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SPECIAL POLICY REPORT

Major Scientific and Technology Innovation for Green Transition

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Major Scientific and Technology Innovation for Green Transition

CCICED Special Policy Study Report

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Executive Summary

In 2024, global surface temperature anomalies exceeded the critical threshold of 1.5°C for the first time, leading to an increase in extreme weather events such as heatwaves, heavy rainfall, flooding, typhoons, hurricanes, and wildfires. These phenomena underscore the escalating climate risks worldwide. Addressing climate change proactively and accelerating the transition to a green economy have become universal priorities.

China has set ambitious targets in its 14th Five-Year Plan and long-term vision, aiming to reduce greenhouse gas emissions by 7-10% below peak levels by 2035. The country plans to increase non-fossil fuel energy consumption to over 30% and expand wind and solar power capacity to at least 36 gigawatts (GW), six times the 2020 levels. These measures demonstrate China's firm commitment to green transformation and climate resilience.

Currently, the rapid expansion of wind and solar energy has outpaced the grid's capacity to effectively manage their inherent variability and uneven geographic distribution. This imbalance has led to a trio of bottlenecks-curtailed renewable energy adoption, reduced grid resilience, and increased stability risks-that threaten the safe, large-scale integration of high levels of renewables. This report focuses on innovative and supporting technologies around wind and solar power renewable energy, new type grids, and energy storage, pinpoints critical technical barriers, and outlines priority R&D directions and policy actions. The goal is to expedite the transition toward a renewable-dominant, multi-energy system that complements various energy sources, thereby supporting the economy-wide shift to green development.

(I).Pathways for Innovation in Wind and Solar Energy Technologies

The rapid growth of wind and solar renewable energy sources has transformed China's energy landscape, making it the largest producer of clean electricity globally. By the end of 2024, China's wind capacity reached approximately 520 GW, and solar capacity about 890 GW, accounting for around 40% of the global share. The share of wind and solar in national electricity consumption increased from 9.7% in 2020 to 18.6% in 2024, surpassing the electricity demand of the tertiary sector. China also exported renewable energy equipment, helping other nations reduce emissions by 41 million tons of CO_2 during the 14th Five-Year period.

Despite these achievements, the development of wind and solar energy faces systemic challenges, including external constraints in international policies, ecological considerations, and upstream and downstream industrial chains. Internationally, policy uncertainties and trade environment fluctuations pose risks. Additionally, land resource scarcity, strict marine use regulations, ecological protection red lines, complex approval processes, and extended project cycles hinder project implementation. The supply of critical upstream raw materials, such as silicon, rare earth elements, and strategic metals, remains tight, and the recycling system for decommissioned equipment is underdeveloped, posing potential risks to the industrial chain.

On the technological front, innovation remains crucial to meet surging demand, although the costs of wind and solar power generation continue to decline. In the cost, between 2010 and 2024, the levelized cost of electricity (LCOE) of photovoltaics and onshore and offshore wind power decreased by about 90% and 60%, correspondingly, while at present the costs of them have been reduced to about 0.25 yuan/kWh and 0.18 yuan/kWh, respectively, which is more than 30% lower than that of thermal power. In the efficiency, that of commercial silicon solar cells has increased by 8.6% over the past decade, nearing theoretical limits, which necessitates the development of new solar energy technologies, while the average of commercial wind turbines globally is about 40%, still below the theoretical maximum, indicating considerable room for improvement. The trend toward larger turbines and deep-sea development also demands higher technical standards for wind power equipment. Wind power equipment is developing towards large-scale and far-reaching offshore direction, with the current single unit capacity of onshore and offshore wind power correspondingly having reached 16 MW and exceeded 26 MW.

Looking ahead, future development in wind and solar energy technologies is expected to follow four major trends. First, improving efficiency and reducing costs: continuously breaking through the conversion efficiency of photovoltaic cells, scaling up wind turbines, increasing the single unit capacity of wind turbines, and further reducing power generation costs; Second, widening the application of intelligent and digitalized systems: focusing on key breakthroughs in AI enabled wind and solar accurate prediction and forecasting, intelligent operation and maintenance, and other key technologies; Third, promoting the development of application scenarios and resources: expanding into deep and open seas, high-altitude wind fields, ultra-high altitudes, “sand-desert-wasteland” and other challenging environments to tap into the potential of undeveloped wind and solar resources; Fourth, accelerating the innovation of the entire industry chain: effectively utilizing and recycling outdated wind and solar facilities, localizing key components, and establishing a green circular system from manufacturing to recycling.

(II).New-Type Power Grids Supporting Renewable Energy Development

China’s renewable energy sector has entered a new stage, with installed capacity accounting for about 45% of total capacity and electricity penetration exceeding 20%. The sector is toward becoming a primary power source, bringing three major challenges: first, replacing traditional energy sources to achieve dual-carbon goals; second, addressing the limited regulation capacity of the power system, which affects energy absorption and profitability; third, enhancing the grid’s performance and system support capabilities for renewable energy integration.

International experience indicates that high renewable energy penetration requires phased development. The International Energy Agency’s “Six-Stage Framework” shows that most countries are in stages 1-3, with Spain, Germany, and Denmark reaching stages 4-5, where renewable energy penetration exceeds 40%, and at times approaches 100%. Both centralized and distributed development emphasize the importance of strengthening grid infrastructure. For example, Germany’s “balancing group” model enables high levels of distributed renewable energy integration.

However, expanding grid capacity alone cannot meet the needs of a green transition. China’s electricity demand is expected to grow rapidly over the next 30 years, with renewable energy installed capacity projected to surpass 60 billion kilowatts, accounting for over 80% of total capacity, and electricity penetration exceeding 50%. New business models such as “prosumers” and deeper marketization will fundamentally change the operation of the power system.

Future grid development will feature a hybrid model of “large-scale power sources and grids” combined with “distributed balancing units and microgrids”. This approach will support the transmission of large-scale renewable bases like deserts, southwestern regions, and offshore wind farms, while also promoting local consumption through distributed systems composed of balancing units and microgrids. By 2030, wind and solar capacity will account for over 60% of total generation, contributing more than 35% of electricity, and by 2060, these figures are expected to exceed 80% and

50%, respectively. The system's flexibility will significantly improve, with flexible regulation sources reaching 30% of power supply and demand-side response exceeding 5% by 2030, and demand-side response surpassing 30% by 2060. Upgrading distribution networks will support the installation of over 1 billion kilowatts of distributed renewable energy and 24 million charging stations by 2030. Cross-provincial and cross-regional transmission capacity will increase from 500 million kilowatts in 2030 to 1 billion kilowatts in 2060, predominantly driven by renewable energy sources.

(III).Energy Storage Technologies and Applications Supporting Renewable Development

Energy storage plays a vital role in high-renewable power systems, fulfilling three primary functions: ensuring grid operational safety through millisecond response capabilities; facilitating renewable energy absorption by managing intra-day fluctuations; and guaranteeing power supply security during extreme weather events and forecast deviations from over a week, requiring multi-day or seasonal storage solutions.

Emerging storage technologies are central to enhancing system flexibility, and capable of balancing energy across seconds to seasons. As renewable penetration increases, the demand for storage accelerates. The IEA estimates that when variable renewable energy (VRE) accounts for 15% of the system, storage contributes less than one-tenth of regulation resources, and at 40%, its share rises to about one-third. Long-duration (generally 10-100 hours) storage, including pumped hydro, compressed air, thermal batteries, and metal-air batteries, is increasingly important. Hydrogen energy, widely recognized globally, remains in experimental or early commercial stages for long-term storage. China's cross-regional transmission capacity is strong, and flexible coal-fired power plants provide some regulation, but higher renewable integration still requires breakthroughs in long-duration storage technologies.

International practices demonstrate the multi-scenario value of new storage solutions. For example, California's electrochemical storage capacity increased from 500 MW in 2018 to 13,200 MW in 2024, supporting rapid photovoltaic growth and reducing curtailment; Scotland's independent storage stations facilitate offshore wind delivery and system stability; and Australia's community battery projects lower peak electricity costs, reduce midday photovoltaic curtailment, and improve power reliability.

China has explored new business models for energy storage, including "energy-based + capacity-based pricing" combined with "spot markets + ancillary services markets", but lacks an effective national market-based price mechanism. Future development should be phased: initially focusing on intra-day regulation with lithium-ion and compressed air storage; mid-term breakthroughs in long-duration (above 10 hours) storage technologies such as mechanical, thermal, and hydrogen storage; and long-term integration of multiple storage types-electric, thermal, gas, and hydrogen-to support seasonal balancing, thereby significantly enhancing system flexibility and efficiency for high renewable penetration.

Policy Recommendations

To accelerate the green transformation of the economy, this study provides the following policy recommendations:

Focus efforts on promoting the innovation of solar and wind energy technologies and enhancing the level of industrial development. First, accelerate the deployment of major scientific research facilities for renewable energy, promote innovation in key materials and equipment, with breakthroughs in next-generation photovoltaic cells, lightweight blades, floating offshore wind, high-altitude wind turbines, and high-precision AI-driven energy models to constantly improve the conversion efficiency and system reliability of wind and solar energy. Second, advance comprehensive energy demonstration projects, including offshore energy centers and multi-energy "sand-desert-wasteland" integrated and ecological coordination regions, to establish replicable and scalable green energy supply systems. Third, deepen industry-academia-research collaboration and international cooperation, including encouraging female scientists and cultivating energy science and technology talent and strategic forces with global competitiveness to facilitate global application and mutual benefits.

Support the green transition, and substantially enhance regulation capacity, construction standards, and operational models of the power grids. This includes strengthening flexible resources such as coal-fired power plant upgrades, hydropower, pumped storage, and new energy storage, establishing market mechanisms, and improving system balancing and capacity assurance. Additionally, accelerating the construction of large grids and new distribution networks, optimizing grid architecture, increasing clean energy transmission channels, and transforming distribution networks into "source-grid-load-storage" collaborative platforms are equally essential. By 2030, the capacity to accommodate 1 billion kilowatts of distributed renewable energy and 24 million charging stations should be achieved. Lastly, developing distributed smart grids, microgrids, and integrated “source-grid-load-storage” projects will enable local consumption and large-scale efficient utilization of renewable energy.

Build a multi-technology, multi-scenario energy storage system, and promote coordinated operation of energy storage and power system. By 2030, the scale of new energy storage is expected to exceed 250 million kilowatts, accounting for 20% of the regulation resources. It is necessary to coordinate and promote the layout of energy storage on the power supply side, grid side, and user side, estimate the system value of energy storage in virtual inertia, voltage support, and other aspects, give full play to the dual regulation role of electricity and quantity, and actively promote the demonstration of long-term energy storage such as thermal batteries and compressed air to enhance the system balance capacity. Looking towards the future, we should fully leverage the advantages of various types of energy storage such as electricity, heat, gas, cold, and hydrogen to achieve optimized operation of diversified energy storage, address the seasonal mismatch between new energy output and load, and finally enhance system resilience.

Key words:

Wind Power; Photovoltaics; Renewable Energy; New-Type Grid; Energy Storage; International Experience; Policy Recommendations.

Nomenclature

Abbreviation	English Term	中文
AS	Ancillary Services	辅助服务
CfD	Contract for Difference	差价合约
CPUC	California Public Utilities Commission	加州公共事业委员会
DER	Distributed Energy Resources	分布式能源
DR	Demand Response	需求响应
DSM	Demand Side Management	需求侧管理
DSO	Distribution System Operator	配电系统运营商
EIA	U.S. Energy Information Administration	美国能源信息署
ESS	Energy Storage System	储能系统
IEA	International Energy Agency	国际能源署
IRENA	International Renewable Energy Agency	国际可再生能源机构
LDES	Long-duration Energy Storage	长时储能
LIB	Lithium-ion Battery	锂离子电池
MG	Microgrid	微电网
Na–S	Sodium–Sulfur Battery	钠硫电池
P2X	Power-to-X	电转多能（氢、热、燃料等）
PHS	Pumped-hydro Storage	抽水蓄能
PPA	Power Purchase Agreement	电力购买协议
R&D	Research and Development	研发
RE	Renewable Energy	可再生能源
SC	Supercapacitor	超级电容
SDES	Short-duration Energy Storage	短时储能
TES	Thermal Energy Storage	热储能
TSO	Transmission System Operator	输电系统运营商
VPP	Virtual Power Plant	虚拟电厂
VRE	Variable Renewable Energy	可变可再生能源 / 新能源

Contents

I. Introduction

1.1 Overview of the Energy Transition Technology Roadmap

The transition to clean energy requires an accessible, reliable, and affordable electric grid. The grid itself offers China the largest single carbon abatement opportunity, and it also enables the transition in transportation, construction, and most industrial sectors.

Over the last two decades, investments and development in grid infrastructure and renewable energy technologies have made on- and off-shore wind, solar PV, and storage more competitive with hydro, nuclear, coal, oil, and natural gas. This remarkable achievement has been driven in many cases by strong policy support from China. Indeed, technological advancements put China's goal to peak before 2030 well within reach, and the path to a zero-carbon future is already beginning to take shape, as outlined by President XI Jinping. In September 2025, China clearly stated in its new round of Nationally Determined Contributions that by 2035, the net greenhouse gas emissions across the entire economy will decrease by 7% to 10% compared to the peak, striving to do more significantly. The proportion of non-fossil energy consumption in total energy consumption will reach over 30%, and the total installed capacity of wind and solar power will reach more than six times that of 2020, aiming to reach 3.6 billion kilowatts. This not only demonstrates China's determination to decarbonize but also shapes the direction for large-scale deployment and institutional innovation over the next decade.

But challenges remain. Many renewable energy technologies are intermittent and have unstable output. Poor grid design or misaligned incentives might undermine optimal deployment of new technologies. Some important technologies still require further research, development and promotion to achieve large-scale application. *Policy therefore plays a role in supporting the development of new technologies, promoting learning and practice through piloting and deployment, and establishing institutions and market mechanisms to help the most promising and scalable technologies thrive.*

Under constraints of limited resources and time, scientific and technological innovation for the green transition must be precisely focused, prioritizing the rapid scaling of proven strategies while balancing near-, medium-, and long-term technological breakthroughs. Four principles underpin this work:

1. Quickly scale the technologies that are already mature. Bolstering these by a factor of two to four, in the next decade, is key to any sound strategy towards China's goal. This process should not be limited to mere expansion; instead, it must incorporate continuous learning and innovation during scaling. Such an approach ensures the development of higher-quality, large-scale applications through iterative improvements, maintaining competitiveness and adaptability in a rapidly evolving technological landscape. For instance, as highlighted in our previous report on coordinated control of power sector pollution, China aims to increase the share of fossil-free energy in power generation to 60% by 2030 and further to 90% by 2040. Realizing these targets depends on both the large-scale deployment of mature technologies and their ongoing refinement through iterative innovation.

2. Deploy enabling technologies, policy mechanisms, and business models. Transitioning away from high-pollution energy sources and fostering the development of clean energy necessitates the abandonment of existing practices, policies, and technological pathways, and adoption of innovative management systems, policy mechanisms and business models. For example, building a resilient clean grid requires introducing new management practices such as inter-provincial trading, expanding transmission line capacity, developing climate-adaptive reliability planning, optimizing the coordination between large-scale grids and distribution networks, and implementing least marginal cost dispatch strategies. A balanced technology mix combined with advanced grid management practices can simultaneously reduce costs and enhance system reliability.

3. Invest in the next generation of promising clean technologies in the near term. Immediate focus should be placed on deploying innovative technologies that complement existing mature solutions such as wind, solar, and energy storage. Examples include technologies that enhance the reliability and security of the power system, such as flexible electric vehicle charging, and industrial end-use applications like thermal batteries and hydrogen electrolysis. These emerging technologies should be guided by strategic roadmaps to facilitate their transition from current development stages to commercial viability.

4. Commit to long-term technology investments. Technologies such as advanced nuclear energy and carbon capture and storage (CCS) will be preferred options beyond 2035. Establishing stable R&D budgets and implementing “technology thresholds” mechanisms are vital to provide sustained, targeted support for technologies that demonstrate potential and steady progress.

Technological innovation, continuous improvement, and rapid scaling of solar and wind power fall into Category 1. Grid planning and market design are categorized as Category 2. Advanced distribution management systems and long-duration energy storage can be classified as Category 3. Technologies such as CCS and next-generation nuclear power, currently under research, belong to Category 4. This four-category framework not only facilitates large-scale clean energy deployment and environmental health improvements but also supports economic development and guides future research and innovation. Most importantly, it distinctly differentiates between technologies that require immediate large-scale deployment and those that necessitate sustainable innovation for long-term progress.

1.2 Report structure

This report emphasizes the core elements of Categories 1–3: existing competitive low-carbon technologies; technologies and practices that support their rapid, large-scale deployment; and near-term investments to enhance their competitiveness alongside complementary technologies. The contents include:

• Chapter 2: Technological Innovation Pathways for Wind and Solar Energy

• Chapter 3: Technologies and Practices to Integrate Renewable Energy into the Power System

• Chapter 4: Technical Role and Business Model for Energy Storage Systems

II. Technological Innovation Pathways for Wind and Solar Energy

Amid the global shift toward green energy, wind and solar power have transitioned from supplementary sources to primary drivers of low-carbon development. In recent years, their installed capacity has grown rapidly, costs have fallen significantly, and technological maturity has steadily improved, laying a solid foundation for large-scale application. At the same time, China has proposed a new round of Nationally Determined Contributions targets for 2035, further clarifying the direction for the green and low-carbon transformation of the energy system and providing strong policy support for the continuous innovation and accelerated development of this sector.

However, the rapid penetration of these new energy sources creates challenges such as their inherent intermittency, and grid integration difficulties, and consumption issues. They place higher demands on the flexibility, stability, and intelligence of the power system. Overcoming these bottlenecks requires technological breakthroughs. Wind and solar technologies are undergoing a profound transformation from single-equipment innovation to system-level collaboration, and from the trend of larger-scale wind turbines and more efficient photovoltaic systems to the development of deep-sea and offshore projects, the integration of multi-energy complementary systems, and advancements in intelligent operation and recycling.

This chapter focuses on the current status, bottlenecks, and future directions of wind and solar technology development, outlines key technological pathways, and proposes policy recommendations to advance technological breakthroughs and industrial upgrading, aiming to provide insights for building a safe, efficient, and clean new energy system.

1.Current Status, Trends, and Challenges in the Global Development of Wind and Solar New Energy

1.1 Current Status and Regional Differences

Global additions in wind and solar capacity and power generation **have reached record highs.** In 2024, the global capacity additions for renewable energy capacity peaked at 585 GW (Figure 1), with wind and solar power accounting for 96.6% of the total-113 GW and 452 GW, respectively-both setting new benchmarks [1]. The newly installed wind capacity primarily came from onshore wind power, accounting for 95.5% of the total newly installed wind capacity, while newly installed solar capacity was dominated by photovoltaic power generation, making up over 99.9% of the total newly installed solar capacity. The rapid growth in global installations has directly driven an increase in power generation. In 2024, global wind and solar power generation reached 2,497.3 TWh and 1,650.3 TWh, respectively, representing a threefold and 6.5-fold increase compared to 2015. Their shares in global total power generation reached 8.09% and 6.91%, respectively. New wind power installations were mainly onshore, representing 95.5% of the total, while new solar installations were almost entirely photovoltaic, accounting for over 99.9%. This rapid expansion has significantly increased power generation, with wind power producing 2,494 TWh and solar power generating 2131 TWh in 2024. Compared to those in 2015, these figures represent approximately threefold and 6.5-fold increases, respectively now accounting for 8.1% and 6.9% to global electricity generation [2].

