Changes in the Global Energy Landscape and New Characteristics of Energy Technology Development Under the Ukraine Crisis: Postprint

Authors: Wang Chao, Sun Fuquan, Xu Ye, Jiang Xiangqiang, Wang Chao

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Abstract

Energy serves as the lifeblood of economic operation. The outbreak of the Ukraine crisis has triggered a regional energy supply crisis and global energy market turbulence, precipitating profound transformations in the global energy landscape and the development trajectory of energy technology, which exert far-reaching influences on China's technological strategy in the energy domain. This study, grounded in an analysis of strategic pivots in energy policy across major global economies and integrating perspectives from international energy trade, global low-carbon transition, and national energy security, concentrates on discerning trends in energy technology strategy. The article posits that: (1) localization of energy supply has emerged as the developmental orientation for global energy technology strategy; (2) in the clean energy era, the cost attribute of energy technologies is progressively intensifying; (3) the global community is accelerating the research and development process for clean energy technologies; and (4) international scientific and technological cooperation in the clean energy sector confronts novel challenges. Additionally, by examining the current state of China's energy structure, the paper proposes policy recommendations from the vantage points of strategic deployment, research and development platforms, R&D orientation, innovation systems, and international cooperation. The research findings furnish references and insights for China in constructing a new paradigm for its energy system and formulating a novel strategy for energy technology.

Full Text

Changes in Global Energy Landscape and New Developments in Energy Science and Technology amid Ukraine Crisis

WANG Chao1*, **SUN Fuquan**1, **XU Ye**1, **JIANG Xiangqiang**2
1 Chinese Academy of Science and Technology for Development, Beijing 100038, China
2 Petroleum Exploration and Development Research Institute, SINOPEC, Beijing 102206, China

Abstract

Energy is the lifeblood of economic activity. The outbreak of the Ukraine crisis has triggered a regional energy supply crisis and global energy market turmoil, profoundly transforming the global energy landscape and the trajectory of energy science and technology development, with far-reaching implications for China's energy technology strategies. Based on an analysis of energy strategy shifts in major world economies, this study examines strategic trends in energy science and technology through the lenses of international energy trade, global low-carbon transition, and national energy security. The findings indicate that: (1) localization of energy supply has become the strategic direction for global energy technology development; (2) in the clean energy era, the cost attribute of energy technology is increasingly prominent; (3) the world is accelerating clean energy technology research and development; and (4) international scientific and technological cooperation in clean energy faces new challenges. Furthermore, considering China's current energy structure, this paper proposes policy recommendations from the perspectives of strategic deployment, R&D platforms, research orientation, innovation systems, and international cooperation. The results provide valuable references and insights for China to construct a new energy system framework and formulate new energy technology strategies.

Keywords: Ukraine crisis; science and technology strategy; clean energy; energy security

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1. Introduction

Energy is the lifeblood of economic operation. The outbreak of the Ukraine crisis has triggered a regional energy supply crisis and global energy market turmoil, leading to profound changes in the global energy landscape and energy science and technology development trends, with far-reaching impacts on China's energy sector technology strategies. This article, based on research into energy strategy shifts among major world economies and integrating perspectives from international energy trade, global low-carbon transition, and national energy security, focuses on analyzing strategic trends in energy science and technology. The article argues that: (1) localization of energy supply has become the development direction of global energy science and technology strategies; (2) in the clean energy era, the cost attribute of energy technology is gradually strengthening; (3) the world is accelerating the research and development process of clean energy technology; and (4) international scientific and technological cooperation in the clean energy sector faces new challenges. Additionally, combining the current situation of China's energy structure, policy recommendations are proposed from the perspectives of strategic deployment, R&D platforms, research orientation, innovation systems, and international cooperation. The research results provide references and insights for China to build a new pattern of energy systems and new strategies for energy science and technology.

