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Discussion on Policy Frameworks and International Cooperation Mechanisms in the Global Energy Transition

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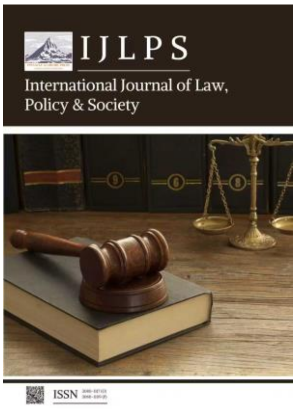

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Abstract: Major economies worldwide have entered a new stage of energy transition characterized by deeper structural adjustment, institutional innovation, and an intensified interplay among government regulation, market dynamics, and technological advancement. In this phase, clean-energy development is no longer limited to achieving reliability, cost reduction, and carbon-reduction targets; instead, it has evolved into a key component of national security strategies, industrial upgrading, and long-term competitiveness. Countries are redesigning regulatory frameworks, restructuring pricing mechanisms, and strengthening coordination across energy, manufacturing, and digital sectors to respond to growing uncertainties in global supply chains and shifting geopolitical landscapes. At the same time, technological breakthroughs-such as utility-scale battery storage, green hydrogen production, carbon capture and utilization (CCUS), and intelligent grid systems-are accelerating the diversification of global energy portfolios and reshaping the competitive order of emerging energy industries. These developments also place new demands on cross-border governance, as the increasing interconnection of regional infrastructure, the push for harmonized green-finance standards, and expanding clean-energy technology cooperation require more coherent international mechanisms. Nevertheless, geopolitical tensions, divergent subsidy policies, and fragmented regulatory systems continue to hinder the formation of a stable and mutually beneficial global cooperation environment. By comparing national policy frameworks, analyzing institutional coordination mechanisms, and evaluating the evolution of international cooperative models, this study identifies the main barriers and driving forces influencing global clean-energy transition. It further proposes strategic pathways to enhance cross-regional coordination, strengthen technological synergy, and promote more predictable and efficient global governance. The findings aim to provide theoretical insights and practical references for accelerating a coordinated, resilient, and effective global clean-energy transformation in the coming decades.

Keywords: energy transition; international cooperation; policy framework; technical collaboration; green governance

1. Introduction

Due to a combination of factors-including shifts in global energy demand, tightening resource constraints, and rapid advances in emerging technologies-the world's energy system is undergoing profound structural transformation. The imperative to reduce greenhouse gas emissions not only reshapes the trajectory of energy consumption, but also exerts far-reaching influence on the reconfiguration of industrial chains, the evolution of market competition, and the reconstruction of global governance mechanisms. As energy production and consumption patterns accelerate their transition toward low-carbon and diversified forms, traditional development models centered on fossil fuels are being challenged, while new forms of clean-energy industries begin to assume central positions in national development strategies [1].

However, the pathways and drivers of energy transition vary significantly across countries, reflecting differences in resource endowments, economic structures, technological capabilities, and institutional arrangements. Many countries still face multidimensional constraints related to energy security, power system flexibility, grid stability, and the availability of critical minerals required for renewable technologies. These limitations shape their transition strategies and determine the degree to which clean-energy deployment can be expanded or optimized. For example, some economies prioritize supply security and grid reliability, while others emphasize cost efficiency, industrial competitiveness, or geopolitical autonomy [2].

At the global level, although the urgency of combating climate change has fostered unprecedented momentum for international cooperation, the overall landscape remains complicated and fragmented. Cross-border economic cooperation continues to encounter challenges such as inconsistent technical standards, misaligned policy frameworks, divergent subsidy schemes, and the uneven distribution of clean-energy investment. In addition, geopolitical tensions, trade disputes, and emerging industrial protectionism increase uncertainty for energy-related infrastructure projects and may hinder international coordination in clean-energy technology development, green-finance mechanisms, and carbon-market integration [3].

These complexities indicate that current global energy governance lacks sufficient coherence and adaptability. Therefore, it is essential to conduct more systematic and comprehensive research to identify the mechanisms through which national energy transitions interact, to analyze the factors that shape policy convergence or divergence, and to explore the conditions required to build a more stable, resilient, and mutually beneficial system of international energy cooperation. Only by deepening comparative analysis of national policy frameworks, strengthening understanding of cross-border cooperation patterns, and addressing institutional and technical barriers can the international community collectively promote a cleaner, safer, and more inclusive global energy future.