The United States emphasizes quality enhancement and component recycling in wind and solar projects. The U.S. currently can recycle 90% of decommissioned wind turbine materials [3], and its largest solar

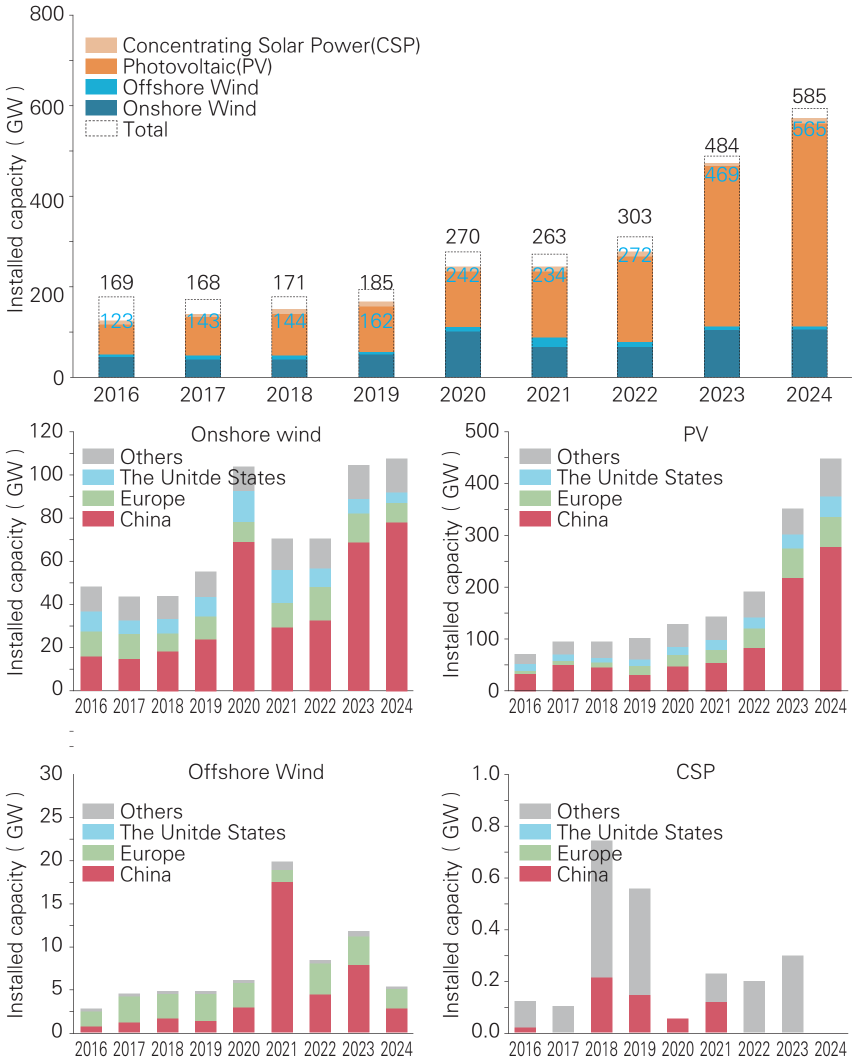


Figure 1. Global changes in newly installed wind and solar capacity (2016-2024) [1].

panel recycling plant can process up to 5 GW annually [4]. In the short term, relying on retrofitting existing assets, technological updates, and recycling systems, the U.S. wind and solar energy sectors are expected to maintain their growth trajectory. In the first quarter of 2025, wind and solar power contributed 98% of the new electricity generation capacity added nationwide. However, the long-term development of the wind and solar industries and enhancement of their competitiveness will increasingly depend on cost reductions through technology, and regional policy support.

European coastal countries and advanced economies such as Japan are prioritizing offshore wind resource development. Europe is accelerating offshore wind initiatives through hydrogen technology innovation, exemplified by the Netherlands' pioneering PosHYdon offshore wind-to-hydrogen pilot in 2020 and German-British collaboration advancing the North Sea Green Hydrogen Corridor in 2025. Europe accounts for 85% of global offshore wind-to-hydrogen projects. To achieve carbon neutrality by 2050, Japan has set offshore wind targets of 10 GW by 2030 and 30-45 GW by 2040, supported by legislation like the Marine Area Utilization Promotion Act, which opens exclusive economic zone waters for offshore wind development. Japan's first barge-type floating offshore wind project, Hibiki, commenced operations in 2025. However, it is noteworthy that despite these economies' high prioritization and active planning for offshore wind development, the actual scale of annual offshore wind capacity increase remains relatively low, and wind power expansion has fallen short of expectations.

Less developed regions, including South America and Africa, are favoring distributed photovoltaic systems. These regions boast abundant solar resources but suffer from weak grid infrastructure, leading to accelerated deployment of distributed photovoltaic (PV) systems. In Brazil, the total installed solar power capacity surpassed 55 GW in 2024, with over 70% attributed to small-scale distributed PV. In African countries like Kenya, Nigeria, and Ethiopia, they are actively promoting off-grid PV and microgrid projects. For example, Kenya encourages the installation of distributed PV systems in rural and remote areas. In 2019,

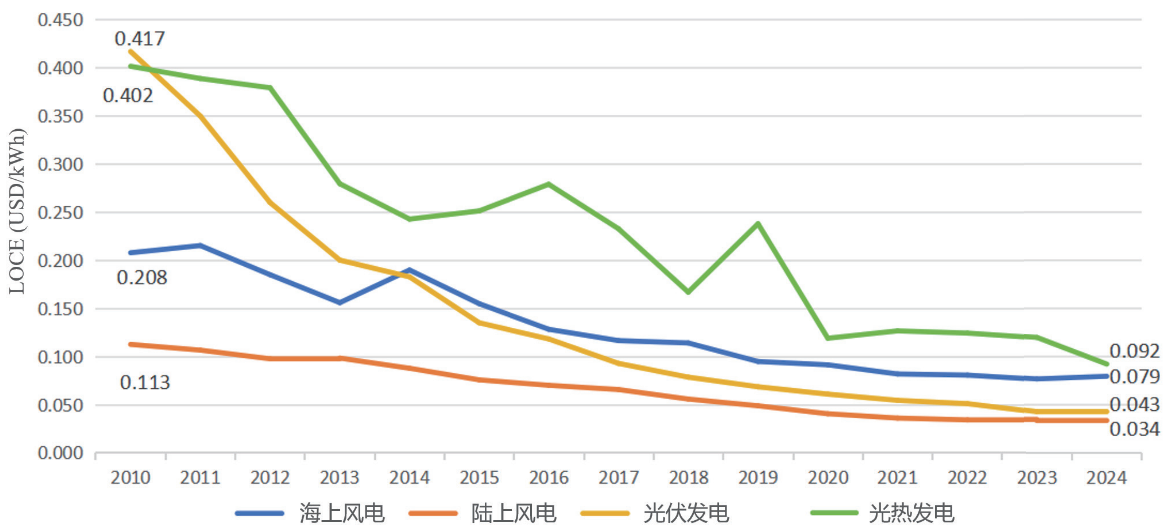


Figure 2. Global average cost trends of wind and solar power generation (2010-2024) [7].

the country launched the Kosap Rural Microgrid Project, with plans to establish 250,000 standalone solar systems and 120 microgrids by 2030.

China is experiencing rapid growth of wind and solar energy sectors and showing enormous potential for expansion. In 2024, China added 374 GW of new renewable energy generation capacity, accounting for 63.8% of the global additions. Solar power installations alone reached 278 GW, nearly half of the world's new capacity for that year. By the end of 2024, China's cumulative installed capacity for wind and solar power reached 520 GW and 890 GW, respectively, both ranking first globally. The country has established the world's largest and fastest-growing renewable energy system. In the first half of 2025, wind and solar power generation reached 1.1478 t kWh, accounting for 23.7% of the nation's total electricity output and representing a 27.4% year-on-year increase. This has become a key driver in transitioning the energy structure toward clean and low-carbon sources. The development and utilization of wind and solar energy in China remain in a phase of rapid advancement. China's current installed solar capacity accounts for less than 10% of its potential, and wind power accounts for 4% [5]. With ongoing technological updating, scenario expansions, and deeper development layouts, their share in the energy supply is expected to further increase in the coming decades.

1.2 Trends and Demand

Currently, wind and solar technologies are maturing, with costs decreasing significantly and industrialization accelerating. These trends are collectively driving the transition of wind and solar energy sources from alternative to primary energy options.

Wind and solar technologies are entering a phase of rapid development. In wind power, onshore technology has become well-established, while offshore wind is progressing from growth to maturity, characterized by the large-scale application of mature technologies and accelerated breakthroughs in cutting-edge technologies. Innovative approaches such as floating wind turbines are beginning to see engineering demonstrations and commercial deployment. In 2025, China successfully connected the world's first 16 MW floating wind platform to the grid, and Dongfang Electric has independently developed and installed the world's largest 26 MW offshore wind turbine. European manufacturers are testing 20 MW-class offshore models, optimizing capacity factors and steadily improving per-kilowatt generation efficiency. In solar PV technology, crystalline silicon cells (monocrystalline PERC, TOPCon, HJT) are predominant, complemented by thin-film technologies like CdTe and CIGS. PV efficiency continues to improve, with commercial silicon modules exceeding 20%, PERC cells approaching the theoretical limit of 24.5%, TOPCon and HJT surpassing 25%, and tandem modules exceeding 30% efficiency [6].

Continuing cost reductions are reinforcing wind and solar as primary energy sources. Over the past decade, costs for wind and solar have decreased sharply, leading to significant reductions in levelized cost of energy (LCOE). Currently, in over 80% of countries, new wind and solar projects are more economical than new fossil fuel plants, indicating that onshore wind and solar power have become the most economical sources of new electricity in most regions. According to IRENA data [7], from 2010 to 2023, global solar PV LCOE decreased by about 90%, while wind (onshore and offshore) costs fell by over 60% (Figure 2). China demonstrates notable cost advantage, with onshore solar LCOE at 0.22 yuan/kWh and onshore wind at 0.18 yuan/kWh. Continued technological advancements, industrial scaling, and supply chain improvements are expected to further reduce per-kilowatt installation and O&M costs for wind and solar energy.

Rapid industrialization is reshaping the global landscape. Advances in technology and decreasing costs in wind and solar power have increased confidence in clean energy investments worldwide. According to BloombergNEF (BNEF) data [8], global investments in clean energy reached $2.08 trillion in 2024, marking a 10.7% year-on-year growth. Renewable energy sectors accounted for over 35% of total capital inflows, establishing them as the primary focus for investment, and the remaining 65% was mainly directed toward industrial energy efficiency retrofits, building energy efficiency, grid upgrades, hydrogen energy, and nuclear power. The COP28 commitments to triple renewable power capacity and double energy efficiency by 2030 are expected to position wind and solar to emerge as the leading contributors to this growth. Moreover, emerging application scenarios such as integrated wind-solar-storage systems, hydrogen coupling, and virtual power plants (VPP) are gaining momentum, fueling demand for high-value products like inverters, energy storage systems, and floating platforms. Countries are leveraging their respective strengths to enhance industrial competitiveness: Germany maintains a competitive edge in high-end renewable energy equipment manufacturing through innovations in key wind turbine components and precision manufacturing technology for PV modules; the United States continues to innovate in inverter technology and new material development; and China, focusing on the entire value chain from raw materials and equipment manufacturing to system integration and operation and maintenance in the wind and solar enterprises, has established a highly integrated industry.

1.3 Challenges Facing Global Wind and Solar Energy Development

As the global energy structure is undergoing profound transformation, wind and solar energy have entered a critical period of rapid growth. It brings challenges in policy environment, technological costs, ecological benefits, and other related aspects.

1) Policy instability in the United States has disrupted the development of global wind and solar energy. The U.S. withdrawal from the *Paris Agreement* has led to a decline in international climate finance commitments. In February 2025, U.S. President Trump revoked $4 billion in pledged funding for the Green Climate Fund, and in July, the U.S. Agency for International Development (USAID), having operated for nearly 64 years, was closed, which have resulted in the suspension of wind and solar projects in regions such as Kenya and Vietnam. Moreover, The One Big Beautiful Bill Act, relaxed fossil fuel regulations, and will eliminate wind and solar tax credits by 2027, potentially stagnating 4500 local clean energy projects, stalling 72% of domestic renewable energy projects, and increasing construction costs in wind and solar by 10-20%.

2) Green trade barriers increase costs of the global energy transition to green and low-carbon solutions. According to IRENA, if developing countries are unable to access affordable imported wind and solar equipment and technical support, their 2030 installation costs will increase by 15%.

3) Land constraints and ecological conflicts hinder project deployment. In China, centralized PV and onshore wind farms are projected to occupy 44,000 km² by 2060, with offshore wind requiring over 62,000 km² of maritime space [9]. Land use restrictions and ecological concerns have made project siting increasingly complex. In October 2024, China's Ministry of Ecology and Environment issued regulations requiring renewable energy projects to avoid ecological red zones and to maintain a minimum distance of 700 meters from residential areas [10]. In December 2024, France ordered the shutdown of a wind farm for the first time due to turbine-related deaths of endangered species. Competition for land, coupled with ecological constraints, has extended project development timelines, driven up costs, and hindered project implementation. Moreover, deep-sea wind and solar projects involve maritime zoning, environmental protection, and fisheries production, necessitating cross-country and multi-agency coordination and regulation.

2.Key Methods to Advance Wind and Solar Energy Development

2.1 Policy-Driven Mechanisms

In the rapid global development of wind, solar, and other new energy sources, policy has consistently been the most fundamental and direct driving factor. Countries around the world are continuously strengthening their policy support systems through strategic planning, by formulating development plans or regulations and improving market mechanisms for resource allocation. These efforts focus on key aspects such as target setting, approval procedures, incentive structures, and grid integration, thereby laying a solid institutional foundation for advancing renewable energy technologies and industries.

1) Global Policies Promoting Wind and Solar Industry Development. Major developed economies are consistently upgrading their support policies for wind and solar energy, setting clear renewable energy generation and capacity targets to stimulate industry growth. For example, Japan revised its "Green Growth Strategy" (released in 2020) in 2021 to the "Carbon Neutral Green Growth Strategy by 2050", aiming to install 10 GW of offshore wind capacity by 2030 and up to 30-45 GW by 2040, while reducing offshore wind costs to 8-9 yen/kWh between 2030 and 2035 and solar PV costs to 14 yen/kWh by 2030. In 2022, the European Union released the *REPowerEU* plan, which raised the 2030 renewable energy target from 40% to 45% and set a goal of reaching 600 GW of solar PV capacity by 2030 [11], along with a series of documents focusing on offshore wind development (see Case 1). In 2024, the United Kingdom released its *Clean Power Plan 2030: A New Era of Clean Electricity*, which sets targets of 43–50 GW of offshore wind capacity, 27-29 GW of onshore wind capacity, and 45-47 GW of solar PV capacity by 2030, with the aim of reducing reliance on fossil fuels to 5% of total electricity generation by 2030 and completely eliminating fossil fuel generation by 2035 [12].

Emerging economies are also exploring renewable energy policies tailored to their national conditions. For example, Brazil's *Wind Energy 2030* plan encourages private investment and offshore wind development; India has introduced a *Wind-Solar Hybrid Policy* to enhance output stability; Vietnam has adopted a competitive bidding model to improve resource allocation efficiency; and African countries are addressing infrastructure gaps through regional cooperation initiatives such as the *Desert Power Initiative*.

Overall, both major developed and emerging economies are expected to further increase the share of wind and solar power in their energy mixes, contributing significantly to the development of the wind and solar industries, global energy transition and carbon neutrality goals.

2) China's Integrated Innovation Pathway in Policy Systems

A distinctive feature of China's wind and solar policies is their systemic coordination and full-chain coverage, combining top-down strategic planning with bottom-up market mechanism innovation. The *Energy Conservation and Carbon Reduction Action Plan* issued in 2024 set targets for the share of non-fossil energy and incorporated energy conservation and carbon reduction indicators into performance evaluations, thereby creating a closed loop that links strategic objectives with policy implementation.

At the policy mechanism level, China has developed a dual-track model of "centralized + distributed" deployment. One is that large-scale initiatives such as the *Wind Power for Thousands of Townships* program and the *PV-Based Desert Control* project promote resource aggregation in key regions, generating economies of scale. The other is that urban-oriented measures such as mandatory green building coverage and the integrated development of PV-storage-charging systems expand opportunities for distributed growth.

At the market mechanism level, China is accelerating the construction of a renewable energy integration system centered on mandatory quotas, green power trading, and green certificate accounting, strengthening the market attributes of renewable energy resource allocation. In 2024, green certificate transactions increased by more than 300% year-on-year, becoming a vital platform for green power valuation and resource allocation.

At the industrial policy level, China places strong emphasis on supply chain resilience and breakthroughs in core technologies. The *Wind-PV Industry Chain Security Project* focuses on critical equipment segments, using fiscal funding and first-set insurance mechanisms to mitigate adoption risks and promote an upgrade from cost-based advantages to technological leadership. Besides, reforms in approval systems and risk governance are being deepened. Measures such as the "positive list" for environmental impact assessments and project compliance rectification continue to improve project quality and environmental compatibility, guiding the industry's transition from quantity-driven to quality-oriented development.

This policy architecture, inspired by international best practices yet tailored to Chinese conditions, exemplifies an innovative institutional pathway featuring systemic coordination, full-chain coverage, and parallel strategic-market mechanisms, serving as a referential model for global green transition policies.

2.2 Technology-Driven Development

From individual technological breakthroughs to system integration optimization, and laboratory research to engineering implementation, the global wind and solar industries continue to achieve significant technological advancements in key areas. These innovations are enabling demonstration projects to scale up, improve efficiency, and enhance adaptability. The combination of technological innovation and policy support has become a dual engine, and is propelling rapid development in the wind and solar sectors.

Offshore wind and solar technologies are unlocking resource potential. As land resources become increasingly limited, floating wind turbines and offshore PV systems are gaining global attention. Both domestic and international companies are accelerating the development of deep-sea wind and solar resources through innovating in key areas such as large-capacity turbines, floating PV structures, and anti-corrosion solutions. These innovations are driving the release of deep-sea energy potential.

Efficiency improvements in wind and solar power are driving upgrades of renewable equipment manufacturing. With the efficiency of wind and solar power approaching theoretical limits, high-efficiency renewable energy conversion technologies have become key drivers for sustained development of this industry. In the wind sector, it is evolving toward larger capacities and higher efficiencies through innovations like ultra-long blades and permanent magnet direct-drive turbines. In PV, breakthroughs in crystalline silicon cell efficiency, such as perovskite tandem cells, TOPCon, and HJT technologies, are leading the way,

Case 1

EU’s Active Development of Offshore Wind Power

“Offshore Renewable Energy Strategy” issued in 2020

In 2020, the “Offshore Renewable Energy Strategy” established offshore wind as a key component of Europe’s energy system. The strategy set ambitious targets: increasing offshore wind capacity from 12 GW in 2020 to at least 60 GW by 2030 and further to 300 GW by 2050.

“Ostend Declaration” issued in 2023

It outlined plans to transform the North Sea into “Europe’s largest green energy hub”. Nine nations (Belgium, Denmark, France, Germany, Ireland, Luxembourg, Netherlands, Norway, and UK) are committed to expanding North Sea offshore wind capacity to 120 GW by 2030 and over 300 GW by 2050.

“Strategic Research and Innovation Agenda for Ocean Energy” issued in 2024

It was issued by the European Technology and Innovation Platform for Ocean Energy (ETIP Ocean). This pivotal document focuses on six key areas: equipment design and verification, next-gen technologies, analytical tools, enabling technology integration, market development, and coordinated actions, while defining priority R&D initiatives through 2030. With €1.4 billion funding, nearly 200 projects will be deployed across the full innovation chain-from technological validation to commercial application.

complemented by optimized flexible modules and floating materials.

Intelligent operation and maintenance systems ensure the safety and stability of wind and solar power assets. In wind power, digital twin platforms and AI-based scheduling systems significantly enhance stability. In PV, AI-integrated modules and diagnostic platforms enable gigawatt-level fault identification and prediction, supporting high-percentage grid integration. Digitalization and artificial intelligence deeply empower the entire lifecycle of wind power, where AI-driven predictive maintenance and digital twin technologies can reduce failure rates, lower maintenance costs, and improve energy output stability.

Multi-energy complementarity and system integration address renewable energy consumption challenges. To facilitate high-percentage renewable energy integration, developing multi-energy coupling systems has become a key research focus. Pilot projects worldwide are integrating PV, wind power, solar thermal, and molten salt storage to ensure long-duration, stable power supply. Multi-energy complementarity and system integration will strongly support large-scale utilization of wind and solar energy.

Offshore energy hubs promote clustered marine energy development. China is exploring multidimensional resource utilization through "wind power + photovoltaics + aquaculture" and "marine energy multi-energy complementarity", with pilot initiatives in Shandong, Zhoushan, and the South China Sea. Wenzhou, in Zhejiang Province, has taken the lead in deploying a demonstration project for an offshore energy island, leveraging island resources to build a hub for offshore renewable energy, with a focus on developing deep-sea wind power (see Case 2). Similarly, The EU is developing North Sea energy resources, utilizing islands as renewable energy hubs (see Case 3) and leading the global upgrade of offshore energy systems. Clustered offshore energy development enhances marine economic output and supports energy transition in coastal regions.

2.3 Financial Support

Wind and solar projects commonly face challenges such as substantial initial investments, uncertain returns, and extended payback periods. Their ability to achieve scaled and commercialized development largely depends on the adaptability and robustness of financial system support. With the advancement of the "dual carbon" goals and the deepening of green finance concepts, major global economies and multilateral institutions are actively exploring innovative financing tools and mechanisms to enhance the resilience and efficiency of capital safeguards for renewable energy investments.

1) **Innovations in international financial instruments and mechanisms**

The international green finance system is evolving from traditional single-bond financing toward a multi-layered structure that includes carbon finance, derivatives, and hybrid instruments. Innovations in international financial mechanisms are accelerating the capacity to fund wind and solar projects.