Since the outbreak of the Ukraine crisis on February 24, 2022, Western countries have imposed unprecedented multi-round, comprehensive, and large-scale sanctions on Russia. The Ukraine crisis has further highlighted the strategic importance of energy, and Western sanctions against Russia and Russia's countermeasures have brought lasting, profound, and widespread impacts on the global energy landscape. As the world's largest natural gas exporter and second-largest oil exporter, Russia holds a pivotal position in the global fossil energy supply chain. The European energy crisis triggered by the Ukraine crisis has stimulated major European and American economies to accelerate adjustments to their national energy strategies, which will inevitably lead to profound changes in the global energy landscape, international energy trade, global energy transition, and energy science and technology development trends, also generating significant impacts on China's economic and social development and energy science and technology strategies.

2. Soaring International Fossil Energy Prices Triggered by the Ukraine Crisis

2.1 Pre-Crisis Energy Market Conditions

Before the Ukraine crisis, international energy prices had already risen sharply in 2021 due to post-pandemic economic recovery, insufficient investment in traditional energy, and increasingly prominent volatility issues with new energy, causing Europe to face its first energy supply crisis in recent years. With OPEC+ production capacity releases falling short of expectations in 2022 and slow recovery in U.S. shale oil production, international oil prices continued to climb, with Brent crude oil futures prices breaking through the $90/barrel threshold on January 26, 2022.

2.2 Post-Crisis Price Surge

Following the outbreak of the Ukraine crisis, international crude oil, natural gas, and coal supplies tightened, with prices rising across the board [Figure 1: see original paper]. In the crude oil market, international oil prices fluctuated upward under sanctions against Russia, remaining at high levels. From the first to third rounds of Western sanctions, international oil prices soared from over $90/barrel to over $130/barrel within half a month (the first time in seven years breaking $100/barrel) [4]. In natural gas markets, European gas prices repeatedly hit record highs. The European benchmark Dutch Title Transfer Facility (TTF) natural gas spot price fluctuated dramatically. On the day the crisis broke out, the price had risen 50.18% compared to early February 2022. As Western sanctions continued and Russia issued its "ruble settlement order," natural gas prices surged to $69.32/MMBtu on March 8, 2022, 12 times the price in the same period in 2021, and reached a peak in August 2022. In coal markets, international thermal coal supply was tight, with prices soaring throughout the crisis. The European ARA three-port thermal coal price rose continuously after the conflict, skyrocketing from $195/ton on the day of the conflict to $328/ton on August 22, 2022, an increase of 68.2%.

3. Accelerated Energy Strategy Adjustments in Major Economies

3.1 EU's "Energy Independence Strategy"

Facing the dual test of energy supply crisis and rising energy prices, the EU is striving to eliminate its dependence on Russian energy and enhance energy independence. On May 18, 2022, the European Commission released the REPowerEU Plan (Joint European action for more affordable, secure and sustainable energy), which clarified the main tasks for achieving energy independence [9]. The short-term goal is to stabilize energy prices and ensure gas supply through diversification of natural gas imports and supply of low-carbon gases (hydrogen and biogas). The medium-term goal (by 2027) is to eliminate dependence on Russian energy through accelerated energy transition and improved energy efficiency. Regarding natural gas import diversification, the EU plans to add 50 billion cubic meters of LNG and 10 billion cubic meters of pipeline gas annually. In energy transition, the EU has raised its 2030 renewable energy target from 40% to 45%, focusing on supply chain construction in three areas: solar photovoltaics, wind energy, and heat pumps, while also focusing on technology R&D in hydrogen and biomass energy. In energy efficiency improvement, the EU plans to raise its 2030 energy efficiency target from 9% to 13%.

The EU energy system is heavily dependent on Russian energy imports. Although the EU's renewable energy proportion has increased in recent years, fossil energy still accounts for about 60% of total energy consumption, with external dependence exceeding 70%. Russia is the EU's largest importer in all three fossil energy sectors. In 2021, Europe's dependence on Russian pipeline natural gas, LNG, oil, and coal was 45.25%, 16.08%, 29.66%, and 48.17%, respectively [Figure 2: see original paper] [3]. Additionally, the European energy crisis has driven up energy prices, continuously increasing European energy costs.

