofuels) into smart city energy systems based on technical and economic standards. Reference [10] explored the challenges of renewable energy in the power sector, including technical and operational challenges (such as voltage stability, frequency stability

TABLE 1
RANKING OF HIGHLY CITED PAPERS IN WOS CORE COLLECTON DATABASE

SORTING	ARTICLE TITLE	SOURCE JOURNAL	YEAR	AUTHOR	TIMES CITED
1	Hydrogen energy systems: A critical review of technologies, applications, trends and challenges	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	2021	Yue *et al.* [7]	1526
2	Energy system transformations for limiting end-of-century warming to below 1.5°C	NATURE CLIMATE CHANGE	2015	Rogelj *et al.* [8]	798
3	Politicizing energy justice and energy system transitions: Fossil fuel divestment and a just transition	ENERGY POLICY	2017	Healy & Barry [9]	584
4	Energy storage in the energy transition context: A technology review	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	2016	Gallo *et al.* [10]	570
5	Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	2016	Connolly *et al.* [11]	562
6	The Role of Green and Blue Hydrogen in the Energy Transition-A Technological and Geopolitical Perspective	SUSTAINABILITY	2021	Noussan *et al.* [12]	487
7	Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe	RENEWABLE ENERGY	2019	Child *et al.* [13]	442
8	Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process	JOURNAL OF CLEANER PRODUCTION	2021	Hoang *et al.* [14]	410
9	Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges	SCIENCE OF THE TOTAL ENVIRONMENT	2022	Al-Shetwi [15]	390
10	Full energy system transition towards 100% renewable energy in Germany in 2050	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	2019	Hansen *et al.* [16]	361

Source: Authors based on relevant literature and power quality), policy and standard challenges of renewable energy integration, environmental issues of renewable energy, resource selection and layout, as well as social challenges in achieving a sustainable power future and decarbonization of the power grid. Storage is a key support for addressing the volatility of renewable energy and ensuring the stability of the power grid. Reference [11] highlighted the potential of Power-to-Gas, Power-to-Liquids, and Solar-to-Fuel technologies in the energy transition, while emphasizing the need for further research to overcome deployment challenges in energy storage applications.

Achieving 100% renewable energy systems is a central goal of the global energy transition. Several European-focused studies provide insights and frameworks relevant worldwide. Reference [12] presented a pathway for Europe to reach full renewable energy by 2050, including decommissioning nuclear plants, enhancing thermal efficiency, electrifying private and heavy vehicles, deploying heat pumps and district heating, and replacing natural gas with renewable methane. Reference [13] used the LUT Energy System Transition Model to simulate two pathways for European power sector, showing that a fully renewable system is economically viable, technically feasible, and aligned with the Paris Agreement. Reference [14] examines energy transition in German across heating, industrial, transport, and power sectors, considering renewable energy potential, system costs, and primary energy supply. Collectively, these studies demonstrate that 100% renewable energy systems are achievable with coordinated technological, economic, and policy measures.

The successful advancement of the energy transition depends on multiple supporting conditions, with existing research identifying key bottlenecks and necessary enablers. Reference [15] analyzed integrated energy-economy-environment scenarios to maintain global warming within 1.5°C by 2100, highlighting that energy efficiency and early, stringent emissions reductions are critical within a rapidly closing window. Reference [16] emphasizes the importance of justice and equity in the energy transition, calling for attention to political dynamics and socio-economic considerations in achieving a green economy. Reference [11] examined obstacles to deploying energy storage technologies, indicating that overcoming practical application barriers is essential for the transition.

Analysis of highly cited papers shows that climate-driven energy transition research spans renewable energy scenarios, hydrogen technology, energy system integration, fairness and justice, and policy-market mechanisms. While technically feasible and economically competitive, the transition faces challenges requiring technological innovation, policy support, market design, and social participation. Future research should focus on policy instruments, cost reduction strategies, and scalable deployment models for emerging technologies such as hydrogen storage and long-duration energy storage.

C. Keyword Clustering Analysis

The VOSviewer bibliometric analysis software was used to cluster keywords in the field of energy transition research. Title and abstract fields were extracted from 2,936 references (structured abstract tags and copyright notices were ignored). The counting method was selected as complete calculation, and the threshold was selected as a single phrase appearing at least 30 times. After removing the influence of the subject term energy transition, the top 3 most frequently occurring cluster labels were obtained, as shown in Fig.1. The three clustering topics are: renewable energy and related technologies, energy transition policy and innovation, and energy system transition initiatives. From a climate change-driven perspective, the energy transition literature can be summarized into three main research hotspots: renewable energy-dominated energy structures and supporting frontier technologies, emerging systems and innovations for the energy transition, and recent initiatives in energy system transformation.

Comparing the results of the initial sample and the highly cited sample reveals that both analyses maintain a consistent research focus, emphasizing renewable energy, supporting technologies, and energy transition strategies. The differences are notable, however. Highly cited papers place greater emphasis on the role of energy technologies such as renewable energy technologies, energy storage, and emission reduction technologies and on the effects and optimization of the energy transition process, particularly in addressing climate change through technological development. Building on these insights, this study will investigate the positioning and evolving structural characteristics of various energy sources, key supporting technologies and potential breakthroughs, and the main pathways and trends of energy transition globally. The research will integrate multidisciplinary theories and systemat-

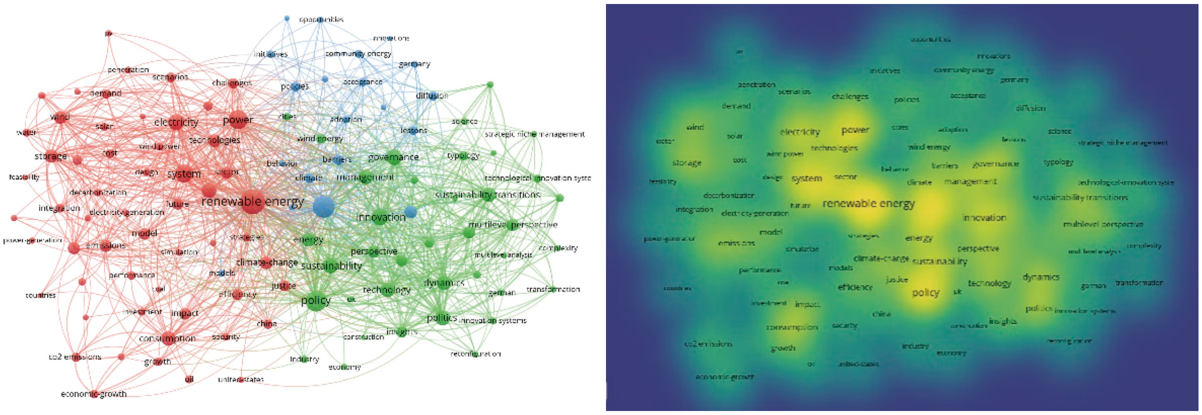

Fig. 1. Clustering and distribution of keywords: network an item density visualization.

ically review recent literature and policies related to energy transition.