In terms of market-based financing and risk sharing, market-driven pricing mechanisms such as long-term Power Purchase Agreements (PPAs) and Contracts for Difference (CfDs) play a critical role. These tools generate price signals through competitive bidding, providing developers with predictable long-term revenue while continuously driving down costs and improving efficiency through market competition. The green bond market continues to innovate, with global issuance reaching approximately $571 billion in 2024. Features like “generation-linked” repayments and “carbon reduction swaps”, which tie repayment terms to project performance, better align with the cash flow characteristics of wind and solar projects. Moreover, carbon market mechanisms are becoming deeply integrated. Instruments such as carbon revenue pledging and carbon-guaranteed loans convert future carbon asset revenues into immediate financing capacity, significantly enhancing liquidity during the early development stages of projects.

Regarding policy and multilateral institutional support, the EU’s carbon pricing mechanism has facilitated green credit systems that effectively promote the integration of carbon assets with clean energy investments. Countries like Germany and the UK have incorporated carbon revenues into project credit systems to reduce funding thresholds. Multilateral institutions such as the Asian Development Bank support private sector participation through low-interest loans and hybrid guarantee models, significantly lowering the weighted average cost of capital (WACC). In the US and Japan, fiscal incentives including tax credits and accelerated depreciation help alleviate financial burdens on project developers.

In risk management and guarantees, tools like weather derivatives, political risk insurance and payment guarantees further mitigate external risks, making wind and solar projects more bankable. These financial innovations are vital in transitioning wind and solar projects from merely “investable” to fully “financeable”, supporting the global shift toward green energy.

2) **Construction of China’s Green finance system**

Currently, China’s wind and solar industry financing model has successfully transitioned from subsidy dependency to a “policy guidance and market mechanism synergy”, and established an investment and financing system characterized by multi-dimensional linkages among fiscal policy, monetary policy, carbon finance, and capital markets.

In policy coordination, the People’s Bank of China has launched RMB 500 billion in technology innovation relending facilities with an interest rate as low as 1.75%, providing targeted support for green equipment upgrades and R&D by small and medium-sized enterprises. This program is planned to expand to RMB 800 billion–1 trillion in 2025, offering long-term, stable, and low-cost funding for technological breakthroughs and domestic substitution in wind and solar equipment. Besides, ultra-long-term special government bonds have provided fiscal support for renewable energy equipment upgrades and intelligent transformation, including wind and solar, helping to form a synergistic mechanism of “fiscal funds + commercial loans + risk reserves” that channels social capital into key industrial segments.

Green finance instruments are expanding. In 2024, China’s cumulative issuance of climate bonds reached USD 5.56 billion, with green bonds accounting for more than 80% [13, 14]. Provinces such as Zhejiang and Shandong have established green guarantee and risk compensation funds to provide interest subsidies and credit enhancement support for small and medium-sized wind and solar enterprises, significantly improving

Case 2

Zhejiang Marine Energy Island

Wenzhou Dongtou Deep Sea Wind Power Mother Port

In September 2024, Zhejiang Energy Group led the establishment of Zhejiang Marine Wind Power Development Co., Ltd., aiming to explore new pathways for deep-sea offshore wind energy development. The company formed the Wenzhou Offshore Wind Power Mother Port, and is responsible for the full-cycle construction and operation of the project. In the long term, the project is expected to provide an annual capacity of 3 million kilowatts of deep-sea offshore wind power, supporting the province's goal of achieving 28 million kilowatts of deep-sea offshore wind energy. By 2030, the goal is to create a highland for the entire wind power industry chain in East China, serving the whole country and even the international markets.

Case 3

North Sea Offshore Energy Hubs

Belgium's Princess Elisabeth Island

This innovative energy island integrates offshore wind, floating PV, and green hydrogen production to establish a transnational interconnection platform. It is set to become the world's first artificial energy island combining both high-voltage direct current (HVDC) and alternating current (HVAC) systems. The island's high-voltage infrastructure will consolidate export cables from the 3.5 GW Princess Elisabeth offshore wind zone and serve as a future interconnection hub for the United Kingdom and Denmark.

Netherlands' Hollandse Kust Noord

This project integrates floating PV systems with short-duration battery storage and electrolyzers for green hydrogen production. It features 69 optimized 11 MW turbines, which are designed to reduce wake effect losses, integrated with floating solar, energy storage, and a 200 MW hydrogen plant-forming a closed-loop "wind-PV-storage-hydrogen" system. Upon 2025 commissioning, it is expected to produce 60,000 kg of green hydrogen daily.

Denmark's Brintø (Hydrogen Island)

Located on the Danish section of Dogger Bank, this hub aims to connect up to 10 GW of offshore wind capacity by 2030. It will anchor North Sea energy infrastructure, and produce approximately 1 million tons/year of green hydrogen (7% of the EU's hydrogen demand for 2030).

financing accessibility. Carbon finance is also becoming embedded in the investment and financing ecosystem. By the end of 2024, the national carbon market had recorded a cumulative trading volume of 630 million tons of CO_2. Wind and solar projects have enhanced asset liquidity and monetization capacity through tools such as carbon credit ABS and CCER-pledged loans.

Multi-level capital markets also provide direct financing channels for industrial development. Wind and solar enterprises have accessed funding for high-barrier technologies and global expansion through IPOs, convertible bonds, and infrastructure REITs. In 2023, the first wind power REIT was successfully issued, raising more than RMB 7 billion, which indicates the strong capital market recognition of renewable energy asset securitization. Overall, under the combined effect of policy guidance and institutional innovation, China has built a green finance support system covering the full life cycle and the entire industrial chain, providing a solid foundation for the high-quality development of the wind and solar industries.

2.4 Gender Equality Empowerment

Gender equality is increasingly contributing to the development of wind, solar, and other renewable energy industries by optimizing talent structures, enhancing team performance, and strengthening financial linkages, thereby significantly improving social acceptance, implementation resilience, and overall competitiveness of projects.

Optimizing talent structures to unleash diverse potential. According to IRENA data, women accounted for 32% of the global renewable energy workforce in 2019, and as high as 40% in the solar PV sector, well above the 22% share in the traditional energy industry [15]. By 2024, women's participation in China's renewable energy sector had risen to 30%-35%, significantly higher than 27.1% in 2019 [16]. Educational institutions and industry organizations are jointly expanding pathways for women to engage in core wind and solar technologies and management. Interdisciplinary programs in materials science, environmental engineering, and energy systems engineering continue to attract female talent, while targeted training initiatives jointly launched by universities, industry associations, and enterprises are substantially increasing the proportion of women pursuing advanced studies and employment in key areas such as wind-solar system design, energy storage technologies, project development, and smart energy management.

Enhancing team performance to drive project implementation. Diverse teams strengthen technological collaboration and execution capacity. Research by the International Labour Organization (ILO) shows that increasing women's participation significantly improves communication, collaboration, and decision-making quality [16]. With the high degree of digitalization in the renewable energy sector, positions in system operation, remote dispatching, and community coordination offer strong suitability for women. The State Grid's "Green Women Posts" training program has expanded across multiple provinces, raising the share of women in technical roles and creating more career advancement opportunities. In the new-type power system, women are no longer confined to auxiliary positions but are increasingly taking on central roles in project planning, system integration, and platform operations.

Strengthening financial linkages to shape new competitive advantages. Gender-friendly mechanisms are being gradually incorporated into global clean energy policies and financial evaluation systems, becoming important factors enhancing the competitiveness of wind and solar projects. The EU's Just Transition Fund includes gender equality in its assessment dimensions; in 2023, UN Women and IRENA jointly called for gender indicators to be integrated into monitoring and financing mechanisms related to Sustainable Development Goal 7 (SDG7) [17]. Moreover, multilateral financial institutions such as the Asian Development Bank have embedded gender performance requirements into project management frameworks. For example, gender bonds listed in Singapore raised funds for women-led solar and wind enterprises, while the Global Environment Facility (GEF) established gender responsiveness as a mandatory criterion for wind and solar financing. These practices demonstrate that gender performance is evolving from a matter of social responsibility into a substantive financial advantage, becoming an important driver of financing efficiency and overall competitiveness in renewable energy projects.

3.Technological Difficulties and Key Development Directions for Wind-Solar Renewable Energy

3.1 Current Status of Wind-Solar Renewable Energy Technologies

1) Wind Power Technology: Transformation Driven by System Integration and Intelligent Operations

Wind power technology has undergone multiple stages of innovation and breakthroughs, including large-scale turbines, higher efficiency, intelligent systems, and floating offshore wind. In terms of scale, rapid progress has

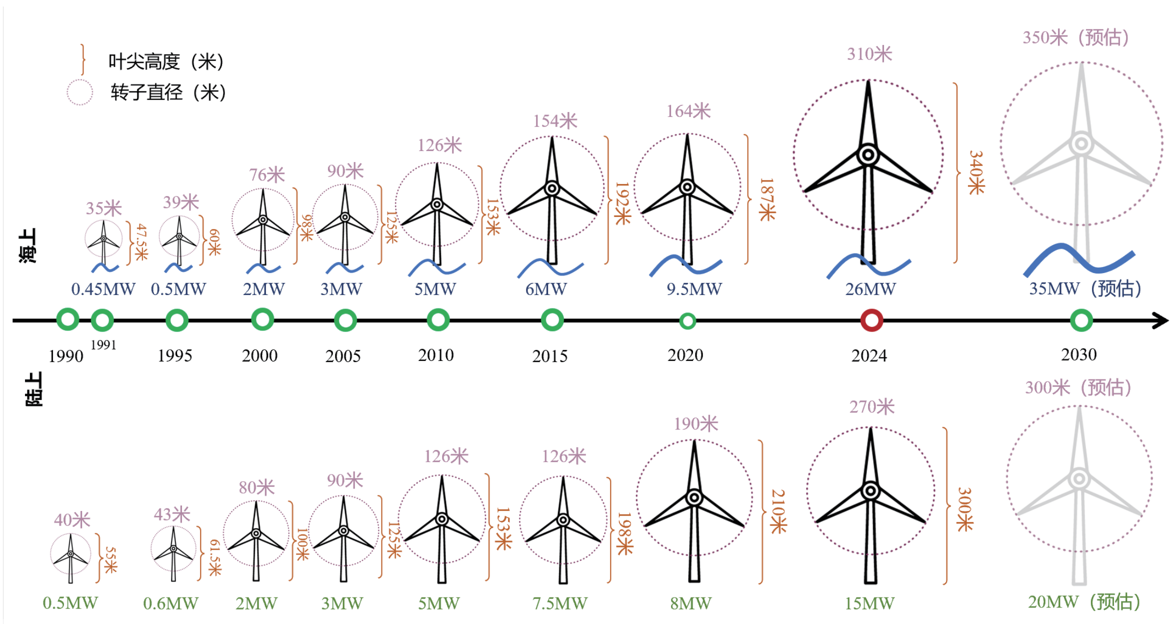


Figure 3. Development trends in large-capacity turbines, long blades, and tall towers [19].

been achieved in developing large-capacity turbines, longer blades, and higher towers (Figure 3). The 26 MW large-scale offshore wind turbine launched by China Eastern Electric is a cutting-edge achievement in this trend. At present, the industry is shifting from single equipment upgrades toward multi-dimensional system optimization, with emerging trends in deep-sea deployment, intelligent operation and maintenance, and multi-scenario integrated applications [18].

Deep-sea offshore wind power offers the advantages of abundant resources and minimal interference [20]. Offshore wind is gradually adopting modular design, digital twin modeling, and unmanned inspection platforms. Floating platforms, enhanced by lightweight design, dynamic mooring system optimization, and AI-driven predictive maintenance, combined with unmanned vessels and satellite-based remote sensing networks, can significantly reduce operation and maintenance costs.

Currently, diversified integrated development models such as “wind-solar-hydrogen storage” and “wind-solar-thermal storage”, “wind power-aquaculture co-development”, and “wind-solar complementarity” are being actively explored to enhance system efficiency through resource sharing and scenario integration. Emerging approaches like “offshore wind power + seawater hydrogen production” have formed industrial pilot projects in some regions, and will become crucial for extending the offshore wind value chain.

The digital transformation of wind power is accelerating with deploying edge sensors, predictive models, and remote-control platforms, which all enable wind farms to evolve from static responses to intelligent dispatching. Industry leaders are developing “smart wind farms” that fuse multi-source data to optimize equipment status, load fluctuations, and meteorological conditions, thereby enhancing operational efficiency.

The wind turbine recycling industry remains in its infancy, primarily focused on blade dismantling and material sorting and with urgent need for breakthroughs in regeneration technologies. Key drivers for scaling up environmentally sound turbine recycling include improving environmental regulations, developing efficient recycling methods for blade composite materials, establishing remanufacturing processes for high-value components, and innovating circular economy models.

2) PV Technology: Evolving from Module Efficiency Competition to System Integration and Scenario Convergence

As mainstream crystalline silicon technologies approach their theoretical efficiency limits, PV cell technology is showing a diversified development pattern featuring parallel technical routes and multi-functional applications. Technologies like N-type TOPCon continue to dominate, while high-efficiency, costlier alternatives such as heterojunction (HJT) and intersect- back-contact (IBC) and heterojunction-back-contact (HBC) cells are penetrating high-end markets, forming complementary relationships with mainstream products [21] . Novel PV structures like single-junction perovskite and perovskite/silicon tandem cells are pushing performance boundaries, emerging as potentials for mid-to-long term industry transformation. This multi-path advancement not only enriches the PV technology portfolio but also provides more tailored solutions for diverse applications, from utility-scale plants to distributed systems, and building integration to portable devices, which showcases “multi-scenario adaptability and multi-functional synergy” as key development characteristics.

The PV industry is undergoing a profound **transformation toward system integration and scenario convergence.** Building-integrated photovoltaics (BIPV) is gaining momentum, with PV modules embedded into architectural elements such as roofs, facades, and shading structures, and becoming crucial for urban energy decarbonization [22, 23]. Notably, high-transparency cadmium telluride thin-film modules are increasingly used for specialized applications like building facades due to their lightweight and flexible design. Current R&D efforts focus on improving low-light performance and flexible encapsulation. Additionally, the rapid growth of distributed PV is fostering the commercialization of "PV-storage-charging" integrated systems. The coordinated development of PV with energy storage, EV charging stations, and smart meters is creating new energy consumption ecosystems characterized by "self-generation with smart dispatch".

The integration of smart inverters, energy management systems, and flexible power control technologies has become a key factor in enhancing overall performance. Emerging approaches such as flexible modules, transparent modules, and advanced encapsulation technologies are also progressing rapidly, expanding PV applications into new scenarios including portable, vehicle-mounted, and wearable devices. System adaptability is becoming a new benchmark for evaluating PV value, moving beyond the traditional focus on unit-area efficiency. By 2030, global decommissioned PV modules are projected to reach 8 million tons, with China accounting for about 1.5 million tons [24]. Current pyrolysis-based recycling methods are energy-intensive and polluting, highlighting the urgent need for greener dismantling processes. Improvements in metallic electrodes and perovskite stability will define the next frontier of PV technology, while "PV+" applications require materials resistant to potential-induced degradation (PID) and corrosion.

3) Transcending Equipment Boundaries: New Features and Key Support for Integrated Wind-Solar Systems

As wind and solar power generation increases its share in power systems, the traditional "single power generation equipment efficiency competition" model is giving way to system-level comprehensive optimization. The wind-solar industry is exhibiting multi-dimensional evolutionary trends [25], with system coupling and multi-energy complementarity becoming important development directions. Demonstration projects employing multi-mode coordinated operation schemes for wind-solar-storage-thermal and source-grid-load-storage systems are becoming more prevalent, significantly improving system flexibility and resilience through dynamic balancing and cascaded utilization of multi-energy flows [26].

Artificial intelligence and digital energy management systems underpin these advancements. AI algorithms enable high-precision literature knowledge extraction, power generation forecasting, and experimental plan optimization, combined with high-throughput material preparation, characterization, and evaluation equipment, have greatly shortened the R&D cycle and cost of new energy materials, facilitating continuous breakthroughs in materials for wind turbine blades, PV cells, energy storage, and green fuel synthesis. Virtual power plants (VPPs) are progressing from pilot projects to large-scale operations by aggregating distributed PV, energy storage, and adjustable load resources to participate in electricity markets, thereby enhancing grid flexibility and renewable energy utilization. Microgrids are evolving into integrated “source-grid-load-storage-charging” systems. Relying on smart energy management systems to achieve solar-storage coordination and demand response, they will significantly increase the green power self-sufficiency and operational efficiency of zero-carbon parks.

3.2 Technological Bottlenecks and Constraints

1) Major Technical Challenges in Wind Power Development

Power generation efficiency challenges. Wind power faces multiple technical barriers in enhancing efficiency through turbine upscaling. Increasing turbine capacity is crucial for reducing LCOE, but the “square-cube law” causes nonlinear increases in structural loads. Designing Ultra-long blade design requires balancing lightweight construction with strength, fatigue resistance, and extreme wind load tolerance, complicating manufacturing precision, mold rigidity, and material layup. The drivetrain components, including gearboxes and generators, must optimize thermal performance under high torque loads. Taller towers improve structural stability but introduce engineering risks during transportation and installation. These factors demand high manufacturing standards, component machining precision, and robust infrastructure support.

Environmental adaptability bottlenecks. The deep-sea environment poses serious challenges to adaptability. For traditional fixed foundations, economic feasibility declines significantly in waters deeper than 60 meters, making floating wind power a key solution [27]. However, floating platforms and their mooring systems face risks such as wave load impacts, dynamic response control, and subsea cable wear, while lacking long-term validation under large-scale operation. In addition, deep-sea power transmission relies on costly solutions, and the laying of subsea cables, the complexity of fault detection and repair, and energy conversion losses all present further challenges.

Operation and maintenance challenges. Wind power O&M faces challenges of high costs and insufficient levels of intelligence. Most wind farms are located in remote, offshore, or high-altitude areas, where conventional inspection and fault maintenance are not only costly but also carry high risks [28]. Traditional strategies based on periodic inspections have limited capability in identifying early-stage faults, while intelligent monitoring and predictive maintenance technologies have yet to achieve wide adoption. Particularly in offshore settings, complex sea conditions restrict O&M frequency, and the heavy reliance on specialized vessels, platforms, and remote monitoring systems further increases life-cycle costs.

2) Major Technical Barriers in PV Technology Development

Efficiency limitations: PV efficiency improvements are constrained by material and technical factors. Mainstream crystalline silicon cells are nearing the theoretical efficiency limits of single-junction materials [29], necessitating tandem cell structures and new materials like perovskite and quantum dots. Technical challenges include controlling new material consistency and managing interface defects. Tandem devices face issues with carrier recombination and current matching, affecting stability, batch yield, and large-area fabrication and finally impeding commercialization.

Environmental resilience: Harsh environments threaten the stability of PV modules. Conditions such as high temperatures, high humidity, high salt spray, and low light significantly impact module encapsulation reliability, electrical performance, and structural stability, especially in offshore or extreme climates [30]. Seawater salt spray and chloride ions can lead to corrosion of module mounting structures, and waves, typhoons, and sea ice loads may cause panel breakage or structural collapse, thereby system failures.

Operation and maintenance limitations: PV O&M suffers from data management and automation deficiencies. Large-scale PV plants feature wide distribution and diverse equipment types. Existing monitoring systems often lack consistent standards, leading to data heterogeneity and complicating scheduling and optimization. Some regions experience delayed response to abnormal output, insufficient fault location accuracy, and lack of power generation performance diagnosis. Moreover, manual maintenance is labor-intensive and automation levels are low, constraining system efficiency improvements. Developing intelligent sensing, digital twins, edge computing, and AI-based prediction systems is critical for improving efficiency.

3) Constraints on Large-scale Wind and Solar Deployment

Resource assessment and prediction accuracy: Accurate assessment of wind and solar resources remains a challenge. The uncontrollable nature of renewable energy output from wind and solar poses challenges to grid frequency stability, voltage control, and backup resource allocation especially when integrated at high proportions. Uncertainties in mid- and long-term assessment models for wind and solar resources affect project revenue estimates, while short-term power prediction errors increase grid dispatch costs and limit high-proportion integration [31]. Improving the accuracy of wind and solar resource assessment models, optimizing data collection systems, and developing intelligent output prediction methods are prerequisites for ensuring the economic viability and grid stability of wind and solar renewable energy.

System integration and coordination: Enhancing the capacity for large-scale integration requires better coordination of "source-grid-load-storage" systems. In the context of high-proportion integration of wind and solar renewable energy, it is imperative to mitigate fluctuations through dispatch-side energy storage or load-side response resources. Current system coordination among storage, load, and generation remains insufficient, with limited peak-shaving and frequency regulation response capabilities. Developing modular inverter systems, flexible access interfaces, integrated "source-grid-load-storage-charging" solutions, and control strategies will improve system operational flexibility and power generation reliability.