3.2 Germany's Reflection on "Energy Transition Strategy"

Since the 21st century, Germany's energy transition policy has earned it a global moral high ground. As a top performer in global energy transition, Germany has actively promoted "coal abandonment" and "nuclear abandonment" while vigorously developing renewable clean energy. However, the Ukraine crisis has disrupted Germany's energy transition process, forcing the Scholz government to reflect on and adjust its energy development strategy due to energy supply gaps. First, the government recently considered extending the lifespan of existing nuclear power plants, but it was too late; analysis concluded that restarting German nuclear plants was no longer possible. Second, Germany plans to extend the operation of coal-fired power units and further expand coal usage to fill the power supply gap caused by the loss of Russian gas. Third, Germany is accelerating renewable energy deployment, planning to advance its 100% renewable energy power generation target to 2035, with new photovoltaic installed capacity increasing from 7 GW in 2022 to 20 GW in 2028, a 64.8% increase from earlier plans.

Germany's energy development has been caught in a dilemma between its overly aggressive energy transition strategy and real-world economic energy interests. The EU's multi-round sanctions against Russia have forced Germany to accelerate its decoupling from Russian energy dependence, with its dependence on Russian oil declining rapidly from 29.6% in February 2022 to 19.3% in September 2022 [Figure 3: see original paper] [12].

3.3 France's Restart of "Nuclear Renaissance Strategy"

Constrained by scarce domestic fossil resources, France's energy development has been characterized by "nuclear dominance with green electricity following." In 2020, nuclear power accounted for 70.6% of France's electricity generation, the highest proportion globally [13]. Additionally, France's renewable energy installed capacity has maintained rapid growth in recent years, reaching 65,381 MW in 2022, ranking third in Europe, an 8.25% year-on-year increase [14].

France considers energy security a prerequisite for energy transition. In its 2019 Energy and Climate Law, the French government proposed closing 14 nuclear reactors by 2035 to reduce nuclear's share in its electricity mix to 50% while nearly doubling renewable energy generation. However, professional assessments concluded that existing technologies could not guarantee the flexibility and diversity requirements for high-proportion renewable energy power systems, leading the French government to postpone the closure of nuclear power plants. The Ukraine crisis has accelerated France's strategic shift toward nuclear energy, restarting its nuclear renaissance strategy. First, France plans to build new nuclear units, starting with six EPR2 units from 2028, followed by eight additional units. The first new unit will be operational by 2035, with total new nuclear capacity reaching 25 GW by 2050. Second, France plans to extend the lifespan of existing nuclear units from 40 to over 50 years, provided they meet safety conditions.

3.4 U.S. Implementation of "Energy Control Strategy"

The Ukraine crisis has enabled the United States to achieve its strategic goal of energy control over the EU. By encouraging restrictions on Russian energy exports and pressuring against the operation of the Nord Stream 2 pipeline, the U.S. cut off the EU's energy supply source, forcing the EU to turn to the U.S. to fill its energy supply gap, thereby eroding Russia's energy market share in Europe and enhancing U.S. global energy market discourse power. On March 25, 2022, the U.S. and EU established a Joint Energy Security Working Group, with the U.S. committing to export at least an additional 15 billion cubic meters of LNG to the EU in 2022 and provide about 50 billion cubic meters more by 2030. From a short-term perspective, the U.S. aims to assist the EU in ensuring natural gas supply and stabilizing global fossil energy prices. From a long-term perspective, the U.S. seeks to coerce the EU into reducing its dependence on Russian energy and achieving U.S. energy control over Europe.