2. Policy Changes and Governance Mechanism Reshaping in the Global Energy Transition

2.1. The Policy Evolution Path of Global Energy Transition

Although energy policies in different historical periods have different target frameworks, they have always been dynamically adjusted around system constraints, resource conditions and the status of technological innovation. Early policies focused on incremental construction and the improvement of power supply accessibility, with an emphasis on reliability and infrastructure construction. As climate issues have become a global focus, emission reduction has been incorporated into the development plans of various countries, promoting large-scale investment in renewable energy. As a result, the installed capacity of solar and wind power has grown rapidly. However, as the proportion of new energy continues to rise, the traditional supply and demand system characterized by centralization and large volume gradually reveals problems such as vulnerability, increased dispatching difficulty, and restricted cross-regional collaboration.

Amid these changes, energy policy is shifting toward more integrated and market-oriented frameworks. New electricity-market designs increasingly incorporate capacity mechanisms, ancillary services, demand response and distributed resources, broadening system participation and altering operational logic. Policy tools are becoming cross-sectoral, reinforcing coordination between national and regional planning. Approaches vary: Europe pursues institutional alignment, the United States relies on competitive innovation, and China builds scale and supply-chain strengths through planning. Despite differing models, a move toward multi-level collaborative governance is now a global trend.

2.2. Technology-Driven and Innovative Trends in Energy Transition.

Scientific and technological changes are becoming the dominant force influencing the energy transition. Breakthroughs in solar energy, wind energy, energy storage, communication and power electronics are transforming the economic and physical boundaries of the power industry, driving the energy form from one-way flow to a high-level interactive, automated and decentralized route. The impact on the price structure, especially in the context of the decline in the prices of solar energy and energy storage, is one of the most prominent effects of technological innovation and also an important destructive factor promoting the world's energy transformation.

As can be seen from Table 1, due to the significant reduction in the costs of solar power generation and Energy storage technology, the new generation of energy has the market capacity to compete with traditional fossil energy in supply (energy Confront) in some regions. Therefore, more countries are expected to promote the development of low-cost green hydrogen production, virtual power plants, regulation means and new energy storage technologies. The operation mode of the energy system has undergone fundamental changes. End users have gradually become the main body of two-way interaction, distributed energy has become the new calling unit, and energy storage is regarded as a key pillar supporting the reliable operation of high-proportion renewable energy systems. Correspondingly, the government's technical support has also shifted towards strengthening system coordination and further exploring its value.

Table 1. Global Cost Trends of Key Energy Technologies (Based on NREL, IRENA).

Technology	Year range	Cost change	Source
Cost of PV system	2010→2021	↓Approximately 82%	NREL (2021)
PV LCOE	2010→2023	Continuous decline	IRENA (2024)
BESS cost	2010→2024	↓About 93%	IRENA (2025)
Onshore wind power LCOE	2022→2023	↓About 3%	IRENA (2024)
The cost of new renewable energy versus fossil energy	2024	91% lower	IRENA (2025)

3. Comparison of Energy Transition Policy Frameworks in Major Countries and Regions

3.1. Characteristics of the European Union and the United States in energy regulation and market Design

The energy management agency in the United States operates in a relatively decentralized manner by independent Rtos/ISOs, mainly responsible for formulating and controlling the operation models and pricing mechanisms of various regional markets. Due to the strong independence of each state, the United States has developed rapidly in terms of innovation capabilities, such as the frequency regulation market of PJM and the energy storage profit model of CAISO. This market-oriented operation mode contrasts sharply with the transnational organizational model of the European Union. The most significant differences lie in several key parameters. The relevant data is presented in Table 2.

Table 2. Key Indicators of Power Systems in the European Union and the United States (IEA/EIA 2023).