3. EVOLUTION OF THE POSITIONING AND STRUCTURAL CHARACTERISTICS OF VARIOUS ENERGY SOURCES

A. Changes in The Positioning of Fossil Energy

1) Structural Decline and Regional Disparities

Fossil fuels (coal, oil, natural gas) are undergoing a structural shift from dominant to auxiliary energy. Energy transition model analyses indicate that developed countries typically reach a turning point in reducing fossil energy consumption when per capita GDP reaches approximately 25,500 dollars. The national innovation index and urbanization rate are negatively correlated with coal consumption, whereas the share of the secondary industry is positively correlated [17]. These findings suggest that economic development, industrial structure, and technological innovation collectively influence the decline of fossil energy use. Coal, the fossil fuel with the highest carbon intensity, is under the greatest pressure. Studies project that China will begin reducing coal consumption between 2028 and 2035, with the share of coal declining to around 47% by 2035 and further to approximately 34% by 2050. During this transition, typical socio-economic characteristics of countries at peak coal consumption include natural gas consumption exceeding 15%, urbanization rates above 70%, secondary industry shares below 30%, and per capita GDP exceeding 20,000 dollars [18].

However, there are significant regional differences in the rate at which fossil fuels are being withdrawn [19]. Developed countries are often the first to reduce fossil fuel use, while developing countries are likely to continue growing fossil fuel consumption due to economic growth and energy security needs. Countries comprising emerging and developing economies in Asia, Latin America and the Caribbean, the Middle East and Central Asia, and sub-Saharan Africa account for two-thirds of the world's population but face significant challenges in their energy transition, receiving only 15% of global clean energy investment, according to Bureau Veritas①.

2) Transition of Natural Gas as A Transitional Fuel to New Energy Systems

Natural gas is an important support for the transition from the existing energy system to the new energy system. During the period when new energy sources are insufficient to support the power system, natural gas can replace fossil energy to ensure energy security while achieving low-carbon development. Under the model of increasing gas and reducing coal, the relatively abundant natural gas resource reserves, sufficient and reliable natural gas import channels, and relatively advanced economic development level are the main reasons why most countries choose high-quality natural gas.

Natural gas can also develop in tandem with hydrogen [20]. Specifically, natural gas can be deeply involved in the production, storage, transportation and application of hydrogen energy, achieving coordinated development of the entire industrial chain. However, with the continuous decline in the cost of renewable energy and stricter climate targets, the long-term positioning of natural gas is facing challenges. Research [21] suggested that in order to achieve carbon neutrality, investment needs to be shifted from natural gas infrastructure to areas such as power grids, energy storage, and hydrogen. The acceleration of the global energy transition may make the transition period for natural gas shorter than expected, especially in regions rich in renewable energy resources and with good financing conditions. However, in power systems where renewable energy is more intermittent, natural gas will still retain its value as a flexible resource for some time. Although natural gas will eventually give way to new energy in the new energy system, it will play a long-term role as a chemical raw material, and the conversion between its fuel and raw material will continue to provide flexibility support for the new energy system [22].

B. The Rise of Renewable Energy

Solar and wind energy have become the main force in the energy transition [23]. Since 2013, the annual increase in renewable energy capacity has consistently been higher than the combined capacity of fossil fuels and nuclear energy, according to IRENA. Global renewable energy generation capacity is projected to increase by 585 GW in 2024, representing 92.5% of all new power generation capacity and an annual growth rate of 15.1%, setting a new record. However, significant regional disparities remain in the expansion of renewable capacity. Most of the new capacity in 2024 will be concentrated in Asia, which is expected to add 421.5 GW accounting for 72% of the global increase.

China accounts for the largest share of global renewable energy growth. Reference [24] projected that China will achieve at least 2,350 GW of wind and solar capacity by 2030, increasing to 2,910-3,800 GW by 2035, corresponding to 49%-56% of its total power generation. To meet these targets, China will need to sustain an average annual growth of 150-220 GW of new wind and solar capacity from 2025 to 2030, and 120-210 GW from 2031 to 2035.

In addition to solar and wind energy, other renewable sources such as hydropower, biomass, geothermal, and ocean energy also play important roles in the energy transition. In the Qinghai-Xizang Plateau region of Sichuan Province, China, the exploitable hydropower capacity reaches nearly 60 million kilowatts, accounting for almost two-fifths of Sichuan province's total. Biomass remains a significant source in some regions. For instance, in Uganda, it accounts for 90% of energy consumption [25]. With improved technologies and management practices, biomass has the potential to provide cleaner and more efficient energy services in these areas.

C. The Strategic Value of Hydrogen

Hydrogen, as a zero-carbon energy carrier, plays a key role

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① https://group.bureauveritas.com/newsroom/2025-global-energy-transition-report-leveling-transition in decarbonizing hard-to-reduce sectors such as heavy industry, long-distance transportation and chemicals. The bridging role of hydrogen is reflected in the stability of the power system and the consumption of renewable energy [26]. Renewable energy has obvious characteristics of uneven distribution and unstable production. It is matched with electrolytic water hydrogen production, energy storage and peak shaving capacity. When the power generation is too high, hydrogen is produced and stored. When the power generation is insufficient, hydrogen power generation is used to make up for the gap, thereby smoothing the intermittency and volatility of new energy power generation and achieving large-scale, long-term and cross-seasonal peak shaving.

On the other hand, green hydrogen (produced by electrolysis of water using renewable energy) is also an important part of the energy transition and has become a core carrier of deep decarbonization. Hydrogen produced from green electricity can be used locally as fuel or chemical raw materials, which can relieve consumption pressure to a certain extent in the short term. The energy conservation, pollution reduction and carbon reduction demands of some chemical enterprises can also be met by replacing hydrogen produced from fossil fuels with green hydrogen.

Green hydrogen is positioned as a key decarbonization for non-electrified sectors such as industry and heavy transportation [27]. The IEA predicts that global annual hydrogen demand for hydrogen metallurgy could reach 6.6-14 million tons by 2030, and annual hydrogen demand for green methanol and green ammonia will exceed 48 million tons. France has made it clear that carbon-free hydrogen (green hydrogen, powder hydrogen, white hydrogen) is a national strategic priority. At the same time, the development of hydrogen has sparked discussions among scholars amid the environmental impact and cost competition of different hydrogen production paths. Grey hydrogen and blue hydrogen based on fossil fuels are currently dominant, but green hydrogen based on renewable energy is more sustainable in the long term.

Reference [28] showed that the synergy of vehicle to grid (V2G) and photovoltaic (PV) can reduce the demand for green hydrogen power generation, providing a quantitative basis for policy-making. This indicates that the coordinated development of hydrogen and renewable energy in the energy transition of countries driven by climate change is of great strategic significance and is also a clean energy that many countries around the world are accelerating to develop and utilize.

In summary, the energy structure in the transition is evolving from a high-carbon, fossil-fuel-dominated system to a low-carbon, renewable-centered ecosystem, with hydrogen and renewable energy developing in parallel. The share of traditional fossil fuels is declining, with their role shifting from dominant to auxiliary. Renewable energy has moved from a supplementary source to a leading role, with wind, solar, and other renewables driving most new capacity additions and power generation. Electricity substitution for direct fossil fuel combustion has significantly increased its share in the terminal energy consumption structure. Meanwhile, strategic importance of hydrogen is rising. Green hydrogen, as a large-scale energy storage medium and a decarbonization tool for hard-to-abate sectors, is increasingly being integrated into the top-level planning of energy system transformations in various countries.

4. KEY SUPPORTING TECHNOLOGIES FOR ENERGY TRANSITION

The global energy transition aims to increase the proportion of clean energy usage, gradually reduce the emissions of greenhouse gases such as CO2, rely on technological innovation, and apply advanced digital technologies to build a more sustainable and higher-quality new energy system [29]. The main challenges of the energy transition include technological maturity, economic feasibility, infrastructure transformation, and policy support [30]. Although renewable energy technologies have advanced significantly, their intermittency and variability remain major obstacles to the reliable and stable operation of power grids [31]. Furthermore, key technologies such as energy storage, smart grids, and carbon capture require further development and optimization to enable deep decarbonization of the global energy system.