The significant increase in U.S. LNG exports to Europe will greatly stimulate the development of the U.S. domestic oil and gas industry. The shale oil and gas revolution has surged U.S. domestic production, enabling America to eliminate dependence on foreign oil and gas imports and become a global oil and gas supply growth center and major exporter, substantially enhancing its international energy market discourse power. Following the Ukraine crisis, the U.S. has intensified domestic shale oil and gas resource development. On one hand, given Europe's oil and gas supply shortages and Middle East production constraints, the U.S. has increased domestic production to support energy exports to Europe, achieve energy control over Europe, and maintain and strengthen U.S. global hegemony. On the other hand, the U.S. has implemented a "dual pricing" policy for LNG exports to Europe, with export prices about 3-4 times higher than domestic prices. The sharp rise in international energy prices and LNG exports to Europe have brought huge economic benefits to the U.S. energy industry.

3.5 UK's "Energy Security Strategy"

Following the Ukraine crisis, the UK government released its British Energy Security Strategy, which continues relevant policies from the 2020 Ten Point Plan for a Green Industrial Revolution but further focuses future energy development on three major areas: offshore wind, nuclear energy, and hydrogen energy.

In offshore wind, given climate factors and land resource constraints, along with abundant offshore wind resources, the UK has always prioritized offshore wind as a key focus for renewable energy development, aiming to become a global offshore wind leader and floating offshore wind pioneer. The UK government plans to streamline administrative approval processes to accelerate offshore wind projects, striving to achieve 50 GW of offshore wind installed capacity by 2030, including 5 GW of floating offshore wind capacity.

In nuclear energy, first, the UK plans to increase civil nuclear deployment to 24 GW by 2050 (three times the current level), with eight reactors operational, raising nuclear power's share to 25% of the UK power system (compared to the current 15%). Second, the UK has established a Nuclear Enablement Fund (£120 million) to accelerate the development of advanced nuclear technologies such as Small Modular Reactors (SMR) and Advanced Modular Reactors (AMR).

In hydrogen energy, first, the UK aims to form green hydrogen production capacity greater than 1 GW by 2025 and establish a business model suitable for hydrogen industry development. Second, by 2030, the UK targets low-carbon hydrogen production capacity to reach 10 GW, with green hydrogen accounting for over 50%.

4. Outlook and Reflections on the Global Energy Landscape amid Ukraine Crisis

4.1 Coal as Europe's Short-to-Medium-Term Alternative Energy

Against the backdrop of continuous shocks to European energy security, Europe's short-term energy strategy has shifted from "climate security" to "energy security." To address energy supply shortages, rising natural gas prices, and dependence on Russian energy, coal will become Europe's fastest alternative energy source in the short-to-medium term based on analysis of energy policy, energy prices, energy security, and resource endowments [15]. European coal-fired power generation is expected to rebound significantly, with coal power remaining the cornerstone for ensuring European electricity demand.

First, in terms of energy policy, European countries have restarted coal power to cope with natural gas supply shortages. In response to the EU's commitment to reduce Russian natural gas imports by two-thirds by the end of 2022, Germany, Italy, the UK, and others have successively postponed the retirement of coal-fired power plants and extended their service lifespans. Second, regarding energy prices, rising natural gas prices have highlighted coal's price advantage. After the Ukraine crisis, constrained by the suspension of European pipeline gas, insufficient LNG infrastructure, and locked-in international LNG long-term contracts, Europe's global "gas rush" has significantly pushed up global natural gas prices, further highlighting coal's price advantage. Third, concerning energy security, renewable energy cannot bear the responsibility of ensuring European energy security in the short term. Although Europe has a high proportion of renewable energy, issues of insufficient total volume, unstable supply, and high costs mean it cannot yet guarantee European energy security. Fourth, in terms of resource endowments, Europe is relatively rich in coal resources. In 2020, Europe's proven coal reserves accounted for 12.8% of the global total, far higher than its global shares of oil and natural gas at 0.8% and 1.7%, respectively [5].