Indicator	European Union	The United States	Source
The proportion of power generation from renewable energy	44%	22%	IEA
Cross-border power transmission capacity	> 80 GW	< 20 GW	ENTSO-E
Market structure	Regional unification	RTO/ISO+ State level	EIA
ETS covers the power industry	Full coverage	Some state-level	EU ETS
Energy storage role	Flexibility + Peak shaving	Frequency regulation core	IEA

3.2. Differences between China and the European Union in Planning Systems and Industrial Synergy

China's energy planning system is formulated at the national level, promoting the expansion of renewable energy through comprehensive power planning, regional transmission plans and electricity price reforms. China, with the world's strongest photovoltaic and energy storage industrial chain, leads the pack in terms of installed capacity and also enjoys a distinct cost advantage. The EU's planning leans more towards institutional coordination, such as the Green Deal and REPowerEU. However, due to the relatively scattered manufacturing chain, its energy transition mainly relies on market rules, technical standards, and international investment cooperation to drive it forward. The relevant situation is shown in Table 3.

Table 3. China and the EU Renewable Energy and Industry Chain Indicators (IRENA/IEA 2023).

Indicator (2023)	China	European Union	Source
Newly installed photovoltaic capacity	216 GW	56 GW	IRENA
New installed capacity of wind power	55 GW	17 GW	IRENA
The proportion of photovoltaic module production capacity	~85%	<5%	IEA
New capacity of energy storage	22 GW	3 GW	IEA
System planning approach	National coordination	Regional synergy	Official data

3.3. The Divergence in Technological Strategic Orientations among the United States, Japan and South Korea

The strategy of the United States mainly focuses on disruptive technological innovation, with a key layout in cutting-edge battery technology, hydrogen energy, power electronics, small modular reactors (SMR), and other fields, and accelerates the commercialization process of technology through fierce market competition. Japan's strategy emphasizes system security and the safety and reliability of the supply chain, focusing on promoting projects such as the construction model of a hydrogen energy society architecture, fuel cell research and development, nuclear power plant life extension technology, and high-end power grid equipment. South Korea's strategy is to build on its status as a major battery manufacturing country by strengthening the production capacity of energy storage devices, the construction of hydrogen energy application environments, and the output capacity of intelligent manufacturing equipment. The specific content is shown in Table 4.

Table 4. Key Indicators of Technology Strategies for the United States, Japan, and South Korea (IEA Hydrogen/Storage 2023).

Indicator	The United States	Japan	South Korea	Source
Hydrogen Energy Production Capacity Planning (2030)	10 Mt	3 Mt	2 Mt	IEA
Cumulative installed capacity of energy storage	15 GW	<2 GW	3 GW	IEA
R&d investment in solid-state batteries	>500 million USD	>200 million USD	>100 million USD	DOE
SMR Project	15+	2	1	IAEA
Hydrogen refueling station	~70	>160	~40	Transport Ministries of all countries

3.4. Institutional Differences in Energy Governance Structures between Developed and Emerging Economies

Emerging countries with low new-energy penetration and limited grid capacity typically rely on government-led, top-down policies to advance new energy projects. In contrast, developed countries-supported by mature markets, stronger grid interconnection, and higher renewable penetration-tend to use more open, flexible, and multi-sector management approaches.

As can be seen from Table 5, these structural differences directly affect the choice of policy tools, the degree of marketization and the mode of international cooperation. To make the connection between institutional differences and energy structures more intuitive, the following is a typical power structure comparison chart of the IEA to present the actual technical basis of the energy structures of the two types of economies.

Table 5. Energy Structure Differences between Developed and Emerging Economies (IEA 2023).

Indicator	Developed economies	Emerging economies	Source
Proportion of coal-fired power	20-25%	>55%	IEA
The proportion of renewable energy	38-45%	25-30%	IEA
Proportion of gas and electricity	25-30%	<15%	BP
The penetration of flexibility technology	high	low	IEA
Transmission interconnection level	high	Medium to low	ENTSO-E

Figure 1 illustrates the structural differences between the two types of economies. Developed countries, supported by established wind, gas, and nuclear systems, can integrate diverse power sources through flexible resources and mature markets. Developing countries, however, still depend heavily on coal due to rising demand, limited grid capacity, and low adoption of flexibility technologies. These differences shape each country's emission-reduction trajectory and influence their respective needs for technology and financing in cross-border interconnection, storage deployment, and energy cooperation.