A. Solar and Wind Energy Technologies are Accelerating

Solar PV technology is one of the most mature and widely applied technologies in global renewable energy and the fastest-growing renewable power source. According to data from the Global Solar Council, it took 68 years from 1954 to 2022 to reach 1 TW of installed capacity. From 2022 to 2024, the installed capacity of PV power will reach 2 TW within two years and will continue to grow rapidly [32]. Over the past decade, the price of solar panels has plummeted by nearly 90%, making them one of the lowest-cost sources of electricity in many parts of the world. The current research focus on solar technology includes improving conversion efficiency, reducing manufacturing costs and enhancing system stability. New types of solar cells, such as perovskite cells and heterojunction cells, are constantly pushing efficiency limits, laying the foundation for the wide application of solar PV power generation.

Wind energy technology has also made remarkable progress. Depending on the installation geographical environment, it can be classified into onshore wind power, offshore wind power and airborne wind energy. In 2024, the global wind power market is expected to grow at a compound annual growth rate of 4.9% from 2025 to 2030 [28, 33], demonstrating the growth potential of wind power in the transition of the global energy structure. Wind turbines are growing in capacity and efficiency, and by 2030, wind energy is expected to be more cost-competitive than fossil fuels in many regions around the world. Offshore wind power is particularly promising because of the abundance and stability of offshore wind resources, but it also faces challenges such as high installation costs, difficult operation and maintenance, and uncertain environmental impact. Innovations in wind energy technology are mainly focused on large-capacity turbines, floating foundations and intelligent operation and maintenance [34]. Given the abundant wind resources in the deep and far seas and the few restrictions on the large-scale development of wind power, major economies around the world are stepping up research and development and demonstration efforts [35]. The National Offshore Wind Research and Development Consortium of the United States is developing new mooring/anchoring systems, remote digital unmanned operation and maintenance systems for offshore wind power to reduce the transmission costs and risks [36].

B. Technological Innovation in Hydrogen Production, Storage, and Transportation

Hydrogen, as a clean energy carrier, is playing an increasingly important role in the energy transition. Hydrogen can be a potentially important source of flexibility for clean power systems, large-scale and cross-seasonal long-duration energy storage and is a crucial technology for achieving carbon neutrality in power systems, responding to fluctuating renewable energy sources such as wind and solar power, and improving the reliability of low-carbon power systems. Hydrogen production technologies are classified into gray hydrogen, blue hydrogen and green hydrogen based on carbon emission intensity [30]. Grey hydrogen relies on natural gas steam reforming (SMR), which accounts for 76% of global production, but is accompanied by 9-12 kg of CO_2 emissions per kilogram of H_2. Blue hydrogen, which reduces SMR carbon emissions by 90 percent through carbon capture and storage (CCS), serves as a transitional solution. Green hydrogen uses renewable energy to electrolyze water, achieving zero carbon throughout its life cycle, but costs up to 4-6 dollars per kilogram, which is 2-3 times the cost of grey hydrogen [30].

Hydrogen production through electrolysis of water mainly includes alkaline water electrolysis, proton exchange membrane electrolysis and high-temperature solid oxide electrolysis [31, 32, 37, 38]. Among them, proton exchange membrane electrolysis (PEMEC) is more suitable for coupling with renewable energy due to its fast response speed and wide load range. The current efficiency of PEM electrolyzers is about 60%, and the platinum loading needs to be reduced from 2 mg/cm^2 to 0.1 mg/cm^2 to cut costs. Emerging hydrogen production pathways such as photocatalytic water splitting (energy conversion efficiency<10%) and biological hydrogen production (yield <3 mol H_2/mol glucose) are still in the laboratory stage.

The storage and transportation of hydrogen is a key link in the hydrogen industry chain. At present, the pressure level of high-pressure hydrogen storage in Japan has reached 70 MPa, while in the United States and South Korea it has reached 50 MPa. High-pressure gaseous hydrogen storage (70 MPa) is mature but has a volumetric energy density of only 40 g/L. Liquid hydrogen storage (−253°C) has a density of 70 g/L, but evaporative loss is 0.3-3% per day. Metal hydrides (such as $LaNi_5H_6$) and MOF materials show potential, but the weight hydrogen storage rate is generally less than 2.5wt%. The cost of building a hydrogen pipeline network is as high as 2 million dollars per kilometre, which restricts large-scale application [1]. Liquid organic hydrogen carriers (LOHCs) and ammonia-hydrogen fusion technology may reshape the storage and transportation landscape [30].

C. Smart Grids and Digital Technologies

1) Smart Grid Architecture and Functionality

A smart grid is a modern grid that integrates advanced sensing, communication and control technologies [39], which can optimize the allocation of energy resources and improve the efficiency and reliability of grid operation. Smart Grid 3.0 (SG 3.0), the pinnacle of energy system transformation, integrates disruptive technologies such as digital twins, blockchain, and the metaverse, and supports hierarchical evolution from nano grids to virtual power plants [40].

The core functions of the smart grid include: adaptive and self-healing capabilities that can monitor system status in real time and automatically respond to faults; user engagement, enabling users to participate in demand response through smart meters and home energy management systems; fault tolerance, capable of withstanding physical and cyber-attacks to ensure power supply reliability; high-quality power supply, meeting the high demands for power quality in the digital society; compatible with multiple power sources to support large-scale access to distributed renewable energy [40].

Power electronic transformers are one of the core components of the smart grid. Compared with traditional transformers, power electronic transformers can not only perform basic tasks such as voltage transformation, electrical isolation and energy transmission, but also achieve complex functions such as reactive power compensation, harmonic control, grid interconnection and new energy grid connection. More importantly, it provides plug-and-play AC/DC interfaces for distributed wind, photovoltaic and other renewable energy generation equipment and energy storage systems, supports bidirectional energy flow, and can even autonomously separate from the main grid in the event of a fault, enhancing the self-healing ability of the power grid.

2) Applications of Digital Technology in Energy Systems

Digital twin technology enables real-time monitoring and predictive maintenance of physical power grids through high-fidelity modeling. The virtual power plant digital twin project at the University of Reutlingen in Germany has demonstrated that the technology can optimize distributed power dispatching and reduce the prediction error of wind and solar power generation to 5-8%. In battery management systems (BMS), digital twins combined with AI algorithms can give early warnings of lithium-ion battery degradation, extending lifespan by up to 20%[40].

The application of blockchain technology in the energy sector has reshaped the rules of energy trading. The Brooklyn microgrid project has for the first time validated the potential of blockchain in peer-to-peer (P2P) energy trading. Ethereum smart contracts boost community energy storage sharing efficiency by 34% through a dual auction mechanism. But the energy consumption problem of public chains still needs to be addressed, and adopting low-carbon consensus algorithms such as Proof of Stake (PoS) is the future direction [40].

The application of artificial intelligence technology in energy systems includes load forecasting, improving prediction accuracy through deep learning algorithms; equipment diagnostics, using machine learning to identify abnormal conditions of equipment; optimized scheduling, achieving multi-objective optimized scheduling through reinforcement learning; Market transactions, using intelligent algorithms to participate in electricity market transactions. Reference [41] proposed the Discrete State Event-driven (DSED) simulation mechanism and the transient segment analysis (PAT) model to develop the universal power electronics simulation software DSIM, making precise simulation of complex power electronic equipment possible.