Impact of climate change: Global climate change introduces new challenges to the new energy system. Rising global temperatures affect PV efficiency and accelerate component aging and transmission equipment. Extreme weather events, such as windless conditions, typhoons, heavy rains, snowstorms, and sandstorms, not only damage wind and solar power equipment but also impair power output predictions based on historical meteorological data. These uncertainties increase operational and maintenance complexities and demand enhanced absorption and storage capabilities within the new energy system.

3.3 Technological Innovation Directions and Key Technology List

Strategies for a green and low-carbon energy transition and high-quality development of wind and solar energy both necessitate the advancement in key technology research and industrial upgrading. Efforts should concentrate on four major directions: efficiency improvement, system integration, intelligent operation and maintenance, and the circular economy, to remove bottleneck constraints and build a clean, low-carbon, safe, and efficient new energy system.

1) Wind power technology should focus on the trends of large capacity, lightweight, intelligent and deep-sea development, prioritizing the following areas:

High-end equipment and advanced materials: Tackle the problem of manufacturing core components such as large-capacity main bearings, lightweight gearboxes, and direct-drive permanent magnet generators. Priorities should be given to the R&D and industrialization of carbon fiber composite blades to enhance unit reliability and reduce manufacturing and O&M costs.

Deep-sea development and multi-energy synergy: Advance floating offshore wind platform design and dynamic coupling technology. Develop flexible DC transmission and dynamic submarine cable systems. Promote the complementary integration of offshore wind with solar PV, energy storage, and hydrogen, and establish a collaborative model of “offshore energy base - onshore regulation - diversified consumption”.

Intelligent Operation and Maintenance: Build a full lifecycle digital management system for wind power. Promote intelligent inspection using drones and robots. Develop integrated technologies for wind resource assessment, power prediction, and fault early warning to enhance system operational safety and economics.

Green and low-carbon circular system: Establish high-efficient recycling and regeneration technology systems for decommissioned components like turbine blades and towers, promoting green development across the entire wind power industry chain.

2) PV technology should focus on high efficiency, high reliability, multi-scenario integration, and intelligent applications, prioritizing the following areas:

Industrialization of new-type cell technology: Actively promote the large-scale application of high-efficiency crystalline silicon cells like TOPCon and HJT. Accelerate the R&D, pilot testing, and commercialization of new technologies such as perovskite/c-Si tandem and thin-film cells, continuously improving photoelectric conversion efficiency and stability.

Multi-scenario integrated applications: Develop highly reliable components and system integration technologies suitable for various scenarios like offshore, high altitude, desert, and building integration. Promote the coordinated development of PV with wind power, energy storage, and hydrogen. Deepen the integration of BIPV and green buildings, and expand integrated “PV-storage-charging” applications.

Intelligent O&M and digital management: Build power plant-level intelligent O&M platforms. Promote AI visual diagnosis, big data analysis, and drone inspection technologies to achieve “unmanned, refined, and intelligent" management of PV power plants.

Decommissioned c**omponent** r**ecycling and** r**esource** c**irculation**: Establish a standard recycling system for PV components. Make breakthroughs in green dismantling and high-value recycling technologies for both crystalline silicon and thin-film modules, achieving efficient resource cycling throughout their lifecycle.

3) Wind-solar i**ntegration and** s**ystem** i**ntegration** t**echnologies need to strengthen cross-industry, cross-domain system integration and collaborative control, prioritizing the following areas:**

Multi-e**nergy** c**omplementarity and** c**oordinated** o**peration:** Develop planning and design platforms for wind-PV-hydro-storage-hydrogen multi-energy complementarity. Promote demonstrations of "source-grid-load-storage" coordinated control technology to enhance system flexibility and absorption capacity.

Digital t**wins and VPPs:** Construct digital twin systems for wind and solar clusters. Build VPP aggregation and control platforms to achieve intelligent coordination and optimal dispatch of widely distributed resources.

Integrated o**ffshore** e**nergy** d**evelopment:** Explore multi-energy coupling (offshore wind, PV, ocean energy) and platform integration technologies. Promote the integrated development of offshore energy hubs and the marine economy.

Overall, wind and solar energy technologies are evolving towards high-end, intelligent, integrated, and green directions. It is necessary to strengthen cross-departmental coordination and policy support, and systematically plan key technology R&D and demonstration applications, thereby to provide solid support for the green energy transition.

4.Policy Recommendations

At present, China's wind and solar energy sector has entered a critical stage of transition from "quantitative leap" to "qualitative breakthrough". To achieve the new national contribution targets with a higher proportion of renewable energy integration, and to address increasingly complex application scenarios along with intensifying global technological competition, it is imperative to implement systematic and forward-looking policy measures. These policies should support technological innovation and industrial development in the renewable energy sector, providing new momentum for sustainable growth.

4.1. Promote technological application and model innovation to scale up mature technologies and upgrade industrial chains.

First, advance "new energy +" multi-dimensional integration to foster a new ecosystem of industrial synergy. Wind and solar should be closely integrated into energy-intensive sectors such as industrial parks, data centers, 5G base stations, transportation hubs, and buildings, with emerging models like "zero-carbon parks" and "zero-carbon computing centers" promoted. These efforts will help form smart industrial clusters centered around renewable energy, jointly advancing green transformation across energy, manufacturing, urban development, and transportation.

Second, optimize spatial planning and policy coordination to secure high-quality industrial development. This includes strengthening cross-departmental policy alignment among energy, defense, transportation, and natural resources agencies, optimizing land- and sea-use for wind and PV projects, and exploring standardized development models such as offshore energy centers and agricultural-PV hybrid systems. These measures aim to stabilize and control the development space for renewable energy industries.

Third, establish a comprehensive lifecycle recycling system to secure the supply chain of critical resources. This involves promoting the recycling and reuse of decommissioned wind turbines and PV modules, developing technologies for resource recovery, and improving the entire lifecycle management system covering green design, clean production, efficient operation, cascading utilization, and advanced recycling. Special attention should be given to high-value recovery of critical metals, silicon materials, and rare earth elements. Additionally, supporting policies and standards should be refined to foster large-scale, operational recycling enterprises, ensuring the sustainable development of the wind and solar industry and maintaining stability and security of global supply chains.

4.2. Build major renewable energy infrastructure to coordinate technological breakthroughs and demonstration applications.

First, increase investment in fundamental research on renewable energy technologies and equipment, and promote innovation in cutting-edge technologies. Priority should be given to the construction of major innovation infrastructure platforms, integration of research resources across energy, materials, and information fields. Collaborative R&D should be advanced in areas such as deep-sea floating wind, high-altitude wind turbines, next-generation perovskite/silicon tandem cells, high-efficiency flexible modules, precision forecasting of wind-solar power output, and efficient production of green fuels, fostering the creation of a future-oriented energy system.

Second, deepen digit empowerment to enhance system resilience and intelligence. Investment in climate-adaptive technologies should be increased, while information technologies such as AI and digital twins should be integrated into energy systems. Development of smart dispatching systems and VPP technologies with autonomous learning and optimization capabilities will be key to improving renewable energy integration and system security.

Third, implement major integrated demonstration projects tailored to local conditions to provide replicable and scalable solutions. In the “desertified” regions of northwestern China, large-scale renewable bases should be built to high standards, with coordinated demonstrations of “wind-solar-coal-storage integration” and ecological restoration, exploring synergies between multi-energy complementarity and environmental governance. In coastal areas, integrated “wind-solar-hydrogen-storage” applications should be accelerated, with the establishment of offshore energy hubs and offshore energy centers that serve both supply and conversion functions.

4.3. Strengthen innovation element support and collaborative mechanisms to build an open and inclusive global energy technology cooperation ecosystem.

First, enhance talent supply and build a talent echelon to support the renewable energy sector. Talent cultivation and innovation systems in frontier energy technologies should be improved. Leading enterprises and universities/research institutes should be supported to jointly build pilot testing platforms and technology transfer centers. Dedicated funds and honorary awards should also be established to encourage women scientists to engage in energy innovation, aiming to foster a pool of internationally influential strategic scientists, leading experts, and technological leaders.

Second, construct a multi-layered financial support system to guide effective investment in innovation. Government-guided funds should leverage green credit, green bonds, and transition finance to steer social capital into frontier R&D and demonstration projects in renewable energy. Incentive mechanisms linked to technology maturity and emission reduction benefits should be explored to reduce commercialization risks and innovation costs.

Third, expand international cooperation to enhance global innovation and knowledge sharing in wind and solar technologies. Promoting the global deployment of advanced wind and solar technologies, organizing international scientific programs, and participating in global energy governance will support the transfer and transformation of renewable energy technologies, leading the global transition toward green energy.

III. Research on Power System Design to Support Renewable Energy Development

The electricity grid is the foundation for a low-carbon energy system. Beyond delivering power, a robust electricity grid enables the integration of renewable energy across vast distances and accommodates the shift from fossil fuels to electricity across the economy. China is already adept at grid expansion and linking renewables and demand across wide geographies. This chapter focuses on the grid infrastructure and operational practices that can further help solve the renewable integration challenge: maintaining a secure, low-cost electricity system as the variability of supply increases.

In this chapter, we focus only on the grid and operational practices, rather than the whole suite of flexibility solutions needed to balance renewable energy as the share increases, for the sake of focus and length of this research project. As the following section will show, due to success in rapid clean energy and grid construction, China is entering a new phase of renewable development where the existing system flexibility may be insufficient, requiring additional investment and new operational practices. There are many technologies that can provide flexibility, including grid interconnections, storage (addressed in the following chapter), demand response and virtual power plants, sector coupling, and vehicle-to-grid interaction. New planning practices and market designs can also help support development of these solutions. We focus here on grid infrastructure and operational practices because they are two vital foundations for addressing renewable integration challenges, and we hope to explore others in future studies.

1. Challenges faced by high-proportion renewable energy power systems and requirements for grid development

1.1 Current Status of Renewable Energy Development and Grid Integration in China

China's new energy development has entered a new stage. In 2024, China's wind and solar power generation reached 1.84 trillion kilowatt-hours (kWh), surpassing the total electricity consumption of the tertiary (service) sector nationwide. The renewable electricity penetration rate (as a share of total national power generation) reached 18.5%, exceeding 20% based on total electricity consumption, with the maximum instantaneous share of renewable generation surpassing 50%. According to the six-stage classification defined by the International Energy Agency (IEA), China has entered the third stage of renewable energy development, while provincial power grids in Qinghai, Eastern Inner Mongolia, and Gansu have achieved renewable electricity penetration above 30%, marking their entry into the fourth stage.

China has become a major driver of the global energy transition and climate action. With abundant wind and solar resources and vast development potential, China's new energy sector has achieved world-leading advances through continuous technological breakthroughs and industrial accumulation, forming the largest clean power supply system in the world. The sector has established a strong foundation for further growth-26 MW single-unit wind turbines have been successfully rolled out, and photovoltaic cell conversion efficiency continues to improve steadily. Meanwhile, emerging technologies and business models such as flexible DC transmission, "Internet + smart energy," large-scale new energy storage, and integrated energy systems are rapidly evolving. Collectively, these developments position China as a key force in driving the global energy transition and responding to climate change.

1.2 Challenges Faced by High-Proportion Renewable Energy Development

(1) Power and electricity balance and power supply security issues in high-proportion renewable energy power systems

The minimum output of renewable energy sources remains relatively low, providing limited support for maintaining power system balance at some times. Because solar and wind generation are intermittent and variable, they contribute to power flow balance but provide only weak support for overall system stability. As a result, additional generation resources are required to ensure reliable power supply when high shares of renewables are integrated into the grid – renewables cannot do so on their own. Variability along different time scales (seconds, hours, days, seasons) create different challenges for ensuring adequate supply to meet growing demand. Practically speaking, there are times when solar and wind output is near zero, e.g. on a windless night.

There is a mismatch between the seasonal characteristics of renewable energy power generation and electricity consumption, leading to seasonal power balance challenges. Wind power and photovoltaic power generation exhibit some complementary monthly power distribution patterns so optimized planning of renewable portfolios can mitigate the seasonal impact of increasing the share of renewable energy to some extent. However, the monthly power distribution of renewable energy does not align perfectly with load demand, resulting in seasonal power balance challenges. Under a much higher penetration of renewable energy, these seasonal imbalances may become more acute.

During extreme weather events such as cold and heat waves and droughts, electricity demand significantly increases and some supply risks increase, making it challenging to ensure reliable power supply. Over the past 35 years, the regions in central and eastern China without district heating have experienced 43 cold waves, with the largest single event affecting an area of 1.1 million square kilometers, temperatures dropping by up to 14℃, and peak load increasing by up to 20 million kilowatts. In recent years, extreme heat events have also become more frequent and intense, driving sharp increases in air-conditioning demand, while prolonged droughts have reduced hydropower output and further stressed supply. Wind and solar output do not necessarily correlate to these high demand periods, and may even introduce correlated risks, where low output coincides with high demand.

(2) Stability and Safety Issues in High-Proportion Renewable Energy Power Systems

The “double high” characteristics (high proportion of renewable energy and high proportion of power electronic equipment) of high-proportion renewable energy power systems are becoming increasingly prominent, leading to significant changes in the control foundation of power systems and posing major risks and challenges to safe and stable operation. Power electronic power sources currently lack the control characteristics of traditional generators, and their control scale has grown significantly, expanding from source-centric control to encompass all links in the source-grid-load-storage chain; system state uncertainty has increased, vulnerable components have multiplied, and fault forms, paths, and characteristics have become more complex.

Under current conditions, technical constraints limit the capacity to accommodate renewable energy sources. Under the existing technical framework, to ensure system stability, conventional units must maintain a certain safety level when operating, which reduces the system’s peak-shaving capacity and further limits the scale of renewable energy sources that can be accommodated, resulting in technical constraints on cross-regional power transmission and the scale of renewable energy sources. Under current technical constraints such as system frequency regulation performance and safety control measures, the renewable energy carrying capacity of large power grids is limited. In the future, new technological innovations will be required to further enhance the renewable energy carrying capacity of large power grids.

(3) Increasing pressure on overall costs

Evidence from domestic and international research suggests that as the share of renewable energy grows, total power supply costs are subject to change. Renewable energy reduces the need to build and operate thermal power plants. However, total system costs may rise due to the cost of the renewable facilities and the need to retain some backup thermal generation capacity, enhance grid flexibility, upgrade transmission and distribution networks, and adopt other measures to maintain system stability as rotational inertia declines. These costs are closely tied to the penetration rate of renewable electricity. At low levels of penetration, the system can generally accommodate renewable integration through adjustments in conventional power plant operations, and total system costs remain flat or fall due to the low cost of renewable equipment and avoided costs for thermal power. However, as the penetration rate rises, system costs can increase. There are generally upward inflection points when there is enough renewable energy to meet daytime loads with thermal plants turned down as far as possible (around 15% penetration), and again when there is enough solar and short-term storage to meet total load on most days, but not on days with low renewable production (around 80% penetration).

1.3 The Proposal for a New Power System Centered on Renewable Energy and Its Requirements for Grid Development

In March 2021, the Ninth Meeting of the Central Financial and Economic Affairs Commission first proposed the concept of “building a new power system with renewable energy as the mainstay.”

In May 2022, the Notice of the General Office of the State Council on Forwarding the Implementation Plan for Promoting High-Quality Development of New Energy in the New Era issued by the National Development and Reform Commission and the National Energy Administration [32] proposed that innovative models for the development and utilization of renewable energy should be explored, and efforts should be intensified to plan and construct a renewable energy supply and consumption system based on large-scale wind and solar power bases, supported by clean, efficient, advanced, and energy-saving coal-fired power plants in their surrounding areas, and transmitted through ultra-high-voltage power transmission and transformation lines that are stable, safe, and reliable. accelerate the construction of a new power system adapted to the gradually increasing proportion of renewable energy, “comprehensively enhance the power system’s regulation capacity and flexibility; focus on improving the distribution grid’s ability to accommodate distributed renewable energy; and steadily promote the participation of renewable energy in power market transactions.”

In July 2023, the “Guiding Opinions on Deepening Power System Reform and Accelerating the Construction of a New Power System” was issued, clearly stating that the new power system should take ensuring energy and power security as its basic premise, meeting the power demand of high-quality economic and social development as its primary goal, the construction of a high-proportion renewable energy supply and consumption system as its main task, and the multi-directional coordination and flexible interaction between power generation, transmission, consumption, and storage as its strong support. It should be based on a robust, intelligent, and flexible power grid as the hub platform, and technological innovation and institutional innovation as the fundamental guarantee. The system should possess the characteristics of being clean and low-carbon, safe and adequate, economically efficient, supply-demand coordinated, flexible, and intelligent.

In February 2024, President Xi Jinping emphasized during the 12th collective study session of the Central Political Bureau:[33] “We must adapt to the needs of energy transition, further improve the infrastructure network for renewable energy, advance the intelligent upgrading of power grid infrastructure and the construction of smart microgrids, **and enhance the power grid’s capacity to accommodate, allocate, and regulate clean energy.**”

2. International Practices and Experiences in Supporting High Proportion of Renewable Energy Integration into the Grid

2.1 Multiple countries and regions have achieved high proportions of renewable energy in their power systems

Based on the penetration rate of renewable energy electricity and the proportion of renewable energy output, the development of renewable energy can be divided into six stages. Research findings from the International Energy Agency (IEA) indicate that the impact of renewable energy on power systems varies with different penetration rates. Depending on the proportion of renewable energy in the power system and the extent of its impact on the system, the development of renewable energy is categorized into six stages. Each stage faces distinct challenges, requiring targeted measures to ensure the safe and economical integration of renewable energy [34].

Stage 1: Electricity penetration rate below 3%, renewable energy integration has no significant impact on the power system.

Stage 2: Electricity penetration rate of 3–15%, where the integration of renewable energy has a limited impact on the power system. Through enhanced power forecasting, full utilization of existing system regulation resources, and optimized dispatch, renewable energy can be fully integrated.

Stage 3: Electricity penetration rate of 20–25%, the duck curve emerges (very low net load during the day followed by a rapid evening ramp up), net load volatility intensifies, and renewable energy significantly impacts power system operations. The need for system flexibility often exceeds the capabilities of the existing power system.

Stage 4: Electricity penetration rate of 25–40%, with renewable energy output nearly equal to load demand

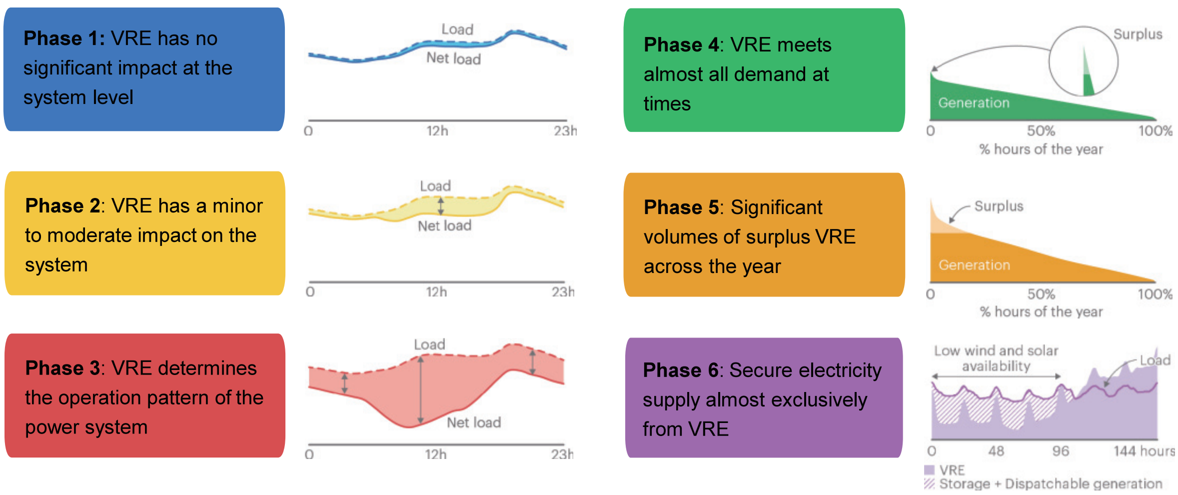
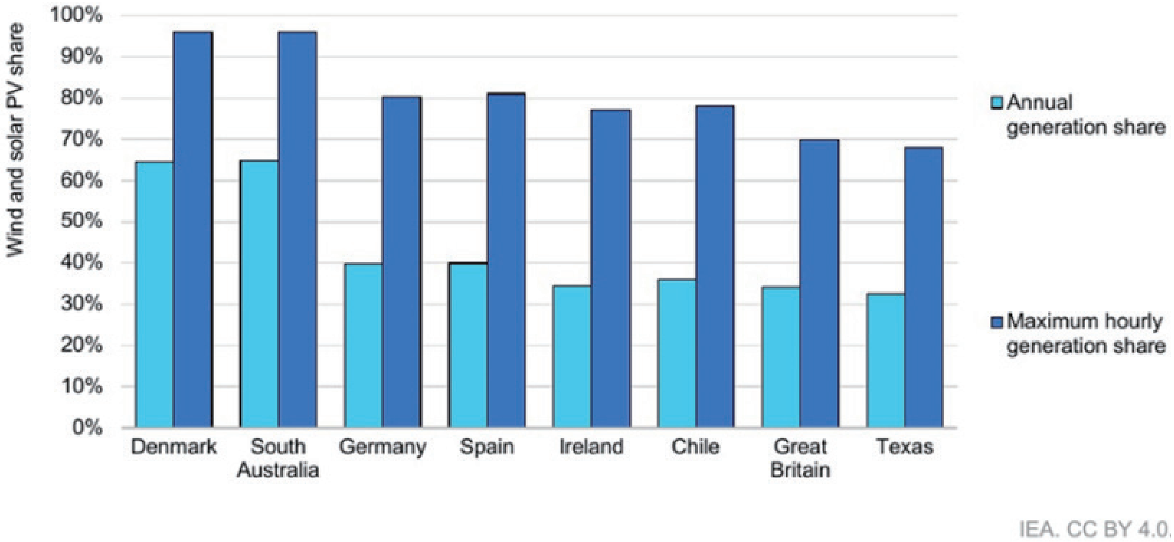


Figure 4 Six Stages of Variable Renewables Integration [35]

during certain periods, posing challenges to system operational stability. During periods of high renewable energy generation, risks to power supply reliability emerge. Connection standards should require grid-forming capability for inverter-based resources to maintain stability at this stage.