4.2 Reconstruction of International Oil and Gas Trade Map

Russia's energy export center is shifting "from west to east." In 2020, European countries in the OECD accounted for 71.9% of Russia's total natural gas exports. After the Ukraine crisis, as the EU turned to U.S. LNG, Russia's European energy market has been eroded by the United States. In this context, Russia's energy export center is shifting "from west to east." First, after the conflict broke out, India purchased Russian oil in excess quantities, with crude oil exports to India reaching 300,000 barrels/day in March and increasing to 700,000 barrels/day in April. Russian crude oil's share of India's total crude oil imports has surged from less than 1% before the conflict to about 17% today. Second, China and Russia signed energy supply agreements [16], with the two countries signing 10-year supply agreements for 200,000 barrels/day of crude oil and 10 billion cubic meters of natural gas in early February.

The United States is expanding its influence in the global fossil energy market through oil and gas exports. The shale oil and gas revolution has surged U.S. domestic production, enabling America to eliminate dependence on foreign oil and gas imports [17], achieve U.S. energy independence, and become a global oil and gas supply growth center and major exporter, substantially enhancing its international energy market discourse power.

4.3 Divergent Energy Transition Processes Among EU, U.S., and Russia

As the Ukraine crisis continues to ferment, high fossil energy prices and sanctions against Russia are expected to significantly differentiate global energy transition processes. The EU is comprehensively accelerating its clean energy transition pace, while the U.S. oil and gas industry revival may constrain its transition process, and Russia's energy low-carbon transition faces severe challenges.

The EU's short-term energy "growing pains" are stimulating rapid development of its clean energy industry. Europe is a global advocate and supporter of low-carbon energy transition. Although the EU plans to diversify natural gas imports, expand domestic natural gas production and reserves, build LNG receiving terminals, and restart coal-fired units to boost its fossil energy industry and solve short-term energy crises, developing green energy to achieve energy independence has become a universal consensus for Europe in the long term. The European Commission and member states such as Germany and France have recently adjusted their energy strategies, significantly raising clean energy development goals and substantially shortening clean energy deployment cycles, fully reflecting that clean energy remains the focus of Europe's long-term energy strategy.

The revival of the U.S. domestic oil and gas industry may constrain the energy transition process. The Biden administration previously released The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050 [18], committing to building a zero-carbon power grid by 2035 and achieving net-zero emissions by 2050, promoting clean energy development and limiting fossil energy investment. After the Ukraine crisis, based on the U.S. national strategy of energy control over Europe, the Biden administration urged increased domestic oil and gas exploration and development. Baker Hughes drilling data reveals that the number of U.S. drilling rigs reached 719 in May 2022, an increase of 266 rigs (58.7%) compared to the same period in 2021 [^2^]. The recent surge in international oil prices has generated substantial profits for U.S. oil companies, boosting investment in the U.S. domestic market and stimulating the U.S. oil and gas industry. However, this has further highlighted the high cost of clean energy, which may to some extent affect the commercial promotion and R&D investment in clean energy technologies.

Russia's national financial losses have weakened its capacity for low-carbon energy transition. Energy exports are the lifeline of Russia's national economy, with oil and gas revenues accounting for about 45% of Russia's 2021 income. As a global energy power and major carbon emitter, Russia had proposed achieving carbon neutrality by 2060. After the Ukraine crisis, due to Western sanctions across economic, military, technological, cultural, and energy domains, as well as restrictions on oil and gas export, Russia's economy has suffered severe blows. Russia's medium- and long-term economic development will become more dependent on its fossil energy industry, and its energy transition will face constraints from national finance, economic development, and technological innovation, substantially reducing the probability of achieving its 2060 carbon neutrality goal.

4.4 Global Energy Structure Accelerating from "Fossil Energy Dominance" to "Fossil+Clean Energy" Co-dominance

Fossil energy remains the dominant energy type globally today. According to U.S. Energy Information Administration (EIA) research, in 2020, global energy consumption shares were coal (25.87%), oil (30.32%), natural gas (24.49%), renewable energy (14.75%), and nuclear energy (4.57%). By 2050, these proportions are projected to shift to 19.93%, 28.04%, 21.8%, 26.53%, and 3.69%, respectively [19]. The Ukraine crisis has exposed the vulnerability of Europe's energy system and the security risks of fossil energy monopolies, forcing the EU to further promote clean energy development and stimulating the global energy structure to accelerate its transformation toward a "fossil+clean energy" co-dominant pattern.