Metaverse technology provides an immersive new dimension for energy management. Metaverse construction plans launched by governments across China have opened a three-dimensional visual interface for grid operation and maintenance. With extended reality (XR) technology, operation and maintenance personnel can virtually inspect substation equipment. The industrial metaverse case of Siemens in Germany shows that the technology reduces on-site operation risks while increasing fault response speed by 40% [41].

D. Carbon Capture, Utilization and Storage (CCUS) Technology

1) CCUS Technology Links and Development Status

Carbon capture, utilization and storage (CCUS) technology is one of the key technologies for achieving carbon neutrality, mainly including four links: capture, transport, utilization and storage [42]. In terms of capture technology, advanced adsorption materials such as metal-organic frameworks (MOFs) and covalent organic frameworks (CoFs) demonstrate outstanding CO_2 capture capabilities. Among them, amine-functionalized materials such as polyethyleneimine (PEI) -modified mesoporous silica had an adsorption capacity of 4.73 mmol/g at 90°C, while TEA-treated MG-MOF-74 crystals achieved a CO_2 adsorption capacity of 350 mg/g. In pretreatment techniques, pressure/temperature swing adsorption (PSA/TSA) combined with membrane separation can significantly increase feed gas purity and reduce regeneration energy consumption to 2.3 MJ/kg (CO_2) [35]. While capture technologies for point sources are relatively mature, Direct Air Capture (DAC) is much less developed and faces immense scalability challenges due to its low CO2 concentration and high energy requirements. In terms of CO_2 utilization, thermochemical conversion, electrochemical reduction and bioconversion are the main technical approaches. Copper-based catalysts stand out in the hydrogenation of CO_2 to methanol, with $Cu/ZnO/Al_2O_3$ achieving a 23% conversion rate at 200-300°C and 50-100 bar.

Bimetallic catalysts such as $Pt\text{-}Co/CeO_2$ increase the CO selectivity of the reverse water gas shift (RWGS) reaction to 100%. In the electrochemical system, nanostructured electrodes maximize the electrochemically active surface area (ECSA), and the Cu@NC catalyst makes the Faraday efficiency of the C_2 product up to 80%. Continuous flow photo electrochemistry (CFPEC) reactors increase CO yields 16 times over conventional batch systems [35]. In terms of sequestration techniques, geological sequestration is the main approach [43], including depleted oil and gas fields, deep brackish aquifers and unamenable coal seams. Safety of containment, long-term monitoring and leakage risk are key concerns. Infrastructural challenge of building out CO_2 transport and storage networks may include public acceptance and long-term liability for stored CO_2. While CCUS is a necessary tool for specific industrial processes, its role is likely more limited and niche than that of renewable substitution.

2) CCUS Application Scenarios and Coupling Modes

CCUS technology can be coupled with key emission industries such as the thermal power industry, the steel industry, the cement industry, and the petrochemical industry to achieve emission reduction. In the thermal power sector, CCUS is a key technology for achieving near-zero emissions from coal-fired power plants. In the steel industry, CCUS can be used for carbon capture in blast furnace gas and coke oven gas. In the cement industry, CCUS is an important measure to address process emissions. In the petrochemical industry, CCUS can be combined with production processes to achieve carbon recycling. The CCUS coupling model with new energy includes coupling with renewable energy and hydrogen.

Renewable energy can provide low-carbon electricity for CCUS and reduce capture energy consumption. Hydrogen combined with CCUS can produce blue hydrogen and promote the development of low-carbon hydrogen. The hydrogen strategy of EU plans to build 40GW of electrolyzer capacity by 2030 [30], and West-to-East Hydrogen Delivery Strategy of China uses hydrogen-mixed natural gas pipeline technology to increase the hydrogen blending ratio to 20% and achieve low-cost large-scale transportation using existing pipeline infrastructure [31]. Technical and economic analysis shows that when hydrogen prices fall to 900 dollars per ton and electricity prices are below 0.01 dollar per kWh, the cost of CO_2 to aviation fuel (SAF) can be reduced to 2.25 dollars per gallon. At the policy level, a carbon tax of 500 euros per ton of CO_2 would be needed to make SAF commercially competitive [35].

5. MAJOR PATHS AND TRENDS FOR ENERGY TRANSITION

A. Research on China's Energy Transition Path

As the largest developing country, China is striving to promote an energy revolution [44]. In recent years, it has successively issued policy documents such as "Opinions on Fully, Accurately and Comprehensively Implementing the New Development Philosophy and Doing a Good Job in Carbon Peaking and Carbon Neutrality" and "Action Plan for Carbon Peaking before 2030". These documents outline strategic objectives for medium- and long-term energy transition and development. China has explicitly defined "building a clean, low-carbon, safe, and efficient energy system" as the direction for its energy transition. Although a series of achievements have been made, energy development still faces many challenges such as huge demand pressure, many supply constraints and arduous tasks of green transformation, and there is still a long way to go to continue promoting energy transformation [45].

1) Fundamental to the Energy Transition

Energy conservation and energy efficiency improvement are prerequisites for energy transition [46], which can effectively reduce the total demand for green energy and relieve the pressure of system transition. At the same time, the continuous advancement of electrification is an important way to achieve carbon neutrality [47] by enhancing the electrification level of terminal energy consumption to replace traditional fossil energy consumption and lay the foundation for a high proportion of renewable energy access [48].

2) Core Task of Energy Transition

Renewable energy sources represented by wind and photovoltaic power will become the main body of the power system [49]. Coal-fired power will gradually transition from base-load to regulation and reserve capacity, with orderly retirement as system control capabilities improve. The power grid pattern is evolving towards intelligence and flexibility. The main contents are as follows: First, optimize the main grid pattern to form a transmission structure of "west-to-east power transmission, north-to-south power transmission, regional mutual assistance" to enhance the cross-regional resource allocation capacity [50]. Second, strengthen the construction of distribution networks and promote the transformation of distribution networks from passive unidirectional networks to active bidirectional interactive systems to support the large-scale access of distributed new energy. Third, promote multi-network integration and build an energy Internet with electricity-hydrogen synergy [51] and multi-energy complementarity of power, heat and transportation through green hydrogen, electricity-to-fuel, energy storage, electric vehicles to achieve flexible system regulation and multi-energy management [52].

3) Technological Innovation and Green Hydrogen: Key Drivers of Energy Transition

Technological innovation in the energy sector is the fundamental driving force for energy transition [53], and there are huge market space and investment opportunities in zero-carbon and negation-carbon technologies (such as CCUS, industrial carbon recycling) and new energy equipment manufacturing [54]. Among them, hydrogen production from renewable energy has become one of the core directions [55], green hydrogen production capacity of China continues to grow rapidly [56], policy support [32] carbon and power system balance [57].