Stage 5: Electricity penetration rate exceeds 40%, renewable energy generation continues to increase, and renewable energy output exceeds demand for nearly 50% of the year. supply-demand imbalances, with increased periods of power shortages or surpluses, and a sharp rise in the risk of curtailing renewable energy generation.

Stage 6: Electricity penetration rate exceeds 80%, with nearly all electricity demand met by renewable energy sources. The impact of renewable energy on power supply security intensifies, particularly in seasonal



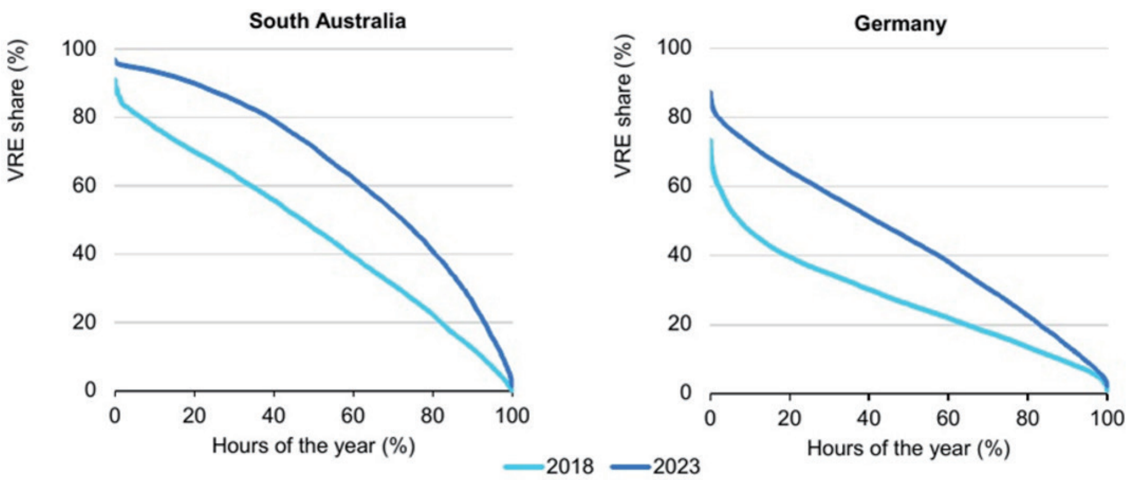


Figure 5 Cumulative distribution of solar photovoltaic and wind power generation shares by hour in South Australia and Germany in 2018 and 2023

balancing. There is increasing demand for long-duration energy storage with seasonal regulation capabilities.

Some countries have successfully achieved high penetration of renewable energy integration. The experiences of these countries, which have entered higher stages of renewable energy development, can provide valuable insights for other nations pursuing renewable energy development. The IEA analyzed 50 countries worldwide (in 2023, these countries accounted for approximately 90% of global renewable energy generation), with 25 countries in the first or second stage of renewable energy development. Japan, Italy, and Australia have entered the third stage; Only a few European countries have entered the fourth or fifth stage. First, the penetration rate of renewable energy in power systems exceeding 40% has become a reality. The UK, Chile, and Northern Ireland have a renewable energy electricity penetration rate exceeding 30%, while Spain, Germany, and Denmark have a penetration rate exceeding 40%. In some time periods, the proportion of renewable energy output in these countries exceeds 70%, with some even approaching 100%. Second, in some countries and regions, variable renewable energy (VRE) is becoming the main power source for power system operations. Take South Australia as an example: in 2018, the penetration rate of renewable energy electricity was below 50% for approximately half of the year, but by 2023, the penetration rate exceeded 70% for approximately half of the year. Another example is Germany, where in 2018, the penetration rate of renewable energy in the power system was below 30% during most time periods; by 2023, approximately 70% of the time periods saw a penetration rate exceeding 30%. Texas, a U.S. state that operates an island grid larger than Germany's, also achieved 30% wind and solar generation in 2024. It hit an all-time high instantaneous penetration of wind and solar of 75% in 2024.

During the early stages of renewable energy development, only modifications to the existing system or operational optimizations are required. However, when renewable energy reaches a higher level of development, fundamental changes to the power system are necessary. Stages 1 to 3 are considered the early stages of renewable energy development, with relatively minor impacts, and most challenges can be addressed through modifications to the existing system or operational improvements. IEA finds that Stage 3, in which we categorize China today, is also the point where the current system may provide insufficient flexibility to integrate new renewable energy sources. Therefore, on the journey to a high-renewables grid, stage 3 is a critical stage where new market signals and business models are needed to reward flexibility, helping to support the continued evolution into future stages. Stages 4 to 6 are considered the advanced stage, marked by increasing impacts of renewable energy on system operations, and increased need for system flexibility across timescales. Fundamental transformations of the power system are necessary to meet the requirements for safe, economical, and reliable integration of renewable energy.

From a global perspective, high-proportion renewable energy power systems can be broadly categorized into two main types: systems dominated by centralized renewable energy sources and systems dominated by distributed renewable energy sources. Denmark, Texas, and Spain are examples of systems dominated by **centralized renewable energy** sources, characterized by large-scale solar photovoltaic or wind power plants connected to the transmission grid. Typically, these power plants are located far from demand centers. To address congestion issues in these systems and prevent renewable energy generation from being constrained, measures such as strengthening the power grid, increasing interconnection capacity, and implementing power flow control are commonly adopted. Due to their large scale, these renewable energy power plants require system services such as fault ride-through, voltage support, and active power management.

Germany is a system dominated by **distributed renewable energy**, characterized by a large number of small-scale solar photovoltaic or wind power plants distributed across the power system. A common example of a user-side photovoltaic system is a residential rooftop photovoltaic system. The large number of distributed photovoltaic systems of different scales and configurations makes it difficult to monitor and control them. This confirms the findings of this survey: to solve the integration problem of distributed renewable energy sources, priority should be given to flexibility measures on the system side (such as enhancing the peak shaving capacity of conventional power sources, configuring centralized energy storage, and strengthening the distribution grid) rather than relying on distributed photovoltaic systems to provide flexibility themselves.

2.2 Strengthening grid construction and improving grid interconnection are objective requirements for the grid in the context of energy transition

The expansion, renovation, and upgrading of the power grid are crucial to accommodating growing consumption of renewable energy. On the one hand, continuous investment is needed to expand grid scale and support the connection, transmission, and consumption of renewable power. On the other hand, strengthening interconnections among large regional grids enables complementary wind and photovoltaic power generation in different regions, allowing renewable energy to be shared more widely and consumed at a higher proportion. According to an analysis by the International Energy Agency, global annual grid investment must double by 2030 to meet the energy and climate commitments made by countries.

Strengthening grid construction is a common experience among countries aiming to achieve high proportions of renewable energy consumption. The grid serves as an optimized allocation platform for building high-proportion renewable energy power systems. The large-scale interregional transmission and broader mutual support and consumption of renewable energy are objective requirements for grid development during the future period of energy transition toward greener systems. According to IEA statistics, all countries currently in the second stage or beyond of renewable energy development have implemented measures such as increasing grid investment and establishing grid congestion management mechanisms. Additionally, 90% of countries have strengthened intra-regional grid interconnection, highlighting the critical role of grids in promoting high-proportion consumption of renewable energy. Taking Spain as an example, approximately 60% of its wind and solar power installed capacity is connected to the transmission grid, with a focus on centralized development and large-scale grid consumption. To ensure the transmission of renewable energy, Spain has continuously strengthened the construction of its backbone transmission grid in recent years. Between 2005 and 2010, 1,741 kilometers of new 400 kV transmission lines were constructed, accounting for 73.1% of the total length of newly built transmission lines. Currently, Spain leads Europe in transmission capacity, with an average of 189 kilometers of 400 kV lines per million kilowatts of installed capacity, far exceeding the average of approximately 100 kilometers in major European countries.

Achieving greater mutual support and consumption of renewable energy through cross-border transmission channels is an important experience for Denmark and Spain in achieving high proportions of renewable energy consumption. Denmark is the first country in the world to enter the fifth phase of renewable energy grid integration, and its experience provides important reference for high proportions of renewable energy grid integration. Denmark's core approach is to rely on abundant cross-border transmission channels and frequent cross-border power exchanges to achieve efficient consumption of wind and solar energy resources. Denmark's power grid is divided into eastern and western sections: the eastern grid is interconnected with Sweden via AC transmission and belongs to the Nordic Synchronous Grid; the western grid is interconnected with Germany via AC transmission and belongs to the Central European Synchronous Grid. Both sections have cross-border transmission capacities exceeding 6 million kilowatts, equivalent to 1.3 times the country's wind power installed capacity and 1.1 times its peak load. During operation, excess electricity generated from wind power is transmitted to Norway, while during periods of insufficient wind power, hydropower is imported from Norway and Sweden, achieving large-scale wind-hydro complementarity. Cross-border interconnection has thus become a key support for Denmark's integration of renewable energy. By comparison, Spain's power grid is interconnected with France, Portugal, and Morocco through multiple 400 kV, 220 kV, and 132/110 kV transmission lines, forming cross-border transmission capacity. For example, the maximum power exchange capacity between Spain and Portugal reaches 3.1 million kilowatts, achieving basic integrated dispatch; the two 400-kilovolt lines between Spain and Morocco have a capacity of 1.4 million kilowatts; and the total transmission capacity of the lines between Spain and France is 2.8 million kilowatts. Looking ahead, Denmark will continue to strengthen cross-border interconnection while exploring energy storage, sector coupling, and leveraging the complementary nature of solar and wind energy to further enhance system flexibility.

2.3 The dispatch balancing model based on balancing groups enhances the system's capacity to accommodate distributed renewable energy.

Renewable energy generation has fluctuating output characteristics, and integrating renewable energy requires careful system design. Generally, the higher the penetration rate of renewable energy, the greater the demand for system flexibility and the higher the system cost. Germany reduces integration costs through the design of its grid balancing and market mechanisms. The key lies in the bottom-up balancing group mechanism established at the distribution grid level, which prioritizes local balancing.

Germany's bottom-up dispatch balancing model based on balancing groups (also known as "balancing units") has stimulated the improvement of prediction accuracy and the regulatory potential within balancing groups for renewable energy, thereby reducing the system costs associated with renewable energy integration. The German power system adopts a bottom-up dispatch balancing model, where balancing groups serve as the virtual basic balancing units of the power system and also function as self-balancing units. They assume responsibility for balancing by establishing a mechanism that subjects them to penalties or rewards based on the imbalance power quantities assessed by the transmission system operator (TSO). The final imbalance deviation of a balancing group is addressed by the TSO through the operation of a balancing market to mobilize resources, ensuring overall system balance, and settling the imbalance quantities. The balancing group mechanism objectively stimulates the improvement of prediction accuracy and the potential for intra-group regulation of renewable energy sources. To reduce penalty costs, balancing groups need to enhance prediction accuracy, increase flexibility, and improve intra-group balancing control capabilities, thereby reducing system balancing requirements and overall system costs.

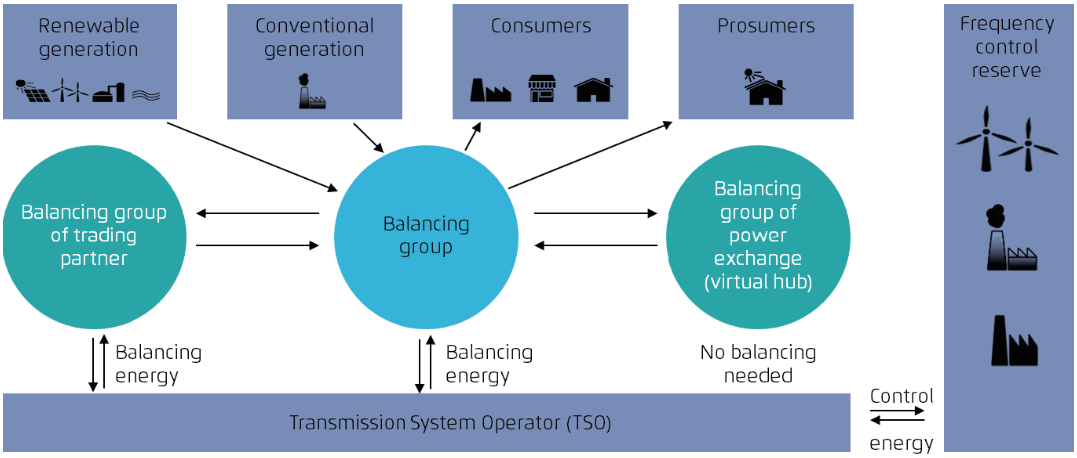


Figure 6 German Balance Group Energy Management [36]

The self-scheduling mode and decentralized market model based on balancing groups have enhanced the system's capacity to accommodate renewable energy. First, this mechanism effectively incentivizes improvements in renewable energy forecasting technology, reducing system balancing errors caused by fluctuations in renewable energy output. In Germany, all renewable energy sources directly participating in the market must be affiliated with a balancing group. Due to the volatility of renewable energy output, the implementation of self-balancing plans becomes more challenging. Therefore, relying on advanced renewable energy forecasting technology to develop accurate and reliable self-balancing plans is a prerequisite for balancing groups to ensure economic benefits. Second, balancing groups have "self-dispatch" flexibility, enabling optimal resource allocation within the group, fully leveraging flexibility potential, and thereby enhancing the system's overall flexibility. Under the balancing group mechanism, grid operators do not directly dispatch power sources but instead adopt the dispatch plans submitted by each balancing group. Compared to grid operators, balancing group managers are more familiar with the resource combinations, operational parameters, and flexibility of resources within their groups. They can leverage "self-dispatch" to tap into flexibility potential, optimize power balance within the group, and reduce balancing costs. Finally, the German electricity spot market designed based on the balancing group mechanism has significantly reduced system frequency regulation demand. Germany has adopted a decentralized electricity market model based on balancing groups. Thanks to improved renewable energy power forecasting accuracy and intra-group balance control capabilities, the spot market has partially replaced some system frequency regulation ancillary service markets, reducing system frequency regulation demand and further enhancing system economic efficiency and stability.

2.4 Integrating grid planning with system flexibility needs

Planning evolutions also support integrated planning of generation, transmission, and distributed energy resources to address the system's need for more flexibility and interprovincial linkages, which help integrate renewable energy. In this practice, generation and transmission are planned together in an iterative fashion to reduce the overall renewable integration costs. Integrated planning can also include different scenarios for customer-sited resources, including VPPs, demand response, and customer solar and storage. The IEA recommends that planning should be open to comment and input from national experts and private industry to improve the quality of the plans.

For example, IEA highlights the Australian Energy Market Operator (AEMO) Integrated System Plan (ISP) as an example of best practice to coordinate transmission and generation planning, especially in a system with high distributed renewables and bulk system renewables together. AEMO's ISP looks out to 2050, the year of its Net Zero goal, and AEMO updates it every two years. With stakeholder input, AEMO developed renewable energy zones for each province and outlined an "optimal development path" for transmission and generation, linking each renewable energy zone with load centers via a nationally coordinated and operated transmission system. It also incorporates forecasts for load growth and distributed energy resources, taking into account local policies and emphasis on distributed energy resource development.

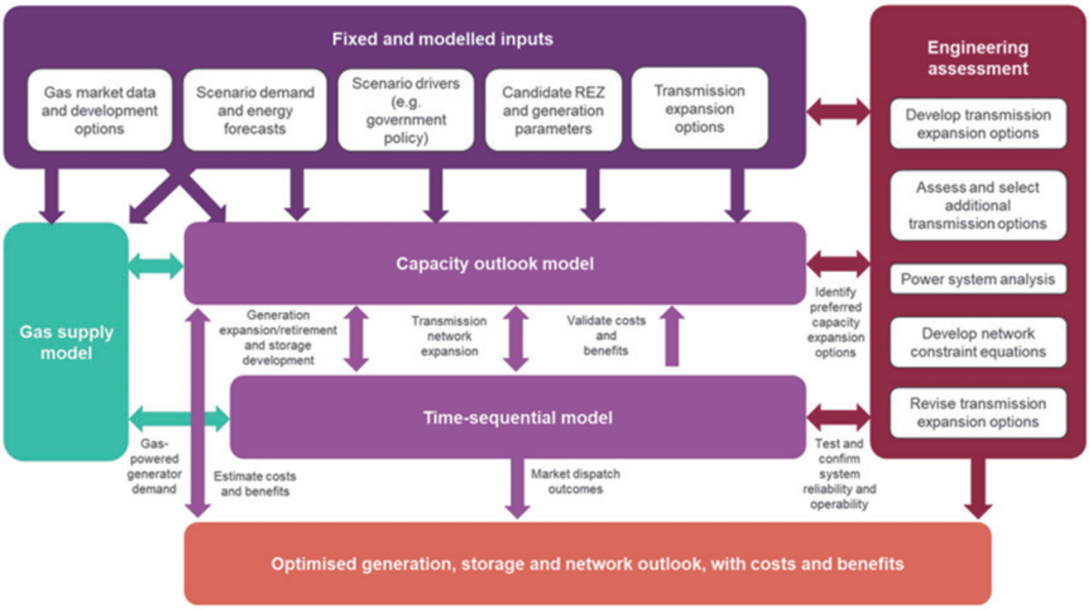


Figure 7 AEMO Integrated System Plan (ISP) modeling methodology

This kind of planning yielded a new insight: Australia could continue to deliver power at a reasonable cost, grow its demand, and maintain system security while rapidly increasing the share of renewable energy to 82 percent by 2030. It also illuminated that the cost of power will shift – while low-cost wind and solar will push down overall generation costs, the cost of grid infrastructure will increase as a share of overall grid expenditures. This national grid plan directs investment in grid infrastructure to bring enough renewables to market to more than double wind and solar penetration in the next five years. By examining different penetrations of renewables in its long-term scenarios, the grid operator was able to get a clear view of what level of ambition was possible and which investments supported multiple technology pathways.

3. China’s grid practices and key focuses in supporting high penetration of renewable energy

3.1 China is a typical power system characterized by centralized development, grid connection, and consumption of renewable energy

China has built a large power grid with strong resource allocation capabilities. China has established a national power grid platform for large-scale optimization of resource allocation, initially forming a grid structure with ultra-high voltage AC and DC transmission systems as the backbone, several regional grids as the main body, and effective interconnection between regions. By the end of 2024, the State Grid Corporation of China had completed 38 ultra-high voltage projects (22 AC and 16 DC), forming the world’s largest ultra-high voltage transmission network. This network has established three major interprovincial and inter-regional transmission corridors for the “West-to-East Power Transmission” initiative, with interprovincial and inter-regional transmission capacity exceeding 350 million kilowatts and cumulative power transmission exceeding 3 trillion kilowatt-hours. The proportion of renewable energy transmitted through national ultra-high voltage DC transmission channels exceeds 55%, enabling the optimized allocation of western clean energy resources on a larger national scale.

The “three-in-one” approach is driving the development and utilization of large-scale wind and solar power bases. Driven by the “dual carbon” goals, in 2021, the National Development and Reform Commission and the National Energy Administration released a planning and layout scheme for large-scale wind and solar power bases. The plan highlights the Kubuqi, Ulan Buh, Tengger, and Badain Jaran deserts as key areas, and envisions that by 2030 China will deploy and build large-scale wind and solar bases in desert, Gobi, and arid regions with a total installed capacity of 455 gigawatts. The large-scale wind and solar power bases centered on the “Sand-Gobi-Waste Land” regions are the focal point for China’s renewable energy development during the 14th Five-Year Plan period and form the foundation for the growth of renewable energy installed capacity. Currently, the first batch of “Sand-Gobi-Waste Land” large-scale wind and solar power bases have been basically completed and put into operation, while the second and third batches are under accelerated construction.