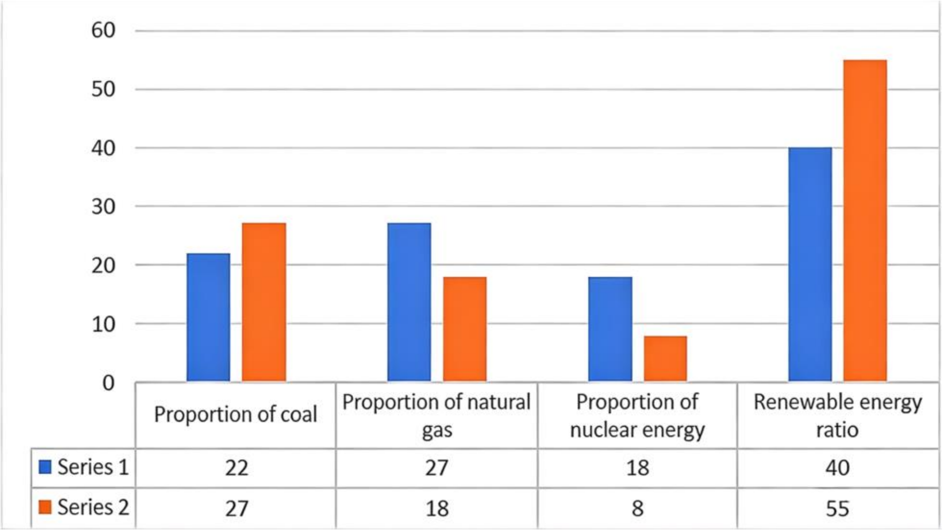

Figure 1. Comparison of Power Structures between Developed and Emerging Economies (IEA,2023).

4. International Cooperation Mechanisms in the Global Energy Transition

4.1. International Collaborative Cooperation Paths for Energy Technology Standards and Certification Systems

The global energy standardization system is becoming increasingly fragmented as renewable energy, high-capacity grid connections, storage, and hydrogen facilities expand rapidly. Countries differ in component testing, grid-access safety rules, storage safety standards, and hydrogen purity requirements, raising interconnection costs and lengthening cross-border certification processes. International standard coordination can thus be viewed as a problem of transnational system consistency, and the degree of standard convergence can be defined as follows:

$$\Omega=\frac{\sum_{i=1}^{n}|S_i\cap C|}{\sum_{i=1}^{n}|S_i|} \tag{1}$$

Here, S_i represents the standard set of the i-th country, and C represents the globally common standard. The closer Ω is to 1, the more convergent the global standard becomes. If it approaches 0, the differentiation is severe. Take hydrogen energy standards as an example. The European Union adopts the "source definition" (hydrogen produced from renewable energy sources as green hydrogen), the United States adopts the "carbon intensity standard" (gCO_2/MJ), and Japan adopts the "full life cycle emission threshold". The intersection of the three is extremely low ($\Omega < 0.3$), making it difficult to recognize each other. To reflect the standard differences in major regions, the consistency in core standard areas is listed below (EA/IEC 2023):

From the results in Table 6, it can be seen that photovoltaic is relatively easier to achieve standardized connection, while hydrogen energy is the area with the most prominent global standard contradictions. At present, the model of standard unification among countries has gradually shifted from the previous "mutual recognition" to "co-construction".

Table 6. Consistency of Global Energy Key Technology Standards (Structured Indicators).

The field of technology	European EN	IEEE/UL of the United States	Chinese GB	Global consistency (high/medium/low)
Photovoltaic module testing	high	Medium	high	Medium to high
Energy storage safety standards	Medium	Medium to low	high	Medium

Grid-connected inverter interface	high	Medium	Medium	Medium
Hydrogen energy purity/definition	high	low	Medium	low

4.2. Cross-Border Joint Research and Development, Demonstration and Verification Collaboration Model for Clean Energy Technologies

With the decline in the price of renewable energy, the expansion of energy storage scale and the development of green hydrogen technology, technological innovation has become an important part of leading global energy cooperation. Due to the long cycle of technological innovation and high experimental costs, countries have begun to rely on cross-border joint technology research and development platforms to carry out collaborative development. International joint research and development can be characterized by a typical technology diffusion model. The improvement in technological maturity brought about by its cooperation can be expressed as:

$$\frac{dT}{dt}=\alpha I(T_{\max}-T) \quad (2)$$

Among them, T(t) represents the technological maturity, I represents the intensity of national R&D cooperation, α represents the efficiency of technological collaboration, and Tmax represents the maximum achievable maturity. This formula indicates that the stronger the cross-border cooperation (the larger I), the easier it is for the technology to approach the upper limit of maturity (Table 7).