B. U.S. Energy Transition Route

The United States energy transition is in a period of complex game between traditional and clean energy [58] and multi-path parallel evolution. The U.S. is rich in resources and adheres to an energy development path oriented towards energy independence [59]. It released strategic petroleum stocks during the President Clinton administration, strongly supported natural gas and nuclear energy development during the President George W. Bush administration, and promoted the National Strategy for Clean Energy during the Obama administration [60]. During the President Trump administration, the America First Energy Plan was proposed to restore the development of traditional fossil energy [61]. The core goal of the plan is to achieve U.S. energy dominance rather than just the energy independence pursued by previous administrations. This strategic shift means that the U.S. should not only meet its own energy needs but also become a major global producer and exporter of fossil fuels, particularly oil, gas and coal, as a core tool to boost economic growth and enhance geopolitical influence. In sharp contrast to the federal policy shift, many states continue to push for clean energy through proactive policies. The New York State government has announced an investment of more than 11 dollars million in clean hydrogen research and development projects aimed at reducing the cost of clean hydrogen storage and distribution and demonstrating the potential of hydrogen applications in hard-to-electrify areas such as transportation [62].

The energy transition in the U.S. has shifted to a dual-track approach that prioritizes traditional energy sources with partial breakthroughs in clean technologies. First, the development of renewable energy remains dominant, with solar, battery storage and wind still growing steadily. According to the U.S. Energy Information Administration (EIA), the U.S. is expected to add a record 64GW of power capacity in 2025①. Despite weakened policy support for renewable energy, market forces and technological advancements are still driving the development of clean energy due to its economic competitiveness. Secondly, hydrogen also plays a significant role in the U.S. energy transition. Especially hydrogen in industries that are difficult to electrify and in heavy-load transportation sectors [63]. Studies suggest that hydrogen could play a significant role in decarbonizing U.S. industries, particularly in the refining and chemical sectors, where annual emissions could be reduced by up to 24% by 2050 if clean hydrogen were used instead of emission-intensive grey hydrogen [1]. Finally, traditional fossil fuels are making a comeback. Despite the rapid development of clean energy, fossil fuels, especially natural gas, still play an important role in the US energy system. Natural gas, as a dispatchable and well-understood source of energy, has special value in supporting the integration of renewable energy and meeting the power demands of AI data centers.

The U.S. Department of the Interior has revoked all designated wind power areas and suspended new project approvals, while several large coal mine projects have been approved. The United States Environment Protection Agency plans to lift carbon emission limits for coal-fired power plants, and the Department of the Interior has also approved several large coal mine projects. This trend suggests that the U.S. energy transition is not a simple replacement of fossil fuels with renewable energy, but rather a multi-mix feature. The continued expansion of fossil fuels also brings risks such as methane emissions, climate change and investment lock-in effects, making it more difficult to achieve long-term climate goals.

C. Europe's Energy Transition Route

The European Union lacks coal, oil, and gas resources, has

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① Solar power will account for 33.3 GW, representing 52% of the total new capacity. Energy storage will contribute 18.3 GW, making up 28.6% of the total new capacity. Wind power will add 7.8 GW, accounting for 12.2% of the total new capacity. Natural gas will contribute 4.7 GW, representing 7.3% of the total new capacity.

high energy consumption but low domestic production, and relies heavily on fossil fuel imports. This dependence drives its clean energy transition toward rapidly expanding non-fossil energy sources. Germany, the largest economy in the EU, reached its carbon peak as early as the late 1970s and incorporated carbon neutrality into its national legislation [64]. Since 2011, Germany has issued the National Energy Efficiency Action Plan and the Climate Action Plan 2050 and has revised the Renewable Energy Act several times to define the direction of energy transition. Germany has adopted a carbon reduction path of phasing out coal, phasing out nuclear, and vigorously developing renewable energy [65]. Phasing out coal has been a key focus for Germany in recent years [66]. In 2020, the German parliament passed the Phasing out Coal Act, which determined to exit the coal market by 2038. At the same time, the German government has made it clear that vigorously developing renewable energy is the direction of the energy transition [67], proposing that 60% of terminal energy consumption and 80% of total power generation come from renewable energy by 2050, and hoping to eventually achieve 100% renewable energy consumption.

France, on the other hand, has adopted a carbon reduction transition path of ensuring the fundamental position of nuclear energy and vigorously developing renewable energy. In response to the shortage of fossil energy resources, France launched a large-scale nuclear energy development program in the 1970s. Currently, considering factors such as reducing excessive reliance on nuclear energy, responding to the energy strategy of EU, and competing for leadership in addressing climate change, it has introduced the National Action Plan for Renewable Energy and is actively implementing transition policies towards renewable energy. In recent years, France has gradually focused on the development path of hydrogen production from nuclear power. The National Carbon-Free Strategy 2025, released in April 2025, reaffirms the ambition of France to become a global leader in electrolytic hydrogen and plans to operate 4.5GW of electrolytic equipment by 2030 (a 30% reduction from the original target). The strategic feature of France is to make full use of its low-carbon power structure dominated by nuclear power, with nuclear energy accounting for 46% of the total energy supply, and to develop carbon-free hydrogen such as powder hydrogen (nuclear electrolytic hydrogen), green hydrogen, and white hydrogen.

D. Japan’s Energy Transition Route

As a signatory to the Paris Agreement, Japan has committed to achieving carbon neutrality by 2050 and has set an interim target of reducing emissions by 46% (compared to 2013) by 2030. The power sector, which is a major source of carbon emissions, has become a key area for emissions reduction [68]. The Japanese government views energy transition as a core means to achieve climate goals through policies such as the Seventh Strategic Energy Plan and the GX2040 Vision. The primary driver of energy transition is its extremely low rate of energy self-sufficiency and its excessive reliance on imported fossil fuels. According to the 2025 Energy White Paper, the energy self-sufficiency rate of Japan was only 15.2% in 2023, the lowest among the G7 countries and far below the average of other countries. More than 80 percent of its primary energy supply comes from imported fossil fuels, making the Japanese economy highly vulnerable to international geopolitical risks and fluctuations in energy prices.

Japan, which has relatively limited resource, once vigorously developed nuclear power. After the Fukushima nuclear accident, its energy strategy further emphasized technological innovation. It released the Basic Strategy for Hydrogen Energy and the Fifth Basic Plan for Energy, accelerating its deployment in new energy power generation and the hydrogen industry to compete for leadership in energy technology. Japan is the most active country in hydrogen development around the word, aiming to be the first in the world to achieve a hydrogen society. The 2019 Hydrogen Utilization Schedule sets clear targets: by 2025, the price of hydrogen fuel cell vehicles will be on par with that of hybrid vehicles. By 2030, 900 hydrogen refueling stations will be built to commercialize hydrogen power generation. The cost of hydrogen supply will be reduced to 30 yen per standard cubic meter, no higher than that of traditional energy.

In summary, based on the experience of the United States, Europe and Japan, the different resource endowments and technological advantages of countries around the world determine the differences in the path of clean and low-carbon energy transition. Most European countries, the United States and Japan have completed the industrialization stage, high-energy-consuming industries have withdrawn or shifted, economic growth has largely been decoupled from energy demand, and most countries have achieved carbon peaking. Controlling the total energy consumption and optimizing the consumption structure are the main ways to achieve carbon reduction. The experience of various countries shows that promoting the efficient and clean use of coal, accelerating the replacement of clean energy, and vigorously developing renewable energy and natural gas are realistic choices for achieving energy transition.

6. RESEARCH CONCLUSIONS AND PROSPECTS

A. Conclusions

First, the global energy structure is undergoing a systemic transformation, with its core feature being a shift from high-carbon fossil energy dominance to a core role of low-carbon renewable energy. Fossil energy has retreated from its dominant position to that of an auxiliary energy source, while wind, solar, and other renewable energies have become the absolute main body and future dominant energy sources for new electricity generation, significantly increasing the proportion of electricity in end-use consumption. Green hydrogen, as an energy storage and decarbonization tool, is increasingly prominent in strategic terms.