Distributed renewable energy primarily relies on centralized grid connection, step-up transformation, and integration into the main power grid for consumption, while the carrying capacity of the distribution network is insufficient. By the end of 2024, China's wind and solar power grid-connected installed capacity exceeded 1.4 billion kilowatts, with distributed generation accounting for approximately 27% of the total. Distributed power generation is dominated by distributed photovoltaic power, with an installed capacity of 375 gigawatts. China's distributed photovoltaic power generation is primarily grid-connected, with rooftop photovoltaic power generation also mainly achieving full grid connection. Since 2021, the National Energy Administration has introduced policies for county-level photovoltaic pilot projects to promote the development of household distributed photovoltaic power generation. Household photovoltaic power generation is primarily connected to low-voltage 380/220-volt grids. Preliminary statistics show that in regions such as Hebei, Shandong, and Henan, where household PV is the main form, the proportion of households with full grid connection exceeds 80%, with Hebei exceeding 90%. In some regions, the demand for grid connection of distributed PV is increasingly conflicting with the grid's carrying capacity.

3.2 New business models drive innovation in local and on-site consumption of renewable energy

With the development of renewable energy, the relationship between power production and consumption is undergoing profound changes, and new business models are emerging. Technologies and models such as integrated power generation, transmission, consumption, and storage; green power direct supply; vehicle-grid interaction in the transportation sector; photovoltaic storage and direct flexible power supply in the building sector; and green power-based hydrogen production in the chemical industry are being widely promoted. Power users who both consume and produce electricity, known as "prosumers," are emerging vigorously, becoming an important balancing and regulating force in the power system and a key driver for renewable energy development.

To address the challenges of renewable energy development, it is essential to foster new business models and operational paradigms. In the long term, China's electricity demand will continue to grow steadily, with net peak load characteristics becoming increasingly pronounced. The new power system must fully leverage the collaborative regulation capabilities of the demand side. It is necessary to actively cultivate new business models such as virtual power plants, low-carbon industrial parks, and vehicle-grid interaction, and promote the coordinated development of the demand side and supply side through planning, operations, and institutional mechanisms. **First, developing distributed renewable energy requires innovative business models.** Expanding the application scenarios of distributed renewable energy development with local utilization is the primary objective. It is advisable to focus on public buildings, residential communities, large flexible loads, electric vehicle charging stations, and transportation infrastructure along railways and highways, develop new models for the integrated development and utilization of renewable energy across multiple sectors to enhance the scale of renewable energy development and address integration challenges. **Second, enhancing the flexibility of the power grid and achieving supply-demand coordination requires innovative business**

models. Developing new business models to encourage the participation of high-quality regulation resources on the user side, such as distributed battery storage, virtual power plants, electric vehicles, and interruptible loads, in flexible interactions with the power system can greatly stimulate the regulatory potential of the user side and enhance system flexibility.

New business models can enhance the comprehensive regulation capabilities of the power grid. On the one hand, new business models can enhance demand response capabilities. Relying on innovative development models such as virtual power plants, vehicle-grid interaction, and source-grid-load-storage integration, and guided by policy mechanisms such as time-of-use pricing and peak-valley pricing, the flexible and soft development of loads can be promoted to actively adapt to the output characteristics of power sources, accelerating the transition from a “source follows load” to a “source-load interaction” flexible operation mode. By 2030 and 2035, the national demand-side response capacity will be increased to 5% and over 8% of peak load, respectively. **On the other hand, new business models increase regulatory resources, enhancing the large-scale power grid’s ability to accommodate renewable energy.** Preliminary calculations indicate that by 2030, new business models could provide the system with 10,000 megawatts of regulatory resources.

3.3 Developing renewable energy sources and innovative business models require grid transformation

First, the operational coordination mechanisms between large-scale power grids, distribution grids, and microgrids are not yet fully established. Distributed intelligent grids/smart microgrids are integral components of multi-level power grids. The construction and layout of smart microgrids are closely tied to power generation, transmission, and consumption, but in practice, they are not sufficiently integrated with local industrial planning, power generation planning, and grid planning, nor are they adequately integrated with overall power system planning. Coordination mechanisms between multi-subject, multi-form power grids are still inadequate, and safety responsibilities are unclear, which affects the overall integrity, safety, and renewable energy carrying capacity of the power system.

Second, traditional power dispatch models are unable to adapt to the development of new business models. With the increasing number of renewable energy sources, distributed power sources, electrochemical energy storage technologies, and electric vehicles being connected to the grid, the power system’s information sensing capabilities are insufficient. Existing control and regulation technologies cannot achieve comprehensive observability, measurability, controllability, and adjustability (the “four capabilities”), and the control and regulation system management framework is inadequate to meet the requirements of the new development landscape. Second, the current power dispatch mechanism primarily relies on a planned dispatch system centered on conventional power sources, which cannot adapt to the frequent adjustments of transaction plans under a power market environment or the flexible changes of “multi-directional interaction” between power generation, transmission, consumption, and storage under conditions of high renewable energy grid integration.

3.4 Enhancing the distribution grid's capacity to accommodate renewable energy sources and supporting the innovative development of renewable energy

With the advancement of green energy transformation, distributed power sources and new business models are developing rapidly, and the active characteristics of distribution grids are becoming increasingly prominent. Distribution grids are transforming from single power supply and distribution service providers to platforms for the integration and interaction of power generation, transmission, load, and storage, and for efficient resource allocation. They will provide important support for the high-proportion consumption of renewable energy and the safe and stable operation of the power system.

Build a new type of distribution grid that is safe, efficient, clean, low-carbon, flexible, and smart. Focusing on the overall goal of building a new power system that relies mainly on renewable energy, and on the basis of enhancing supply security, promote the transformation of the distribution grid from a traditional "passive" unidirectional radial network to an "active" bidirectional interactive system in terms of form, and from a single power supply and distribution service provider to a platform for the efficient allocation of power generation, grid, load, and storage resources in terms of function. By 2030, the carrying capacity and flexibility of the distribution grid will be significantly enhanced, with the ability to accommodate approximately 100 million kilowatts of distributed renewable energy and approximately 2.4 million charging stations; Achieve multi-level coordination between main, distribution, and micro grids, aggregation and interaction of massive resources, and plug-and-play for diverse users, effectively promoting the integration of distributed smart grids with the main grid, meeting the development needs of distributed power sources, electrochemical energy storage technologies, and various new business models, and advancing the realization of energy green transformation goals through high-level electrification.

Establishing a new active distribution grid dispatch mode with main, distribution, and microgrid coordination. Focus on areas with rapid development of new entities such as distributed renewable energy, user-side energy storage, and electric vehicle charging facilities to explore and apply a new active distribution grid dispatch mode with main, distribution, and microgrid coordination, and encourage other regions to conduct exploration in accordance with local conditions. Improve city and county-level power dispatch mechanisms, strengthen distributed resource control capabilities, and enhance the local balancing capabilities and active support capabilities of distribution grids for the main grid. Establish a source-grid-load-storage coordinated control mechanism, continuously improve the power control mechanism for renewable energy, optimize protection and control strategies in regions with high penetration rates of distributed renewable energy, and enhance the regulation capacity, resource allocation capacity, and self-healing capacity of distribution grids.

3.5 Develop distributed smart grids/smart microgrids to promote renewable energy substitution

Distributed smart grids/smart microgrids are a new type of power production organization that adapts to the local consumption of distributed renewable energy. They are small-scale power generation, distribution, and consumption systems that primarily use renewable energy as their power source, have certain intelligent regulation and self-balancing capabilities, and can operate independently or be connected to the main grid. They strengthen source-grid-load-storage coordinated control and are expected to play a positive role in promoting the local consumption of renewable energy, improving power supply reliability and economic efficiency, and other aspects. Currently, smart microgrids in China are still in the demonstration and pilot stage.

Promote the transition of distributed smart grids/smart microgrids from demonstration projects to widespread application to facilitate the development of distributed renewable energy. Combining renewable energy resource conditions, focusing on typical scenarios such as industrial and commercial parks, residential communities, remote area power supply, critical load power supply security, and vehicle-grid interaction, actively carry out demonstration construction of distributed smart grids/smart microgrids, clarify physical boundaries, reasonably allocate source-load-storage capacities, strengthen autonomous peak regulation and self-balancing capabilities, and achieve compatibility and coexistence with the large power grid and integrated development. Enhance the controllability and adjustability of distributed renewable energy. Leveraging technologies such as flexible regulation of load-side resources, grid-integrated coordination of generation, storage, and consumption, and collaborative operation control, improve the interactive model among multiple elements of generation, storage, and consumption. This will enhance the self-peak regulation and self-balancing capabilities of distributed smart grids/smart microgrids, increase the proportion of renewable energy self-generation and self-consumption, and alleviate the grid integration pressure on the main grid.

Promote cross-sector integration and development of renewable energy in multiple fields through business model innovation. Promote cross-sector integration of renewable energy with industries such as manufacturing, transportation, construction, agriculture, and forestry, and advance in-depth, three-dimensional development of projects like photovoltaic desertification control, photovoltaic corridors, and marine pastures, to form an innovative replacement development pattern characterized by deep integration and sustained substitution. Encourage business model innovations that promote the substitution of renewable energy in multiple varieties, fields, and forms, vigorously develop comprehensive energy services that support efficient coordination between supply and demand, and accelerate the implementation of new business models such as vehicle-grid interaction and electricity-carbon asset management. Support the development and growth of new business entities such as digital energy, virtual power plants, and rural energy cooperatives, and cultivate new business models adapted to the clean, efficient, and safe substitution of energy.

4. Key areas for grid technology innovation to support high-proportion renewable energy development

4.1 Adapting to the trend of grid transformation for high-proportion renewable energy

The new power system presents an overall structure where "large power sources and large grids" and "distributed, small (micro) grids" are compatible and complementary. To achieve higher proportions of renewable energy development, it is essential to pursue both centralized and distributed approaches. On the one hand, considering the need to support large-scale power transmission and consumption from desert, grassland, and wind-rich regions, southwest water-wind-solar energy bases, and offshore wind power bases, the future power system will still primarily consist of AC/DC regionally interconnected large-scale grids. It is necessary to fully leverage the role of large-scale grids as platforms for optimizing resource allocation, promote the innovative development of the next-generation West-to-East Power Transmission initiative, and continuously optimize the main grid structures in various regions around the objective of large-scale power transmission, addressing structural shortcomings and enhancing the safety and load-bearing capacity of large-scale grids. On the other hand, small (micro) grids are close to end users and serve as key carriers for promoting distributed development and local consumption of renewable energy, complementing and coexisting with "large power sources and large grids." Large grids must become an important support for the development of smart distribution grids, distributed intelligent grids, and microgrids.

4.2 Technological innovation trends for power grids with higher proportions of renewable energy sources

As renewable energy development enters its fifth and sixth stages, power systems with extremely high penetration rates of renewable energy will not only need to address issues similar to those encountered in previous stages, but will also face new technical and economic challenges. As fluctuating renewable energy sources become the mainstay of power systems, higher requirements will be placed on grid stability and flexibility, and in-depth reforms will be required in power system operation, planning, and financing.

First, power system safety and stability operation technology. Break through key technologies in the field of power system safety and stability operation. Develop power system simulation analysis and safe and efficient operation technologies, dynamic process simulation technologies for power systems with large-scale renewable energy integration, and other technologies to enhance the analytical understanding of new power systems centered on simulation. Conduct research on wide-frequency oscillation analysis and suppression technologies, key technologies for the operation of DC power grid systems, and stable operation control technologies for power grids with high proportions of renewable energy and power electronics equipment, to improve the safety and stability of power system operation. Promote research on online prevention and control technologies for power system safety and stability risks, construction technologies for comprehensive defense systems for new power systems, and identification and prevention technologies for unconventional safety risks in power systems to enhance the power system's safety, stability, defense, and emergency response capabilities.

Second, new transmission technologies. Focusing on adapting to higher proportions of renewable energy sources, promote research on the application of high-voltage, large-capacity flexible direct current and flexible alternating current transmission technologies. Focus on developing ultra-high voltage flexible direct current technologies, multi-terminal ultra-high voltage flexible direct current technologies, flexible direct current grid networking technologies, and controllable grid phase-changing and current-changing technologies suitable for large-scale renewable energy transmission. In the medium to long term, further breakthroughs will be made in low-frequency transmission and superconducting direct current transmission technologies. Strengthen innovative research into disruptive technologies such as wireless power transmission.

Third, distribution network technology. Focusing on responding to the gradual increase in the penetration rate of distributed power sources, we will promote key technologies for the coordinated operation and control of medium- and low-voltage distribution networks, distributed power generation coordination and optimization technology, distributed power source grid connection and voltage coordination control technology, and the development of low-cost, high-efficiency, low-voltage flexible equipment. This will enable the orderly connection of large-scale distributed power sources to the distribution network, flexible grid connection, and coordinated optimization of multiple energy sources, thereby improving the operational efficiency of distribution networks and enhancing their load-carrying capacity.

Fourth, intelligent dispatch technology. Innovate new active distribution grid dispatch models. Focus on regions where new entities such as distributed renewable energy, user-side energy storage, and electric vehicle charging facilities are developing rapidly, and explore the application of new active distribution grid dispatch models based on the coordination of main, distribution, and microgrids. Encourage other regions to conduct exploratory work in a manner suited to local conditions. By improving municipal and county-level power dispatch mechanisms, strengthen the control capabilities over distributed resources, enhance the local balancing capabilities at the distribution grid level, and improve the active support capabilities for the main grid.

5. Policy Recommendations

To facilitate renewable energy becoming the primary power source and the main contributor to new electricity generation, focus on coordination between the bulk power grid, distribution grid, and emerging microgrids. Explore innovative power dispatch models that continuously enhance the grid's capacity to accommodate renewable energy, and promote the transformation of renewable energy production and supply from centralized development and large-scale unified transmission and distribution to a balanced approach between regional self-balancing and cross-regional optimized allocation. This work should proceed quickly - by 2030, the proportion of renewable energy installed capacity will exceed 60%, and the proportion of renewable energy electricity generation will exceed 35%.

This work can further focus in three priority areas:

(1) Leverage the role of large-scale power grids in optimizing resource allocation, promote the quality upgrading and healthy development of the main grid structure, and support the efficient development and utilization of high proportions of renewable energy.

Balance national-level resource optimization and grid rational zoning, strengthen inter-provincial and inter-regional power transmission channels, enhance power resource optimization capabilities, and principally prioritize the transmission of clean energy power. Strengthen AC grids at both sending and receiving ends and address grid weaknesses. Scientifically optimize corridor design plans, strengthen risk control of dense transmission channels, and meet the requirements for safe and stable operation of the system. Combine new transmission technologies to promote the flexible construction and transformation of DC transmission, optimize the grid structure, and form a main grid structure that is layered, zoned, flexible, and adaptable. Promote the transmission of large-scale, high-proportion renewable energy. Focus on the development and transmission of electricity from the “desert, grassland, and wasteland” bases in the northwest region and the integrated water, wind, and solar energy bases in the major river basins of the southwest region. This should be achieved by reasonably configuring the types and scales of power sources at the sending end, optimizing power system connection schemes, and adopting power source integrated coordinated control, flexible DC transmission, Self-adaptive STATCOM and Line Commutation Converter (SLCC), low-frequency transmission, and grid-forming technologies, and reasonably deploy reactive power compensation and energy-saving devices to enhance the safe and stable operation and flexible control of transmission channels. Increase the proportion of green electricity transmitted through these channels and explore pure renewable energy transmission methods to promote the higher proportion of renewable energy transmission and consumption.

(2) Enhance the carrying capacity of distribution grids to support the development of renewable energy and new business models.

First, **meet the grid connection demands of large-scale distributed renewable energy sources**. In line with distributed renewable energy development goals, strengthen distribution grid construction in a targeted manner, improve grid stability measures, and ensure power quality. Coordinate distribution grid capacity, load growth, and regulation resources, conduct systematic analyses of the impact of renewable energy grid connection, assess distribution grid carrying capacity, establish a mechanism for publishing and warning about the scale of renewable energy that can be accommodated, and guide the scientific layout, orderly development, nearby connection, and local consumption of distributed renewable energy sources. **Second**, **meet the electricity demand of new types of loads** such as large-scale electric vehicles. Conduct analysis of electric vehicle charging load density under different scenarios, establish an information release mechanism for the capacity of electric vehicle charging facilities that can be connected to the distribution grid, and guide the reasonable layered connection of charging facilities to the medium and low-voltage distribution grid. Strengthen analysis of two-way interaction and condition matching, scientifically coordinate the layout of charging facility sites and distribution grid construction and renovation projects, and help build an electric vehicle charging infrastructure network with a city-wide layout, a highway-based layout, and a rural point-based layout. Combine load characteristic analysis with the orderly arrangement of distribution grid upgrades and renovations to meet the electricity demand of electric heating, electric boilers, port shore power, and other electricity substitution facilities. **Third, support the healthy development of new power system business models**. Tap into the potential for user-side regulation, encourage the innovative development of new business models such as virtual power plants, load aggregators, and vehicle-grid interaction, and improve system response speed and regulation capabilities.

(3) Accelerate the transformation of renewable energy supply and consumption models through innovating the balance mechanism of the power systems and improving the trading mechanism of the power markets.

First, establish a renewable energy development and utilization mechanism and grid development model oriented toward green and low-carbon development. Promote the shift in clean energy production and supply from the past model of centralized development and large-scale unified transmission and distribution to a balanced approach that emphasizes both regional self-balancing and cross-regional optimized allocation. Coordinate grid, supply, and demand-side planning to gradually form an energy production and supply pattern in which clean and low-carbon energy sources are prioritized to meet energy demand and continuously replace existing fossil energy sources. **Second, explore bottom-up dispatch balancing mechanisms** to enhance the local self-balancing capacity of distribution grids, and gradually construct a new active distribution grid dispatch model featuring coordination among the main grid, distribution grid, and microgrid, enabling the distribution grid to serve as an efficient resource allocation platform for power generation, transmission, consumption, and storage. **Third, explore the establishment of a decentralized power market model** based on a balancing group mechanism. Through market-based deviation responsibility and complementary mechanisms, encourage distributed power sources, users, and energy storage entities to achieve self-balancing within groups, thereby reducing the system’s overall demand for flexibility and the costs associated with integrating flexible resources.

IV. Research on energy storage technologies and business models supporting the development of renewable energy

In the previous chapter, we explored technologies, practices, and mechanisms to integrate renewable energy into the power system. We characterized many of the challenges in high-renewable electricity systems, including mismatches between supply and demand, low infrastructure utilization, and system stability. Abundant, low-cost, intelligent storage can be a primary solution to many of these challenges.

In the past, technologies to store electricity were considered too costly a solution for renewable integration at scale, outside of some geographically specific pumped hydro facilities. But the cost of battery electric storage in particular has fallen dramatically in recent years, opening up the frontier for greater cost-effective integration of renewables. In parallel, power electronics have enabled these resources to provide support for system stability, compensating for renewable intermittency. Low-cost storage also opens up possibilities to better optimize transmission and distribution infrastructure, reducing overall infrastructure costs while integrating renewable energy resources. Aligning incentives between system actors and storage operators will be essential to achieving this potential. In this chapter, we explore use cases, technologies, and mechanisms that can promote development of the most valuable applications of energy storage in the near- and long-term, drawing on international experiences.

1. Characteristics of energy storage demand in high-penetration renewable energy power systems and the functional positioning of energy storage

1.1 Types of Energy Storage Technologies and Their Characteristics

Energy storage encompasses multiple technical types, each with distinct characteristics. Based on the storage medium, it can be categorized into electrical energy storage, thermal (cold) energy storage, gaseous energy storage, and hydrogen energy storage. Based on the material form of the energy storage medium, it can be classified into mechanical energy storage (pumped-storage hydroelectricity, compressed air energy storage), electrochemical energy storage (including lithium-ion batteries), electromagnetic energy storage, and physical and chemical thermal energy storage. Based on time scales, energy storage can be classified into short-duration energy storage (seconds to minutes), medium-term energy storage (hours to days), and long-term energy storage (days to seasons). Electrochemical energy storage technology features low cost, fast response times, precise regulation, and the ability to continuously regulate both active and reactive power. Within its rated power range, it has no depth regulation limitations. Additionally, it offers advantages such as flexible site selection and configuration, as well as short construction cycles.