The rapid development of clean energy has laid the foundation for global energy structure transformation. From 2010 to 2020, global renewable energy generation increased from 761.2 TWh to 3,147 TWh, a 313.4% increase. Among these, solar and wind energy installed capacity increased by 1,664.3% and 305.3%, respectively [20]. Meanwhile, new energy storage and hydrogen energy have received high attention in recent years and are expected to achieve leapfrog development and large-scale application in the short term, thereby driving the share of clean energy to increase further. The global energy structure is accelerating its shift toward a "fossil+clean energy" co-dominant pattern.

Energy supply localization is becoming a mainstream international trend. The current European energy crisis has served as a very realistic warning to countries worldwide, significantly elevating the national strategic importance of energy security. Constrained by dependence on Russian energy, EU member states have shown serious divisions in their attitudes toward sanctions against Russia. Germany has faced dilemmas in each round of sanctions against Russia. Consequently, the EU urgently seeks to enhance energy independence, vigorously develop domestic clean energy, and achieve self-sufficiency in energy supply. Moreover, the overarching trend of global energy system low-carbon transformation will help countries worldwide achieve energy supply localization and build independent energy supply systems. Compared with fossil energy, clean energy does not have excessive resource endowment requirements, and scientific and technological innovation is the primary factor for its industrial development, which highly matches Europe's climate, energy, and science and technology strategies. The European energy crisis and the awakening of energy independence consciousness will inspire other countries to deeply consider their energy local supply capabilities under extreme circumstances, and energy supply localization is expected to become a standard configuration for major world powers and a mainstream trend in international energy.

5. New Characteristics of Global Energy Science and Technology Development amid Ukraine Crisis

5.1 Awakening of Energy Independence Consciousness Changing Global Energy Science and Technology Strategy Direction

Energy independence is a fundamental guarantee and security basis for a country's prosperity. The European energy crisis triggered by the Ukraine crisis has forced countries worldwide to reflect deeply on energy security, and significantly improving local energy supply capacity has become an important component and long-term development goal of national energy strategies. The awakening of energy independence consciousness and the trend of energy supply localization will accelerate adjustments in global energy science and technology strategy directions. The global energy system will shift from the traditional model of cross-regional, long-distance, large-scale transmission to more localized, diversified, and low-carbon supply models, with clean energy, distributed energy, long-duration energy storage systems, integrated energy services, and intelligent energy consumption models receiving widespread attention.

5.2 In Clean Energy Era, Resource Endowment Attributes Weaken While Technology Cost Attributes Strengthen

In the fossil energy era, energy attributes were "geological" resources, where resource endowment attributes were stronger than technology cost attributes. Constrained by the spatial distribution differences of ancient organisms in geological history, today's global fossil energy distribution exhibits typical geological historical inheritance and spatial distribution differentiation characteristics. For example, the Middle East is extremely rich in oil and gas resources, while China's oil and gas resources are relatively scarce. Within China, western inland areas are richer in oil and gas resources than eastern coastal areas. The abundance of oil and gas resources in today's world is solidified by geological factors, further highlighting oil's strategic attributes and making it a focal point of contention among nations.

In the clean energy era, energy attributes are "geographic" or "technological" resources, where technology cost attributes are stronger than resource endowment attributes, offering greater potential for human modification. Solar and wind energy, as "geographic" resources, have global 普惠性 (universal accessibility) characteristics, and all countries can improve domestic resource utilization efficiency through technological innovation. Hydrogen, biomass, and nuclear energy, as "technological" resources, have seen talent and scientific and technological elements surpass resource elements as primary development factors. Through scientific and technological innovation to improve energy efficiency and reduce energy costs, technology popularization can be greatly advanced. During the low-carbon, electrification, and intelligent transformation of the global energy system, demand for key mineral resources (such as lithium, copper, nickel, etc.) will increase, but geological resources will generally transform from current "fuel" supply to "material" supply, weakening the resource endowment attribute and strengthening the technology cost attribute.