Second, technological innovation plays an increasingly important role in promoting the decarbonization of energy. From energy storage technologies to CCUS technologies, the development of various emerging technologies is reshaping the global energy landscape. Energy transition shows a trend of technological diversification and system integration. A single technology is difficult to address all energy challenges and requires the coordinated cooperation of multiple energy technologies and systems. Whether it is the molten salt heat storage coupled with high-temperature heat pump green steam supply technology in Shanghai, China, or the vehicle-to-grid (V2G) and renewable energy coordination optimization in Chile, technological innovation and system integration are driving the energy transition of various countries deeper.

Finally, due to different resource endowments and technological advantages among countries, their energy decarbonization paths are diverse. The developed countries that have completed industrialization have decoupled their economic growth from energy demand, and most have achieved carbon peak. The common experience of the U.S., Europe, and Japan in energy transition indicates that controlling the total amount, optimizing the structure, promoting clean coal utilization, and developing renewable energy， hydrogen energy and natural gas are the realistic choices for transformation. However, there is currently controversy in the international community regarding the comprehensive effect of energy transition, and the development path and model of an energy transition that balances low-carbon development, economic growth, and supply security still need further in-depth exploration.

B. Future Prospects

First, deepen the modeling and multi-dimensional assessment research on the complex system of energy transition. Current research has clearly shown that energy transition is a complex system engineering project driven by multiple factors. In the future, it is necessary to develop more comprehensive models that can better reflect its nonlinear and dynamic feedback characteristics. The research focus should be on constructing a multi-dimensional analysis framework that can simultaneously quantify multiple objectives such as energy security-economic cost-environmental climate-social equity, providing scientific basis for policymakers to make trade-off decisions among different development paths. Researches framework that simultaneously addresses both internal constraints within energy systems (including energy categories, carbon emissions, and energy demand within the target system) and external constraints (encompassing economic growth, government policies, and grassroots participation) can effectively guide quantitative modeling of future climate-energy co-evolution. Promote research on risk and resilience assessment during the transition process. Geopolitical risks often threaten the stability and predictability of the energy transition. Such risks materialize as disruptions to supply chains for critical materials in renewable energy and hydrogen production, such as rare earth elements, lithium, and cobalt. Consequently, research should also be intensified on issues like the fundamental trade-offs between rapid decarbonization and energy security amid heightened geopolitical tensions. Besides, long-term transformation modeling should incorporate uncertainty quantification, particularly when energy systems face demand fluctuations, climate extremes, and geopolitical shocks.

Second, explore the multi-energy complementarity and system integration paths in high-renewable energy systems. As renewable energy becomes the main body, its intermittency and instability pose significant challenges to system integration. Future research should go beyond single technological breakthroughs and focus on system-level collaborative optimization. For example, the electricity-hydrogen-heat coupled system design, in-depth study of the coordinated planning and operation mechanisms among renewable energy power generation, electrolysis to produce green hydrogen, long-term energy storage, industrial sector electrification, and hydrogen substitution, and the construction of the optimal coupling model. Research models should also perform real-time, co-optimized dispatch of electricity, hydrogen, and heat networks under uncertainty. Besides, a significant gap exists in incorporating consumer acceptance, flexible demand response, and designing efficient market structures for a multi-energy carrier system. Explore the value of flexibility resources, including demand-side response (such as V2G), new energy storage, smart grids, and the potential, cost-effectiveness, and supporting market and regulatory policies for their development.

Third, conduct research on differentiated transition paths and policy toolkits based on national conditions. Reject the one-size-fits-all transformation model. Future research should focus more on the diversity of paths and the adaptability of policies. Conduct comparative studies of cases at the national and regional levels, by deeply analyzing the transformation strategies of countries with different resource endowments, industrial structures, and development stages (such as China, Chile, Germany, and Saudi Arabia), to summarize their successful experiences and lessons, and form a classified reference transition path map. Promote research on the Just Transition mechanism, focusing on how to design policies to properly handle employment issues in traditional fossil energy industries, regional economic impacts, and energy affordability during the transition process, ensuring the fairness and social stability of the transition. Additionally, in the orderly withdrawal of fossil energy and energy positioning, relevant studies can be advanced on the precise positioning of coal, natural gas, and other fossil fuels as auxiliary energy and flexibility supplements during the transition period, as well as the transformation plans combined with CCUS technology.

Finally, promote research on disruptive technological innovation and international cooperation mechanisms for carbon neutrality. Technological innovation is the core driving force of transformation, but its uncertainty requires forward-looking planning and global collaboration. The world should jointly continue to advance the forward-looking and research of next-generation technologies. Pay attention to the breakthrough potential and development routes of disruptive technologies such as new energy storage, small modular nuclear reactors (SMR), the application of artificial intelligence in energy system optimization, next-generation photovoltaic and wind power technologies. Encourage research on international cooperation and governance model innovation, by breaking technological barriers and establishing effective international technology cooperation and transfer mechanisms, especially for support to developing countries. Drawing on the experience of the international Carbon Neutrality and Energy Intelligence forum, joint research groups could be established focusing on specific technological fields such as hydrogen energy, CCUS, and novel energy storage. For instance, the CNEST project, a collaboration between Tsinghua University's Carbon Neutrality Research Institute and Princeton University has pioneered a system for multinational experts to tackle challenges collaboratively. Furthermore, Through the construction of global unified carbon pricing, green certification, and other market mechanisms, reduce the total cost of global transformation. Furthermore, strengthening international cooperation platforms could also expand multilateral initiatives like CNEST, fostering the joint development of low-carbon technology demonstration zones in Belt and Road countries.

DECLARATION OF INTEREST

The authors declare no conflicts of interest.

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REFERENCES

[1] "Global Energy Review 2025 Dataset." *IEA*, (2025).

[2] D. Tong, Q. Zhang, Y. X. Zheng *et al*. "Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target." *Nature* 572, no. 7769 (2019):373−+.

[3] D. I. A. McKay, A. Staal, J. F. Abrams *et al*. "Exceeding 1.5°C global warming could trigger multiple climate tipping points." *Science* 377, no. 6611 (2022):1171−+.

[4] S. H. Zhang, W. J. Cai, X. Z. Zheng *et al*. "Global readiness for carbon neutrality: From targets to action." *Environmental Science and Ecotechnology* 25 (2025).

[5] G. Gu, and Z. Wang. "Global carbon abatement schemes for the 1.5℃ warming limitation in the post-INDC period." *Acta Geographica Sinica* 72, no. 9 (2017):1655−1668.

[6] X. Pan, and H. Wang. "Assessment and Comparison of Major Countries' Nationally Determined Contributions Under the Paris Agreement." *China Population, Resources and Environment* 28, no. 9 (2019):8−15.

[7] J. Rogelj, G. Luderer, R. C. Pietzcker *et al*. "Energy system transformations for limiting end-of-century warming to below 1.5°C." *Nature Climate Change* 5, no. 6 (2015):519−+.

[8] M. Child, C. Kemfert, D. Bogdanov, and C. Breyer. "Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe." *Renewable Energy* 139 (2019):80−101.

[9] A. T. Hoang, V. V. Pham, and X. P. Nguyen. "Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process." *Journal of Cleaner Production* 305 (2021).

[10] J. Lowitzsch, C. E. Hoicka, and F. J. van Tulder. "Renewable energy communities under the 2019 European Clean Energy Package – Governance model for the energy clusters of the future?" *Renewable and Sustainable Energy Reviews* 122 (2020): 109489.