Energy Storage Type	Energy Storage Medium/Form	Notes
Mechanical Energy Storage	Pumped-hydro storage, compressed air energy storage, flywheel energy storage, gravity energy storage	–
Electrochemical Energy Storage	Lithium-ion batteries, flow batteries, lead–carbon batteries, sodium-ion batteries, sodium–sulfur batteries, supercapacitors, hydrogen storage (fuel cell-based)	–
Electromagnetic Energy Storage	Superconducting magnetic energy storage (SMES), high-power capacitor storage	–
Thermal Energy Storage (Physical & Chemical)	Physical phase-change thermal storage, chemical thermal storage, hydrogen-based thermal storage	Carnot battery

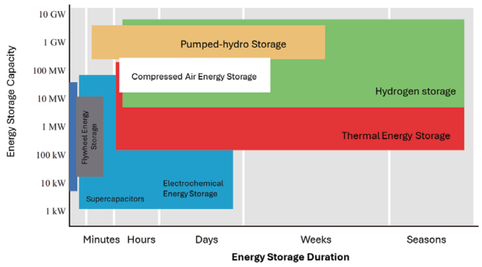


Figure 8 Types and Characteristics of Energy Storage Technologies

1.2 Functional positioning of energy storage in high-penetration renewable energy power systems

Storage provides essential services that complement high-renewable power systems. Electricity demand is inherently variable, within seconds due to random consumer decisions or electronic failures, days following daily consumption patterns, and seasons following responses to weather for example. Renewable power is also inherently variable, as discussed in Chapter 3. As grids go through IEA's phases of renewable integration, the need for flexibility (the ability to control output or demand to balance the system across timescales) increases. Further, as thermal generators are withdrawn from the system, these are important sources of flexibility that may be lost. Consequently, as the proportion of renewable energy increases, additional flexibility-in the form of energy storage-is needed to produce a reliable power supply during times of high net load (high loads and/or low renewable production) and avoid curtailment of renewable energy during times of low net loads.

Energy storage has become a new element in the new power system. The structure of the power system is evolving from a three-element system ("generation, transmission, and load") to a four-element system ("generation, transmission, load, and storage"). To address the system balancing issues caused by the intermittency and seasonal variation of renewable energy generation, it is necessary to promote the large-scale application of multi-time-scale energy storage technologies, with the system structure gradually evolving from a three-element system to a four-element system.

Electrochemical energy storage can provide several essential services for high-proportion renewable power systems. First, it ensures grid stability. This primarily addresses risks arising from the high degree of power electronics in high-proportion renewable energy power systems and the resulting decline in system disturbance resistance, requiring energy storage with millisecond-level response capabilities. **Second, it promotes renewable energy consumption**. This primarily addresses the need to meet the intraday regulation requirements of systems with large shares of renewable energy, particularly photovoltaic power, by configuring energy storage with intraday regulation capabilities. **Third, it ensures power supply security**. This primarily addresses power shortages caused by extreme weather and inaccurate power forecasts for renewable energy sources exceeding several days, requiring energy storage with the ability to regulate power over extended time scales such as cross-day or longer periods. **Fourth, it can serve peak loads.** Storage with several hours of duration can charge during off-peak times and produce power on-peak, reducing the need to build and operate thermal power plants. Storage has already proven competitive with thermal power plants for the first two roles, and may become competitive for the third and fourth role in the future.

The rest of this subsection gives more detail on the services needed in high-proportion renewable power systems and how it may be important for electrochemical storage to serve these needs.

Diurnal balancing and daily peak service are key requirements for high-renewable systems, both because the renewable source adds diurnal variability (the daily solar cycle) and because many thermal plants, especially coal and nuclear, are poorly suited to cycle on that timescale. Their slow startup and high minimum-load requirements (Table 1) make it difficult to have enough capacity online to serve the evening net-load peak while still operating at low enough output during the day to absorb available renewable generation. Electrochemical batteries are uniquely capable of storing midday solar energy-especially when it exceeds daytime demand-and releasing it to serve evening loads. Without storage, operators must either run expensive gas turbines during the peak or keep coal units online all day to ensure capacity for the evening. Both options raise costs and emissions: part-loaded coal plants operate less efficiently, daily cycling increases maintenance burdens, and high minimum-load levels force excess fossil generation to run, crowding out renewables and leading to curtailment. Batteries can resolve these issues by charging on renewable power during the day and discharging through the evening peak, which reduces the coal capacity that must be committed and allows those units to operate more steadily and efficiently. This role is typically served by storage with a duration of 3–6 hours.

Ramping. In IEA Stage 3 and higher of renewable energy adoption, keeping the system balanced during this time requires rapidly ramping flexible resources. Older coal plants may have difficulty providing this rapid

Table 1 Power System Flexibility Conditions and Support Capabilities

Flexibility Resource	Output Range	Ramp Rate	Start-up Time	Regulation Time Scale	Inertia Support	Voltage Support
Thermal Power Units (with retrofits for flexibility)	30% ~ 100%	3–6% (Pn/min)	4–5 h	Seasonal, Intra-day	Yes	Yes
Gas Turbines	20% ~ 100%	8–10% (Pn/min)	2 h	Seasonal, Intra-day	Yes	Yes
Hydropower Units	0 ~ 100%	20% (Pn/min)	< 1 h	Intra-day	Yes	Yes
Pumped Storage	-100% ~ 100%	10–50% (Pn/min)	15 min	Intra-day	Yes	Yes
Demand Response	-	-	< 200 ms	Intra-day	No	Limited (via load control)
Electrochemical Storage	-100% ~ 100%	100% (Pn / 200 ms)	milliseconds	Intra-day	Grid-forming available	Yes

ramp, so meeting this need with these plants may require committing more capacity than needed even for the peak in net load later in the evening, in order to have enough ramping capability for this critical period. This causes high capital costs and high emissions due to running capacity at low utilization rates all day in order to be ready for the evening ramp. Other conventional options for ramping service include electrochemical energy storage, natural gas turbines, high-flexibility coal plants or hydroelectric plants. However, the cost of electrochemical energy storage regulation is higher than that of coal-fired power flexibility transformation and pumped storage, and the flexible regulation capability of coal-fired power still needs to be further strengthened. In the future, coal-fired power plants will evolve into energy storage facilities, which necessitates the coupling of coal-fired power with long-duration energy storage to enhance the flexibility of coal-fired power units for peak regulation and the absorption of renewable energy into grids. Battery storage is ideally suited to this service, since it can ramp very rapidly without creating extra maintenance needs, fuel costs or emissions. BESS can be especially well suited if used for both ramping and evening peak service.

System Peak. Short-duration energy storage (3-8 hours) can be effective at lowering the system net peak in all IEA stages. In stages 3-4, short-duration storage would generally charge from renewable sources, even on the peak day for net demand, then contribute to the net peak in the evening. In stages 5–6, challenges can arise where the net peak is caused by low wind and solar power production on certain days. On these days, long-duration storage (12 hours to seasons) could be very valuable to get through these difficult days without any emissions. However, long-duration storage such as hydrogen hasn't yet shown itself to be cost-effective for this purpose. Until then, it can be cost-effective to use thermal power plants for backup on these key days. In these cases, short-duration storage can also be useful for serving the net peak, similar to stages 1–2: it can charge from spare thermal capacity during off-peak times on the difficult days, and then deliver power to help serve the annual peak later in the day. This has the additional advantage of enabling thermal plants to run at a steadier level all day on these difficult days, rather than being cycled on for only a few hours for the critical peak. This can better match their slow startup and shutdown times, improve efficiency and reduce maintenance requirements for system peak service.

At shorter time scales, **frequency control and inertia** are also critical requirements for high-renewable power systems.[1] These services can be provided either by storage already deployed for diurnal balancing (an increasingly common trend)[2] or by shorter-duration storage built specifically for this purpose, possibly with a duration of two hours or less[3]. As renewable penetration increases, the need for fast frequency response becomes more pressing, since fewer synchronous machines remain online to provide inertia. Traditionally, thermal plants have been kept running at part load to supply these services, but this practice raises costs and emissions. In contrast, storage can deliver frequency regulation and synthetic inertia with minimal operating cost and without additional emissions, making it an essential component of reliable high-renewable systems. Tapping into these capabilities requires suitable interconnection standards and the use of grid-forming

1 https://docs.nrel.gov/docs/fy24osti/90256.pdf

2 https://www.caiso.com/documents/2024-special-report-on-battery-storage-may-29-2025.pdf

3 https://modoenergy.com/research/ercot-battery-energy-storage-system-august-2023-revenues-ancillary-services-ecrs-arbitrage

inverters, which can provide frequency control and synthetic inertia as part of their core functions. This differs from conventional synchronous generators, which supply inertia inherently as a physical property of their rotating mass. Synchronous condensers are another option, and there is also potential for dual-mode thermal plants to run as synchronous condensers most of the year while occasionally switching to conventional generation to help serve seasonal or inter-annual peaks.

In the **transmission and distribution system**, BESS technologies can enhance the regulatory capacity of power systems at three levels: power generation, transmission, and consumption. **First, energy storage at the power generation side**. By deploying energy storage systems at renewable energy power plants, the support capacity of renewable energy for the grid and its grid-connection safety performance can be enhanced. Services at this level include storing surplus power and delivering it later (improving the utilization rate of renewable energy interconnections), and maintaining voltage stability in the network. **Second, grid-side energy storage.** At critical grid nodes, optimize the layout of independent energy storage systems based on system operation requirements to better perform peak shaving, frequency regulation, and peak load balancing functions on a region-wide basis. In remote areas and regions with limited transmission and transformation station sites, constructing grid-side energy storage systems can replace transmission and transformation facilities. **Third, electrochemical energy storage at the user side.** Configure user-side energy storage based on the source-grid-load-storage integration model at end users such as big data centers, 5G base stations, and industrial parks to improve power supply reliability, local consumption capacity of distributed renewable energy sources, and load factor presented to the grid. In addition, energy storage facilities such as uninterruptible power supplies and electric vehicles at the user side can participate in power system regulation through various means such as orderly charging, vehicle-grid interaction, and battery swapping to enhance the flexible regulation capacity at the user side.

Electrochemical storage technologies will gradually become an important source of regulatory resources in high-proportion renewable energy power systems. Power system regulatory resources primarily include conventional hydropower, coal-fired power plant flexibility upgrades, gas-fired peak shaving, pumped-hydro storage, electrochemical energy storage, and demand-side response**.** Demand-side resources such as energy storage and interruptible loads serve as flexible resources with fast response times and good economic viability. However, in high-renewable power systems, traditional power generation sources have low equipment utilization hours and poor power generation economics. Additionally, with the advancement of the energy transition, the scale of new traditional power generation capacity will be limited. Looking ahead, electrochemical energy storage will become an important source of system regulation resources.

As the proportion of renewable energy sources increases, the flexibility requirements of power systems are undergoing new changes, shifting from intraday peak shaving to longer-term energy transfer needs. We preliminarily judge that: In the near to medium term, the primary demand will be for intraday peak shaving and rapid ramp-up; in the medium to long term, peak supply guarantee demand will rise; and in the long term, under very high renewable energy penetration rates, long-term electricity regulation demand across weeks, seasons, and years will become prominent.

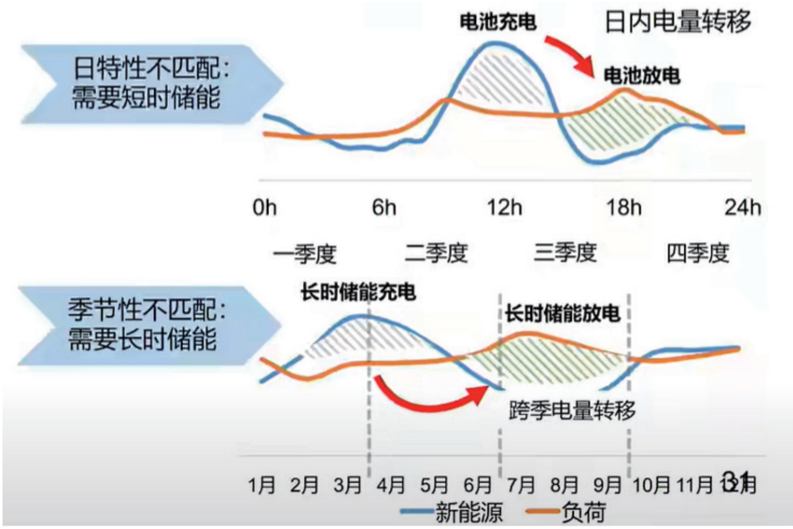


Figure 9 Multi-timescale energy storage regulation

2. International Practices and Experiences in Supporting High Proportion of Renewable Energy Development through Energy Storage

2.1 Energy Storage Requirements for High-Proportion Renewable Energy Power Systems

Energy storage is a critical source of flexibility for high-penetration renewable energy power systems, capable of meeting flexibility requirements across different time scales. The flexibility of power systems is critical for successfully integrating variable power sources such as wind and solar power. It is typically defined as the ability of a power system to achieve balance between power supply and demand across different time scales, including ultra-short-term (seconds), short-term (minutes), intra-day (hours), inter-day, inter-week, and inter-seasonal scales. Increasing penetration of renewable energy can heighten flexibility demands across all time scales.

Power system regulation resources primarily include conventional hydropower, flexibility upgrades of coal-fired power plants, gas-fired peak shaving, pumped-hydro storage, electrochemical energy storage technologies, and demand-side response such as interruptible loads. Energy storage and interruptible loads offer rapid response times and cost-effectiveness. Energy storage systems with different storage durations can address flexibility requirements across various time scales.

The higher the penetration rate of solar energy, the higher the proportion of energy storage in the system's flexible resources, and the greater the system's demand for long-term energy storage. First, as the penetration rate of renewable energy increases, the proportion of energy storage in the system's flexible resources also increases. According to research by the International Energy Agency (IEA), preliminary calculations show that when the share of variable renewable energy (VRE) reaches 15%, energy storage accounts for less than one-tenth of the regulatory resources. However, as the VRE share gradually increases to 40%, the proportion of energy storage significantly rises, reaching approximately one-third. Second, as the penetration rate of renewable energy increases, long-term flexible demand begins to emerge. Recent research on decarbonization options for the United States [37] found that the optimal amount of battery capacity in U.S. power systems (MW) would be roughly equal to the average output from solar power in the system, e.g., if average solar production is around 1,000 MW (corresponding to around 4,000 MW of nameplate solar capacity), then the optimal amount of battery storage is around 1,000 MW. The dependence on wind power is much weaker: around 85 MW of batteries for 1,000 MW of average wind output (corresponding to around 2,600 MW nameplate capacity). The optimal *duration* for storage (MWh per MW of storage) also depends on the penetration of solar: it starts around 1 hour with no solar and rises by about 0.76 hours for every 10% increase in solar penetration. So, in system with 40% solar penetration, the optimal battery duration would be about 4 hours. The dependence of battery duration on wind penetration is likely because wind often varies over multiple days or weeks rather than hours, a duty cycle for which lithium-ion batteries providing 3-6 hour storage are not well suited. This study included hydrogen as an option for seasonal balancing, but it was not selected by the optimizer due to high costs; thermal resources were used instead. This study ignored the typical operating range for BESS of 20% to 80% state of charge, so it likely underestimates the optimal duration. Optimal amounts and durations may also vary in regions with different relative costs of storage, renewable and thermal generators.

Before 2030, most countries worldwide will primarily face intraday flexibility demand. **Countries with higher renewable energy penetration rates or significant heating and cooling electricity demand will also face seasonal flexibility demand**. These demands exist today, but according to IEA research, under scenarios where countries achieve their announced climate and energy targets (i.e., the announced commitment scenarios), global flexibility demand will generally increase. By 2030, short-term flexibility demand (i.e., intraday flexibility demand) will nearly double compared to current levels, with photovoltaic power generation being the primary driver of flexibility demand; long-term flexibility demand (seasonal flexibility demand) will grow at a relatively slower pace, primarily driven by countries with higher renewable energy penetration rates and those adopting electric heating and cooling systems, which will face increased seasonal flexibility demand.

2.2 International Electrochemical Storage Support Policies

Several countries and regions have recognized the important role of electrochemical storage in the development of high-proportion renewable power systems and adopted policies to support deployment of this technology.

Policies that encourage deployment of renewable energy, especially solar power, or that restrict emissions from the power system, create conditions that favor deployment of storage. As more renewable power is adopted, particularly solar, the system begins to see low net load during the day and higher load at night. In efficiently run spot markets, this drives down daytime power prices relative to nighttime prices, allowing storage to earn revenues by arbitraging these differences. Clean energy targets or mandates, renewable energy subsidies or carbon prices expand these price differences further. Carbon pricing also raises the cost of using fossil power plants to provide reserves, making electrochemical storage more competitive to provide this service.

Subsidies for investment in battery energy storage systems (BESS) have been adopted in several countries. In the **United States**, the Inflation Reduction Act of 2022 provided a transferrable 30 percent investment tax credit that will last until 2032. **India** adopted the Viability Gap Funding (VGF) Scheme in 2023 to help meet an estimated need for 236 GWh of BESS by 2031–32 [38]. The subsidies per unit of capacity have been reduced and the program size expanded as the cost of batteries fell. The first tranche initially offered ₹9.6 (¥0.78) per Wh for up to 4 GWh. This was subsequently revised to ₹4.6 (¥0.37) per Wh or 30% of project costs, whichever was lower, to support up to 13.200 GWh. A second tranche was introduced in June 2025, providing ₹1.8 (¥0.15) per Wh regardless of project costs, for up to 30 GWh of BESS [39]. In December 2024, **Spain** allocated €150 million of EU funds to support deployment of 2.82 GWh of BESS (¥0.44 / Wh) [40]. In January 2025, **Japan**'s METI program allocated 34.6 billion yen (¥1.67 billion) to support 27 grid-scale BESS projects [41]. Total capacity was not reported, but reports indicate two of them received 325 million yen for 15.66 MWh of capacity (¥1.0 / Wh) [42].

Capacity accreditation and access to capacity and ancillary service markets have been important drivers of BESS adoption in many regions. These are negative-cost strategies, since they simply ensure that least-cost resources are selected to provide peak-serving capacity or spinning reserves. However, they are an essential complement to other support measures for BESS: support measures or subsidies make BESS more competitive, but power systems will not adopt BESS if it is not allowed to compete to provide these services. Market access has been essential for storage to continue to grow. In the **United States**, FERC Order 755 in 2011 mandated technology-neutral capacity + performance payments for BESS, catalyzing early storage revenues. Later FERC Orders 841 (2018) and 2222 (2020) required regional grid operators to remove barriers for storage and aggregated DERs in energy, ancillary services and capacity markets. In the **United Kingdom**, the National Energy System Operator (NESO) designed new fast-frequency response markets (Dynamic Containment, Regulation and Moderation) to be technology-neutral, in part to take advantage of how well BESS are suited to these tasks [43]. **Ireland** [44] and **Texas (U.S.)** [45] also adopted explicit, technology-neutral ancillary services tariffs that led to rapid utility-scale BESS additions. **Chile's** Law 21505 (2022) recognizes BESS and solar + BESS systems as generators, allowing them to receive payments for adequacy, dispatch, and ancillary services. **EU** regulations require all member states to conduct national Flexibility Needs Assessments using EU-harmonized methodology and account for non-fossil sources of flexibility, including energy storage. Capacity mechanisms must also be technology-neutral and inclusive of non-fossil options, including storage and demand response.

Preferential procurements for storage are a hybrid of market-opening policies and explicit support for BESS, typically consisting of capacity procurement mechanisms that are restricted to low- or zero-carbon resources, or sometimes BESS specifically. Examples include Ontario, **Canada**'s Long-Term 1 Request for Proposals in Ontario (2.2 GW), **Japan**'s Long-Term Decarbonization Power Source Auctions (1.3 GW). In the **European Union**, all capacity markets now have this form, since EU Regulation 2019/943 effectively prevents coal power from receiving capacity payments [46]. EU Regulation 2024/1747 also focuses on the need for non-carbon flexibility options in high-renewable power systems and states that if standard capacity mechanisms are insufficient to meet flexibility needs, member states may apply targeted support schemes for flexible capacity from storage or other clean resources. In this spirit, **France** has a long-term tender program (AOLT) that provides long-term contracts to low-carbon assets, including BESS, that are considered important for resource adequacy. **California** (U.S.) utility regulators have effectively signaled that they will not approve acquisitions of new coal or gas power, in light of the state's requirement to reach 100% clean electricity by 2045. At times, they have also issued orders requiring load-serving entities to specific amounts of "preferred resources", defined as distributed energy resources, renewables, and zero-emitting sources. **New York State** (U.S.) is using a BESS-specific "Index Storage Credit" auction to procure 3 GW of utility-scale resources toward the state's overall target of 6 GW of BESS by 2030. This mechanism will pay winning facilities the difference between a reference price (tied to potential spot market revenues for a standard 4-hour battery) and the required annual payment that they bid into the auction. The mechanism mainly targets 4-hour batteries, but also has duration carve-outs requiring at least 20% of winners to have more than 8 hours of storage, and allowing up to 10% of winners to have 2 hours. 3. Electrochemical Storage Application Examples

Energy storage is driving the continued rapid growth of solar power generation in California, USA. The application of energy storage enables greater utilization of solar power during midday hours while reducing reliance on natural gas and imported electricity during evening peaks. From 2018 to 2025, California's electrochemical large-scale energy storage capacity increased from a few hundred MW to 13,200 MW. The use of energy storage has significantly reduced natural gas-fired power generation within the state (with output dropping to nearly zero during certain periods). Additionally, the deployment of 2,500 MW of customer-sited energy storage helps shift midday solar power generation to nighttime use. Between 2021 to 2025, California's wind and solar power curtailment rates were between 3.1%–5.2%. If power had been curtailed instead of being stored, the annual curtailment rate during the same period would have reached 5.1%–18.4%. Energy storage development in California is driven by a combination of policy support, market opportunities and a planning process focused on least-cost procurement of power and reserves. The state has set ambitious energy transition targets, requiring that 45% of electricity be zero-carbon by 2030 and 100% by 2045.The U.S. federal government provides an investment tax credit covering approximately 30% of the initial cost of installing energy storage systems and California offers additional subsidies covering the rest of the cost of residential energy storage systems for a limited number of low-income customers. Carbon trading has also raised the cost of using natural gas during off-peak hours. In this context, long-term, least-cost plans by utilities, coordinated by the California Public Utilities Commission, have led to rapid procurement of wind energy, solar energy and short-duration energy storage systems. From a business model perspective, energy storage primarily generates returns for its owners through long-term bilateral contracts with load serving entities (LSEs)-regional utilities or community aggregators. LSEs in turn use storage as part of a portfolio of resources to meet customer demand, and recover the costs via a combination of customer bills and spot market participation.