Table 7. Global Scale of R&D Investment in Key Clean Energy Technologies (Interval Values).

Technical direction	Annual global investment (in billions of US dollars	Representative countries	Source
Hydrogen energy production	70-90	EU/US/China/Japan	IEA Hydrogen
Electrochemical energy storage materials	50-70	US/China/Korea	IEA Storage
CCUS	30-40	US/EU	IEA CCUS
Advanced Nuclear Energy (SMR)	20-30	US/Japan	IAEA
AI Power Grid and Digital Energy	15-20	US/EU/China	OECD

4.3. Standardization of Cross-Border Energy Facility Collaborative Construction and Interconnection Technology Collaboration

Cross-border energy channels are an important link in the global energy system, undertaking the key function of connecting resources, load centers and energy supply and production entities among regions. The foundation of global power interconnection in the global energy Internet system is precisely cross-border interconnection. As the proportion of new energy sources worldwide continues to rise, the significance of cross-provincial and even cross-border power transmission in regions rich in wind and solar resources will be further highlighted. The benefits of cross-border interconnection can be described by the following formula:

$$B=C_s+R_s+F_s-K \quad (3)$$

Among them, B represents the net benefit brought by cross-border interconnection, C_s represents cost savings, R_s represents the reduction of spare capacity, F_s represents the improvement of flexibility, and K represents interconnection costs. If B > 0, it indicates that the interconnection is feasible in the technical and economic dimensions.

Europe's cross-border transmission capacity has surpassed 80 GW and is projected to reach 110 GW by 2030. The U.S.-Canada interconnection is about 20 GW with AC/DC hybrid links, while China's planned lines with Southeast and Central Asia exceed 30 GW and 10 GW. Australia's Sun Cable aims for 10-15 GW of capacity. Beyond capacity, cross-border grids must address HVDC control, power electronics standards, regional dispatching, cybersecurity, and emergency response. Thus, such infrastructure depends on unified standards and coordinated technological development.

4.4. A Technical Support System for Global Green Investment and Financing and Industrial Chain Collaboration

Green finance has become the core mechanism for promoting energy cooperation. According to BNEF (2024) data, global clean energy investment exceeded 1.7 trillion US dollars in 2023, but the regional distribution is not even: developed economies account for about 70%, while emerging economies still face significant funding gaps. Green funds are mainly invested in the construction of renewable energy power stations, energy storage systems, battery and hydrogen energy demonstration projects, smart grid construction, as well as green manufacturing and supply chain expansion and other fields.

$$Invest=P+V+M+G \tag{4}$$

Among them, Invest stands for funds, P for public funds, V for private capital, M for international multilateral institutions, G for green bonds, and M for multilateral institutions, such as the World Bank /ADB/AIIB, which play a key "risk mitigation" role in emerging economies. Table 8 below shows the scale of green investment in major regions (BNEF 2024).

Table 8. Global Green Energy Investment Structure (BNEF 2024).

Region	Annual investment (billion US dollars)	Lead the technical direction
China	890	Photovoltaic, energy storage, and power station construction
European Union	530	Wind power, green hydrogen, distributed photovoltaic
The United States	330	Batteries, hydrogen energy, advanced manufacturing
Japan + South Korea	120	Hydrogen energy and energy storage materials
Emerging economies combined	210	Infrastructure and power station construction

In terms of industrial collaboration, industries such as solar energy, batteries, and power electronics have formed global industrial chains: China leads the manufacturing process, while the Americas and Europe serve as technological highlands, and Japan and South Korea focus on the research and development and production of battery materials and high-end equipment.

Conclusion: The global energy transition is accelerating, and the policy system, technical routes, and international cooperation strategies are all undergoing profound changes. The industrial composition, industrial cooperation methods and technological strategic layout of various countries not only reflect their own development levels and governance paradigms, but also to a large extent influence the space and presentation methods of cross-border and cross-regional cooperation. Overall, current energy governance has shifted from a single focus on supply growth to an overall layout emphasizing system flexibility, adjustable resources, and cross-regional interconnection. The global allocation of the entire green industrial chain has also gradually evolved the cooperation model from a "single partner" to a pattern of "multilateral cooperation" and "risk diversification". Looking to the future, energy governance will be based on technological leadership, standard coordination and financial support, and build a more robust, reliable and adaptable energy network in an environment where competition and cooperation coexist.

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