[11] D. Parra, L. Valverde, F. J. Pino, and M. K. Patel. "A review on the role, cost and value of hydrogen energy systems for deep decarbonisation." *Renewable & Sustainable Energy Reviews* 101 (2019):279−294.

[12] M. Noussan, P. P. Raimondi, R. Scita, and M. Hafner, "The Role of Green and Blue Hydrogen in the Energy Transition-A Technological and Geopolitical Perspective." *Sustainability* 13, no. 1 (2021).

[13] D. Connolly, H. Lund, and B. V. Mathiesen. "Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union." *Renewable & Sustainable Energy Reviews* 60 (2016):1634−1653.

[14] R. G. Grim, Z. Huang, M. T. Guarnieri, J. R. Ferrell, L. Tao, and J. A. Schaidle. "Transforming the carbon economy: challenges and opportunities in the convergence of low-cost electricity and reductive CO2 utilization." *Energy & Environmental Science* 13, no. 2 (2020):472−494.

[15] N. Healy and J. Barry. "Politicizing energy justice and energy system transitions: Fossil fuel divestment and a 'just transition'." *Energy Policy* 108 (2017):451−459.

[16] A. B. Gallo, J. R. Simoes-Moreira, H. K. M. Costa, M. M. Santos, and E. M. dos Santos. "Energy storage in the energy transition context: A technology review." *Renewable & Sustainable Energy Reviews* 65 (2016):800−822.

[17] Wang Bing, Lu Feng, Guan Xinmeng, Deng Kailei, Zhang Lu, and Jiang Xinru. "Analysis of Energy Transition Models and Transition Timing under the Goal of Ensuring Supply and Reducing Carbon Emissions." *China Coal* 50, no. 07 (2024):8−18.

[18] Ma Limei, Shi Dan, and Pei Qingbing. "Low-carbon Energy Transition in China (2015-2050): Renewable Energy Development and Feasible Pathways." *China Population, Resources and Environment* 28, no. 02 (2018):8−18.

[19] B. M. Wu, Z. R. Wang, Y. Tian, and S. N. Zheng. "The impact of industrial transformation and upgrading on fossil energy elasticity in China." *Journal of Cleaner Production* 434 (2024).

[20] D. J. Zhou, S. Y. Yan, D. W. Huang *et al*. "Modeling and simulation of the hydrogen blended gas-electricity integrated energy system and influence analysis of hydrogen blending modes." *Energy* 239 (2022).

[21] H. Wojtaszek. "Energy Transition 2024-2025: New Demand Vectors, Technology Oversupply, and Shrinking Net-Zero 2050 Premium." *Energies* 18, no. 16 (2025).

[22] Stan and Di Wu. "Review of Perspectives and Research Prospects on New Energy System Construction." *Journal of Lanzhou University (Social Sciences Edition)* 53, no. 03 (2025):5−14.

[23] P. A. Ostergaard, N. Duic, and S. Kalogirou. "Sustainable development using integrated energy systems and solar, biomass, wind, and wave technology." *Renewable Energy* 235 (2024).

[24] Z. H. Zhang, Z. H. Zhu, X. Lu, D. Zhang, and M. R. Davidson. "Ratcheting up wind and solar targets for decarbonizing the power sector in China and beyond." *Cell Reports Sustainability* 01 (2025):100389−100389.

[25] Nebiyu Girgibo, Karita Luokkanen-Rabetino, Pekka Peura *et al*. "Renewable energy villages roadmap development for Ethiopia, Kenya, Uganda, and Botswana nations." *Next Energy* 8 (2025):100368.

[26] M. Elkholy, S. Schwarz, and M. Aziz. "Advancing renewable energy: Strategic modeling and optimization of flywheel and hydrogen-based energy system." *Journal of Energy Storage* 101 (2024).

[27] A. Kumaraswamy, S. S. Garud, I. A. Karimi, and S. Farooq. "Hydrogen for net-zero emissions in ASEAN by 2050." *International Journal of Hydrogen Energy* 90 (2024):575−587.

[28] F. Ferrada, F. Babonneau, T. Homem-de-Mello, and F. Jalil-Vega. "Integrated long-term energy planning with vehicle-to-grid for decarbonization of the Chilean energy system." *Journal of Cleaner Production* 523 (2025):146381.

[29] A. Maalouf, T. Okoroafor, Z. Jehl, V. Babu, and S. Resalati. "A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems." *Renewable & Sustainable Energy Reviews* 186 (2023).

[30] M. Habibi, M. G. Hosseini, and K. Wang. "Toward sustainable energy: A comprehensive review of hydrogen production, storage, and utilization." *Renewable and Sustainable Energy Reviews* 226 (2026):116193.

[31] Z. Wang, X Liu, W Gu *et al*. "Power-to-Hydrogen-to-Power as a pathway for wind and solar renewable energy utilization in China: Opportunities and challenges." *Renewable and Sustainable Energy Reviews* 226 (2026):116195.

[32] "Global Solar Council announces 2 terawatt milestone achieved for solar[EB/OL]." *Global Solar Council: Global Solar Council*, (2024).

[33] "Wind energy market size, share&trends analysis report 2025-2030." *Grand view research*, (2025).

[34] L. Chen, J. Yang, and C. Lou. "Characterizing ramp events in floating offshore wind power through a fully coupled electrical-mechanical mathematical model." *Renewable Energy* 221 (2024):119803.

[35] Y. A. Alli, O. Ejeromedoghene, T. O. Dembaremba *et al*. "Perspectives on the status and future of sustainable CO2 conversion processes and their implementation." *Carbon Capture Science & Technology* 16 (2025):100496.

[36] "National offshore wind R&D consortium[EB/OL]." *US Department of Energy*, (2025).

[37] "Bloom energy demonstrates hydrogen production with the world's most efficient electrolyzer and largest solid oxide system[EB/OL]." *Bloom energy*, (2023).

[38] "Topsoe celebrates milestone in construction of world's first industrial scale SOEC electrolyzer facility [EB/OL]." *Topsoe*, (2023).

[39] L. Tightiz, L. M. Dang, S. Padmanaban, and K. Hur. "Metaverse-driven smart grid architecture." *Energy Reports* 12 (2024):2014−2025.

[40] H. Zahid, A. Zulfiqar, M. Adnan *et al*. "Transforming nano grids to smart grid 3.0: AI, digital twins, blockchain, and the metaverse revolutionizing the energy ecosystem." *Results in Engineering* 27 (2025):105850.

[41] Z. Zhao, D. Tan, B. Shi, Y. Zhu, and H. Jin. "A Breakthrough in Design Verification of Megawatt Power Electronic Systems." *IEEE Power Electronics Magazine* 7, no. 3 (2020):36−43.

[42] M. T. Mon, R. Tansuchat, and W. Yamaka. "CCUS Technology and Carbon Emissions: Evidence from the United States." *Energies* 17, no. 7 (2024).

[43] M. Mutailipu, Q. N. Xue, T. Li, Y. D. Yang, and F. S. Xue. "Thermodynamic Properties of a Gas-Liquid-Solid System during the CO_2 Geological Storage and Utilization Process: A Review." *Energies* 16, no. 21 (2023).

[44] X. L. Ouyang, Y. C. Yang, K. R. Du, and Z. Y. Cheng. "How does residential electricity consumption respond to electricity efficiency improvement? Evidence from 287 prefecture-level cities in China." *Energy Policy* 171 (2022).