5.3 Technology Sovereignty as the Cornerstone of Energy Sovereignty

Against the backdrop of low-carbon energy system transformation, multi-polar evolution of energy supply and demand, and awakening energy independence consciousness, the driving effect of scientific and technological innovation on energy industry development is increasingly strengthening and has become the cornerstone for achieving national energy independence. France's nuclear energy strategy adjustment is a typical case. After General Electric of the United States completed its acquisition of Alstom's power/grid business in 2015, France's nuclear industry system suffered a severe blow. This European energy crisis has forced the French government to restart its nuclear energy development strategy. In addition to building an independent energy system, its strategic core is to revitalize France's nuclear energy industry chain, i.e., to build a fully independent nuclear energy industry chain and innovation system covering nuclear reactor design, nuclear steam system supply, conventional island equipment supply, and nuclear power operation, reviving France's nuclear industry system.

5.4 Ukraine Crisis Accelerating Clean Energy Technology R&D with Renewed Attention to Nuclear Energy

The Ukraine crisis has driven the reconstruction of the global energy landscape, forcing European countries with high dependence on imported fossil energy to increase clean energy R&D efforts and accelerate the pace of fossil energy substitution. The International Energy Agency's Clean Energy Technology Database reveals [21] that some European countries are in an internationally leading position in the energy transition field. The top five countries in key core technologies for energy transition are the United States, Japan, Germany, France, and the United Kingdom, with advantageous technology areas focusing on electricity, biofuels, and hydrogen energy. Among them, the UK and Germany hold global monopolies in coal gas heating reforming and synthetic hydrocarbon fuel fields; Germany, France, and Italy are internationally leading in solar energy, wind energy, hydrogen, and biomass energy fields [21]. Based on its technological leadership in energy transition, the EU's REPowerEU Plan has significantly raised renewable energy deployment targets to accelerate the construction of an independent energy supply system and strive to eliminate dependence on Russian fossil energy before 2030. It is foreseeable that photovoltaics, wind power, hydrogen energy, and biomass energy will experience short-term explosive development in Europe. Moreover, the UK and France have made major strategic turns in nuclear energy development, increasing R&D efforts in advanced nuclear technology, accelerating the construction of new nuclear power stations, and extending the service life of existing nuclear power plants. Europe's attitude toward nuclear energy has undergone its biggest policy shift since the Fukushima nuclear accident.

5.5 Clean Energy International Science and Technology Cooperation Facing Significant Risks and Challenges

Before the Ukraine crisis, major global economies treated climate change as a political tool for great power games and geopolitical competition, deploying their carbon neutrality strategies from an integrated domestic-international industrial policy perspective, enhancing domestic clean energy technology strength through international cooperation, and seizing international market share through green technology and product exports to achieve domestic economic recovery and industrial upgrading. For example, Japan's 2050 Carbon Neutrality Green Growth Strategy released in 2020 proposed two types of international cooperation models: (1) conducting international cooperation with the United States and the EU to strengthen R&D in key areas and develop relevant international standards and rules; and (2) cooperating with emerging economies to focus on overseas demonstration project construction and seize the international market for green technologies [22].

The Ukraine crisis has triggered energy crises and food shortages, forcing global supply chains to reconstruct and shift toward short-chain and localization, while global economic governance is moving toward polarization and fragmentation, with economic globalization facing stagnation risks. Energy sector scientific and technological cooperation faces greater challenges [23]. Against this backdrop, the U.S. Inflation Reduction Act has further fragmented the global clean energy industry chain [24], hindering the global optimal allocation of capital, technology, and products; intensifying global competition in technology, talent, and industry; and raising the cost of global low-carbon transition.

6. Policy Recommendations for China

The Ukraine crisis has triggered global energy landscape transformation, significantly accelerating the localization and low-carbonization of energy systems, which has major impacts on both China's short-term energy import costs and long-term national energy security. China should base itself on its resource endowment reality, rely on scientific and technological innovation, and build a more resilient national energy system.