[45] D. Wang, X. Liu, X. D. Yang, Z. Y. Zhang, X. C. Wen, and Y. Y. Zhao. "China's Energy Transition Policy Expectation and Its CO₂ Emission Reduction Effect Assessment." *Frontiers in Energy Research* 8 (2021).

[46] X. G. Zhao, X. Meng, Y. Zhou, and P. L. Li. "Policy inducement effect in energy efficiency: An empirical analysis of China." *Energy* 211 (2020).

[47] B. L. Li, M. M. Rahman, and N. Haneklaus. "Assessing China's energy transition pathway: Insights from the synergistic effects of key drivers." *Energy Strategy Reviews* 55 (2024).

[48] C. Suo, Y. P. Li, S. Nie, J. Lv, H. Mei, and Y. Ma. "Analyzing the effects of economic development on the transition to cleaner production of China's energy system under uncertainty." *Journal of Cleaner Production* 279 (2021).

[49] F. Yang, X. Yang, and X. F. Li, "China's diverse energy transition pathways toward carbon neutrality by 2060." *Sustainable Production and Consumption* 47 (2024): 236-250.

[50] S. Zhang, D. W. Yang, H. S. Meng *et al*. "Spatiotemporal pattern evolution and driving factors of China's energy transition from a heterogeneity perspective." *Journal of Cleaner Production* 487 (2025).

[51] D. Q. Jia, X. M. Li, Q. L. Tan, B. K. Li, and X. Y. Lv. "Expanding the economic benefits of waste gasification through carbon and green certificate markets: Optimal bidding strategies in multiple markets." *Energy* 319 (2025).

[52] D. F. Zhu, B. Yang, Q Liu, K. Ma *et al*. "Energy trading in microgrids for synergies among electricity, hydrogen and heat networks." *Applied Energy* 272 (2020).

[53] A. Elia, M. Kamidelivand, F. Rogan, and B. O. Gallachoir. "Impacts of innovation on renewable energy technology cost reductions." *Renewable & Sustainable Energy Reviews* 138 (2021).

[54] L. H. Yang and X. Wu. "Net-zero carbon configuration approach for direct air carbon capture based integrated energy system considering dynamic characteristics of CO2 adsorption and desorption." *Applied Energy* 358 (2024).

[55] C. C. Shao, C. J. Feng, M. Shahidehpour, Q. Zhou, X. L. Wang, and X. F. Wang. "Optimal Stochastic Operation of Integrated Electric Power and Renewable Energy With Vehicle-Based Hydrogen Energy System." *Ieee Transactions on Power Systems* 36, no. 5 (2021):4310−4321.

[56] Y. M. Wan, Y. F Li, D. Wang *et al*. "International trade of green hydrogen, ammonia and methanol: Opportunities of China's subregions." *Renewable Energy* 235 (2024).

[57] R. Q. Su, Y. Xiao, F. Hamza, Z. Mamadiyarov, and A. Wahab. "Scaling up green hydrogen in China: Economic opportunities and challenges." *International Journal of Hydrogen Energy* 131 (2025):60−69.

[58] K. F. Roemer and J. H. Haggerty. "Coal communities and the US energy transition: A policy corridors assessment." Energy Policy 151 (2021).

[59] C. N. Zou, S. Q. Pan, and Q. Zhao. "On the connotation, challenge and significance of China's 'energy independence strategy'." *Petroleum Exploration and Development* 47, no. 2 (2020):449−462.

[60] J. Anderson, D. Rode, H. B. Zhai, and P. Fischbeck. "Reducing carbon dioxide emissions beyond 2030: Time to shift US power-sector focus." *Energy Policy* 148 (2021).

[61] M. Giberson. "Trump's policy may undermine pro-growth intentions." *Nature Energy* 1 (2016).

[62] S. Taboada, L. Clark, J. Lindberg, D. J. Tonjes, and D. Mahajan. "Quantifying the Potential of Renewable Natural Gas to Support a Reformed Energy Landscape: Estimates for New York State." *Energies* 14, no. 13 (2021).

[63] P. K. Liu and J. Q. Gui. "Comparative analysis on the development potential of green hydrogen industry in China, the United States and the European Union." *International Journal of Hydrogen Energy* 84 (2024):700−717.

[64] Y. Zhou, R. Y. Li, Z. X. Lv, J. Liu, H. J. Zhou, and C. M. Xu. "Green hydrogen: A promising way to the carbon-free society." *Chinese Journal of Chemical Engineering* 43 (2022):2−13.

[65] C. C. Chen. "Comparative impacts of energy sources on environmental quality: A five-decade analysis of Germany's Energiewende." *Energy Reports* 11 (2024):3550−3561.

[66] A. F. Onbargi and I. Dombrowsky. "Political inequality and impacts on climate mitigation: the case of Germany's energy sector." *Applied Energy* 393 (2025).

[67] K. Kappner, P. Letmathe, and P. Weidinger. "Causes and effects of the German energy transition in the context of environmental, societal, political, technological, and economic developments." *Energy Sustainability and Society* 13, no. 1 (2023).

[68] E. Shadrina, "EU's and Japan's strategies for energy transition enhancement in Central Asia: Exploring comparative and synergic perspectives, " *Energy Strategy Reviews* 58 (2025).

Shuai Zhou received her Ph.D degree in Electrical Engineering from the University of Auckland (UoA), New Zealand. She is currently a Lecturer with the Dept. of Electrical and Electronic Engineering, Auckland University of Technology (AUT), New Zealand. From Jan. 2024 to Jan. 2025, she was a Research Fellow with the Dept. of Electrical and Electronic Engineering at AUT. Her research interests are in the field of power system control, integration of renewable energy (wind energy and PV systems), smart grids, artificial intelligence applied to power systems.

Xiaolong Yang received the Ph.D. degree in Technical Economic and Management from North China Electric Power University, Beijing, China. He was a visiting scholar at Auckland University of Technology. He currently serves as an Associate Professor in School of Economics and Management, Northeast Electric Power University, Jilin, China. His research interests include power big data, electricity demand-side management, electricity-carbon markets, and technical-economic management.

Tek Tjing Lie is the Head of School at the Auckland University of Technology (AUT) School of Engineering, Computer and Mathematical Sciences. He received his BS degree from the Oklahoma State University, MS and Ph.D. degrees from Michigan State University. He has previously held academic positions in the School of Electrical and Electronic Engineering at the Nanyang Technological University. His research interests are in the fields of Power System Operation and Control, Deregulated Electrical Power Markets, AI Application to Power Systems, Renewable Energy and Smart Grids.

Wanyu Zhao received the Ph.D. degree in management science and engineering from Dongbei University of Finance and Economics, Dalian, China in 2020. She has participated in a joint doctoral program at Purdue University. She currently serves as an Assistant Professor in School of Economics and Management, Northeast Electric Power University, Jilin, China. Her research interests include energy economics, investment economics and industrial economics.

Jieping Han is the head of School at Northeast Electric Power University School of Economics and Management, Jilin, China. She received the Ph.D. degree in management from Jilin University, Jilin, China. She is currently a Full Professor. She also serves as Vice Chairman of the Electric Power Technology and Economics Branch of the China Society of Technology and Economics. Her research interests include electric power economics and management, low-carbon economy and management.

Wendong Shao is currently pursuing the M.S. degree with the School of Economics and Management, Northeast Electric Power University, Jilin, China. Her research interests include energy and electric power economics and management.