6.1 Build a New National Energy Strategy Pattern of Energy Supply and Marketing Localization

Eastern coastal regions, as energy consumption highlands and resource lowlands, should gradually reduce their dependence on "West-to-East Electricity Transmission" and "West-to-East Gas Transmission." Relying on coastal wind and solar resources, they should strengthen the construction of offshore wind power, wind-to-hydrogen, and distributed photovoltaic clean energy systems, creating an eastern "green electricity corridor" with independent energy supply. Western regions should leverage their abundant energy resources to implement a "West Energy for Western Use" and "High Energy Westward Placement" strategy, using western energy for western economic construction and promoting the deployment of high-energy-consuming industries in central and western regions rich in resources.

6.2 Establish a National Energy Technology Strategy "Energy Technology Triangle" for the Short-to-Medium Term

In the short-to-medium term, China should follow the principle of "enhancing existing fossil energy while expanding clean energy increments," building a national energy technology strategy centered on three core pillars: "clean and efficient utilization of coal, unconventional oil and gas exploration and development, and clean energy efficiency improvement." By adopting a scientific and technological innovation policy of "multiple energy sources running simultaneously, multiple tracks proceeding in parallel," China can form a synergy between "fossil energy + clean energy" to achieve a win-win goal of "energy independence" and "low-carbon energy."

6.3 Build Integrated Energy System R&D Platforms to Accelerate Multi-Energy Complementation and Pilot Testing

To eliminate the drawbacks of renewable energy intermittency, China should accelerate the integrated development of "fossil and non-fossil energy" and "renewable energy and energy storage systems." First, build national integrated energy system R&D platforms focusing on key areas such as energy interconnection, cross-sector energy flow, and energy system intelligence. Second, actively promote the construction of source-storage platforms, pilot testing of low-carbon technologies, and application of multi-energy scenarios, encouraging pilot testing of multi-energy complementation to promote iterative development of low-carbon technologies and establish safe and efficient dynamic integration mechanisms for multi-energy complementation as soon as possible.

6.4 Establish Low-Cost-Oriented Clean Energy Technology R&D Guidance

The high green premium of low-carbon technologies has become a key factor hindering their commercial promotion. China should comprehensively promote the low-costization of clean energy technologies. First, increase the weight of cost indicators for low-carbon technologies in national science and technology projects. Second, leverage the role of energy leading enterprises to strengthen technology R&D and market promotion, using scale effects to achieve cost reductions.

6.5 Build an Independent Science and Technology R&D System for the Full Clean Energy Industry Chain

China should systematically deploy innovation chains around the clean energy industry chain, forming an independent scientific and technological innovation mechanism covering the entire industry. First, establish a potential risk early warning mechanism for the clean energy industry chain, identifying risk shortcomings in raw material supply, equipment manufacturing, advanced materials, and key technologies in critical areas, and clarifying priorities for independent scientific and technological 攻关 (breakthroughs). Second, build an innovation resource allocation system with deep integration of industry and innovation chains, refining the positioning and division of labor of innovation entities in the industry and innovation chains, and accelerating the transformation of independent scientific and technological achievements into real productive forces.

6.6 Conduct International Science and Technology Cooperation Around Clean Energy Key Technologies

International scientific and technological cooperation in the energy field should balance strategic and practical considerations. First, identify advantageous technology countries and key frontier technologies in different fields to build differentiated international science and technology cooperation strategies for different technology areas. Second, seize the important opportunity of the EU's vigorous promotion of clean energy technology R&D and Russia's urgent need for external cooperation to accelerate international scientific and technological cooperation in the energy field and rapidly enhance China's core technology capabilities in the energy sector.

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Notes:

MMBtu: million British Thermal Units; 1 MMBtu = 1.055 GJ; 1 barrel of crude oil = 5.8 MMBtu.

Note: Figure translations are in progress. See original paper for figures.