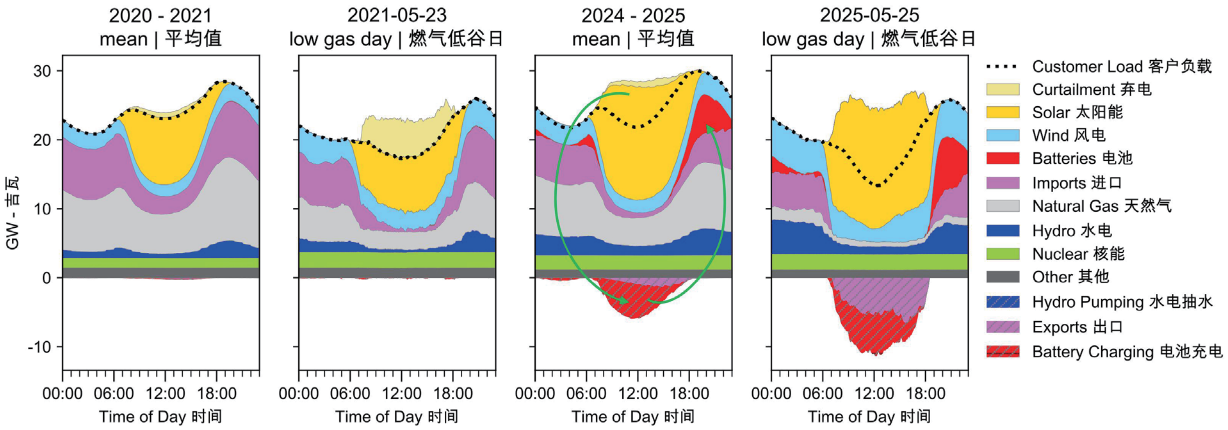


Figure 10 Electricity generation in California and electricity generation on average days and natural gas low-demand days for the periods 2020-07 – 2021-06 and 2024-07 – 2025-06

Scottish energy storage projects support the development of offshore wind power in the UK. The construction of the Blackhillock independent energy storage power station in Scotland has played a crucial role in facilitating the transmission and consumption of local offshore wind power. The northern coast of Scotland is rich in offshore wind resources, with developed wind farms sometimes exceeding local electricity demand. However, the region's weak grid infrastructure faces challenges in power transmission, leading to frequent curtailment of wind power generation due to transmission constraints or stability limitations. The commissioning of the independent energy storage power station not only resolves the transmission and integration of offshore wind power but also provides effective support for the stable operation of the power system. This energy storage power station project offers dual benefits. On one hand, through energy storage, it minimizes curtailment of wind power generation. On the other hand, by adopting advanced inverter technology, it provides inertia and voltage support, enhancing grid reliability and reducing the need for traditional power plants to operate. The plant proved its worth just 11 days after it was commissioned, when it helped stabilize the grid after a nearby 1.9 GW thermal plant suddenly tripped offline [47]. Through the market, the project can achieve multiple benefits. In the UK, independent energy storage power plants can generate revenue from frequency response services, balancing market revenue, peak-off-peak price differentials, and capacity revenue, ensuring reasonable returns for energy storage power plants.

The Australian Community Battery Program complements the development of rooftop solar power. The Australian Community Shared Battery Program has achieved a win-win outcome. It provides community-shared energy storage, which reduces peak grid demand, lowers electricity bills for users during peak hours, effectively minimizes midday solar power curtailment, and enhances the reliability of community power supply. Australia leads the world in residential solar PV adoption, with one in three households having installed a solar PV system. Community energy storage systems typically range from 100 to 200 kilowatts, with storage durations of 2 to 4 hours, primarily serving several dozen nearby households with residential solar PV systems. During the day, excess solar power generated by users is stored in community batteries, which then supply electricity to these households or their neighbors at night, thereby reducing electricity bills. At the same time, community batteries help grid operators smooth peak demand, delay grid upgrades, improve local reliability and power quality, and avoid the need for users to install smaller, more expensive batteries. The community battery program is a highly effective business model innovation, essentially a shared energy storage solution. Currently, two models are being piloted in Australia. In both cases, the grid operator or electricity retailer invests in and builds community batteries. In the first model, rooftop solar users can use the battery for free and also receive electricity credits for stored energy, while the grid operator benefits by delaying grid investments and reducing flexibility costs. In the second model, participants in the program receive the standard feed-in tariff for solar power, but can purchase electricity from the community battery at a lower rate during off-peak hours.

3.Current Status and Business Model Exploration of Energy Storage Technologies in China

3.1 Current Status and Challenges of Energy Storage Technology Applications in China

Cumulative installed capacity of electrochemical energy storage has surpassed pumped-storage hydroelectricity. In 2024, China's electrochemical energy storage additions reached 43.7 GW/109.8 GWh, representing year-on-year growth of 103%/136%, with newly installed capacity exceeding 100 GWh for the first time. From the perspective of project scale, nearly 200 megawatt-scale projects were put into operation, marking a year-on-year increase of 67%. From a technological perspective, the share of lithium-ion batteries remained largely unchanged compared to 2023. Multiple megawatt-scale and megawatt-hour-scale non-lithium energy storage technologies were connected to the grid, achieving significant application breakthroughs. By the end of 2024, China's cumulative installed power storage capacity-including both new technologies and pumped-storage hydropower-exceeded 100 GW, reaching 137.9 GW. Among these, the cumulative installed capacity of electrochemical storage technologies surpassed pumped-storage hydropower for the first time, reaching 78.3 GW/184.2 GWh, with cumulative power/energy capacity growing by 126.5%/147.5 year-on-year.

The operational duration of electrochemical energy storage is primarily 2 hours. From a technological development perspective, future applications could cover energy storage needs within 4 to 8 hours. Among operational electrochemical energy storage systems, those with a 2-hour operational duration account for 67% of total energy capacity; 4-hour systems account for 27.3%; and systems with operational durations exceeding 4 hours account for only 2.6%. Independent energy storage systems are primarily configured for

2 hours; electrochemical storage systems are mainly configured for 2 or 4 hours; and in commercial and industrial applications, storage systems with a duration of 4 hours or more account for over 50% of the total.

The utilization level of electrochemical energy storage needs to be further improved. In 2024, the average annual utilization hours of electrochemical energy storage was 911 hours. Among these, renewable energy power stations with storage had 776 hours; independent energy storage had 995 hours; and commercial and industrial user storage were the highest, reaching 2,252 hours. There is still room for improvement in the overall utilization level.

Currently, the regulation costs of electrochemical energy storage remain higher than those of flexibility upgrades for thermal power plants and pumped-hydro storage. The regulation costs for coal power plants range from 0.05 to 0.12 yuan/kWh, pumped-hydro storage from 0.05 to 0.12 yuan/kWh, and gas turbines from 0.46 to 0.54 yuan/kWh, but electrochemical energy storage costs 0.55–0.60 yuan/kWh. With the rapid development of renewable energy sources, coal-fired power plants are transitioning from supporting roles to flexible capacity providers. This shift introduces new requirements for low-carbon operation, deep flexible peak regulation, and multi-energy complementary integration between coal power and renewable energy sources. In the future, coal-fired power plants are expected to evolve into energy storage facilities, necessitating coupling with long-duration energy storage systems to enhance their flexibility in peak regulation and to better accommodate renewable electricity. The goal is to develop flexible, low-carbon smart power plants capable of achieving synergistic reductions in pollution and carbon emissions, while improving key performance indicators such as peak regulation capacity, levelized carbon emissions, and LCOE, aiming to reach the standards of advanced gas turbine units. Zhejiang University, in collaboration with Zhejiang Material Industry Group and Dongfang Electric, has initiated a demonstration project in Jiaxing, Zhejiang, featuring a 70MW/343MWh molten salt thermal storage system combined with a 2MW/4MWh water-based chemical energy storage system, exemplifying innovative low-carbon energy supply technologies.

Electrochemical energy storage technologies lack pricing mechanisms and mature business models, resulting in generally insufficient profitability. For standalone energy storage, although some regions have introduced policies allowing energy storage to participate in spot markets and frequency regulation markets and earn capacity leasing revenues, these measures are currently insufficient to ensure long-term stable returns for standalone energy storage. On the power generation side, early energy storage primarily relied on mandatory storage policies. With the phasing out of mandatory storage policies and the full integration of renewable energy into the market, market-based electricity pricing mechanisms will drive the participation of renewable energy-coupled energy storage in power markets, increasing the uncertainty of energy storage returns. On the user side, the current time-of-use pricing mechanism fails to fully leverage the regulatory potential of user-side energy storage, making it insufficient to achieve profitability. Additionally, new market players such as aggregators and virtual power plants are emerging in large numbers, all of which require energy storage. However, the lack of well-defined rules during the pilot phase has resulted in insufficient profitability for energy storage.

For daily-regulated energy storage, constrained by charging and discharging limitations, both peak shaving and load balancing operations can exhibit "saturation effects" during high- or low-resource periods. The system's typical peak-to-valley difference in net load serves as a rough upper limit for economical deployment of energy storage capacity (MWh). When energy storage scale exceeds the peak-to-valley difference, further increases in energy storage quickly become uneconomical, since they will not be cycled often. However, with storage duration sized to match only the typical peak-to-valley difference, wind and solar can fail to provide enough energy to charge batteries and serve loads on low-resource days, or conversely, wind and solar may exceed the amount that can be used or stored on high-resource days. Longer-duration storage can help overcome these saturation effects, carrying extra power from high-resource days to low-resource days. It has not yet proven cost-effective in this role, but may in the future. Careful modeling is needed to choose which strategy is best for addressing these concerns: longer-duration storage, extra renewable capacity, backup thermal plants or demand response.

3.2 Long-duration energy storage technology positioning and technical directions

Currently, **there is no consensus on the definition of long-duration energy storage** internationally. Generally, energy storage systems with continuous discharge durations ranging from 10 to 100 hours are considered long-duration energy storage, including pumped-storage hydro, compressed air, molten salt, and emerging technologies such as thermal batteries and metal-air batteries. Globally, hydrogen is gaining increasing attention and policy support for long-duration energy storage, while other forms of long-duration battery storage remain in the experimental or early commercialization stages. Some domestic viewpoints define long-duration energy storage as having a continuous discharge time of at least 4 hours. Currently, energy storage technologies with a storage duration of over 10 hours primarily include thermal energy storage and hydrogen storage, with non-electric energy storage technologies dominating the field.

Long-duration energy storage faces greater economic challenges. Long-duration energy storage is primarily aimed at addressing extreme weather conditions or special event demands. In the medium to long term, it can address the seasonal mismatch between high proportions of renewable energy generation and electricity demand, thereby facilitating cross-seasonal balance regulation. It can also assist with intraday balancing by charging during times when there would otherwise be excess power and filling in occasionally when intraday storage is exhausted. However, long-duration storage systems have not yet reached a low enough cost to be profitable in competition with other seasonal balancing options such as additional wind and solar capacity or thermal power plants. Secondly, existing business models and pricing mechanisms are currently unable to support long-duration energy storage projects in achieving reasonable returns. Currently, grid-side energy storage in China primarily generates revenue through capacity leasing, charge-discharge price differentials, and ancillary services. With the adoption of Document 136, which shifts storage from mandatory procurement to the spot market, it remains to be seen whether revenues will be sufficient to meet the investment return requirements for 4-hour or longer-duration energy storage.

The actual demand for long-duration energy storage in power systems will take time to materialize. Due to China's strong inter-provincial power transmission capacity, large installed base of thermal power plants, and well-developed regulatory capabilities, the urgency for long-duration energy storage in most regions of China is lower than in countries with more mature power systems. However, innovation and strategic planning for long-duration energy storage technologies remain important areas of focus.

3.3 Exploration of Electrochemical Energy Storage Business Models

1. Business Model One: Electricity Price + Capacity Price

Similar to conventional pumped-storage hydropower plants, this model establishes a two-part tariff system to achieve reasonable returns. First, electricity prices are determined through competitive pricing. Second, a mechanism is established to determine energy storage capacity prices. Capacity prices recover costs beyond those associated with charging and discharging operations and generate reasonable returns. Capacity prices are reasonably determined based on industry benchmarks, and an adjustment mechanism is established. Third, costs are allocated and passed on. The capacity charges corresponding to the capacity tariff determined by the government are paid by the grid company and included in the provincial grid transmission and distribution tariff for recovery. Fourth, the allocation method of capacity charges between specific power sources and power systems. For energy storage power plants that clearly serve both specific power sources and power systems, the capacity allocation ratio of the units should be clearly defined, and capacity charges should be allocated between specific power sources and power systems according to the capacity allocation ratio. The capacity charges that specific power sources should bear shall be borne by the relevant beneficiary entities and deducted accordingly when determining the capacity price for energy storage power plants.

2. Business Model Two: Spot Market+ Ancillary Service Market

Generate revenue by participating in the power market. For systems with significant peak-to-off-peak differences, the project can achieve profitability through the reasonable design of spot markets and ancillary service markets. First, revenue from the ancillary services market. This includes frequency regulation ancillary services, which in China are generally priced using a single-rate mechanism based on frequency regulation distance; and reserve ancillary services: the reserve market generally uses a single-rate pricing mechanism based on the winning capacity and time, with reserve fees calculated as the product of the clearing price, winning capacity, and winning time. In principle, the upper limit of the reserve service price shall not exceed the upper limit of the local electricity price. Second, revenue from the spot market. Charging and discharging electricity prices are determined based on relevant market prices. When independent energy storage power plants supply electricity to the grid, the corresponding charging electricity does not bear transmission and distribution tariffs or government-imposed fees and surcharges; however, costs resulting from system efficiency losses must be considered.

3. Business Model Three: Spot Market+ Auxiliary Service Market+ Capacity Compensation

In addition to participating in the market, capacity compensation is added to ensure reasonable returns during the initial development phase of long-duration energy storage. Energy storage participates in power market and ancillary service market transactions according to market rules, independently declares charging and discharging plans, and receives capacity compensation based on the discharged electricity volume. First, revenue from the ancillary services market, including frequency regulation services, which, in principle, adopt a single-price mechanism based on frequency modulation mileage, and reserve services, which, in principle, adopt a single-price mechanism based on the bid capacity and duration, with the upper limit of the reserve service price generally not exceeding the local electricity market price ceiling. Second, revenue from the spot market. The electricity prices for charging and discharging are determined based on relevant market prices. For independent energy storage power stations supplying electricity to the grid, the corresponding charging electricity consumption is exempt from transmission and distribution tariffs and government funds and surcharges; however, costs resulting from system efficiency losses must be taken into account. Third, capacity compensation revenues. Explore the establishment of a market-based capacity compensation mechanism; when conditions permit, a capacity market may be established. Currently, capacity compensation for independent energy storage is generally no more than 0.35 yuan per kilowatt-hour, with a compensation period of 5 to 10 years.

4. China's Energy Storage Development Pathway

This section describes an energy storage development pathway for China that follows the framework from Chapter 1. This advances the use of mature technologies (stage 1), development of next-generation technologies (stage 2) and integration of new technologies to create a clean, reliable, low-cost power system (stage 3).

4.1 First Stage

Scaled development of energy storage across multiple application scenarios and technical routes, with a focus on meeting intra-day system balancing and regulation needs. As a key measure to enhance system regulation capacity, storage should be scientifically planned based on actual system requirements, with an installed capacity of over 500 GW/2,000 GWh by 2030. Multiple energy storage technology routes, primarily intra-day regulation technologies such as lithium ion batteries, pumped storage hydroelectricity, compressed air energy storage, electrochemical energy storage, thermal (cold) energy storage, and steam extraction energy storage from thermal power plants, may coexist. These will be primarily developed through system-friendly "renewable energy + energy storage" power plants, base-level renewable energy-integrated energy storage, grid-side independent energy storage, user-side energy storage for peak shaving and valley filling, and shared energy storage. These will be deployed across the generation, transmission, and consumption sides to meet intra-day regulation needs of the system.

4.2 Second Phase

Major breakthroughs will be achieved in large-scale long-duration energy storage technologies, meeting daily and longer-term balancing regulation requirements. Diversified energy storage technology routes will develop to meet system power supply security and large-scale renewable energy integration demands, enhancing safe and stable operation levels. Breakthroughs will be made in 10-hour-plus long-duration energy storage technologies represented by mechanical energy storage, thermal energy storage, and hydrogen energy, achieving balancing regulation at daily and longer time scales, and promoting the transition of local system balancing modes toward dynamic balancing.

4.3 Third Stage

Multi-type energy storage technologies, including electricity storage, thermal storage, gas storage, and hydrogen storage, operate in coordination across the entire energy cycle, significantly enhancing the flexibility of energy system operations. Various energy storage facilities, such as electricity storage, thermal storage, gas storage, and hydrogen storage, are integrated in an organic manner. Long-duration energy storage technologies, including chemical energy storage based on liquid hydrogen and liquid ammonia, and compressed air energy storage, have achieved major breakthroughs in terms of capacity, cost, and efficiency, meeting the regulation and storage demands of large-scale renewable energy across different temporal and spatial scales. The organic integration and coordinated operation of various types of energy storage in power systems jointly address the issue of long-term system balance regulation under the condition of seasonal output imbalance of renewable energy, supporting the power system to achieve dynamic balance across seasons, and significantly enhancing the flexibility and efficiency of energy system operations.

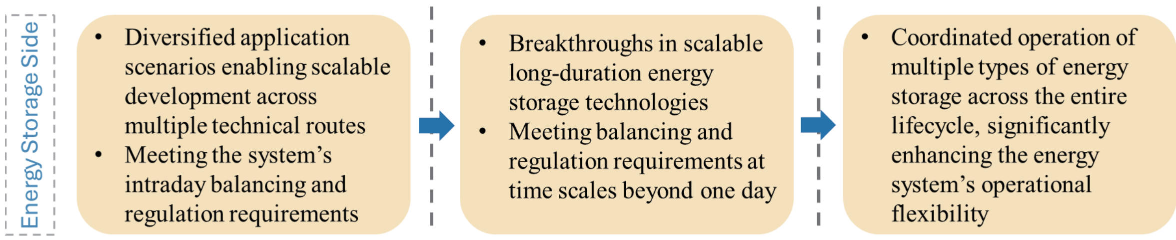


Figure 11 Three-stage development path for energy storage

5. Policy Recommendations

Establish a diversified energy storage system encompassing multiple technologies and application scenarios, promote the large-scale application of energy storage across various time scales, and facilitate the coordinated operation of diverse energy storage technologies with power systems to support the efficient development and utilization of high proportions of renewable energy.

(1) Coordinate system demand and resource conditions to promote the diversified development and application of intra-day electricity storage.

China should adopt a target of 500 GW/2,000 GWh of electricity storage by 2030 and provincial energy councils should use annual storage-specific tenders to make steady progress toward this goal. While meeting local power system demand, inter-provincial and intra-regional resource optimization should be used to ensure reasonable layout and scientific, orderly development and construction. Actively promote the construction of ongoing projects, accelerate the start of new projects, and prioritize the development of a batch of storage facilities that play a strong role in ensuring power system security, promote the large-scale development of renewable energy, and have relatively superior economic indicators. Innovate development models and application scenarios for electricity storage and carry out the construction of small and medium-sized electricity storage stations in accordance with local conditions. Explore and promote the integrated development of renewable energy and electricity storage of all forms.

(2) Based on the actual needs of the power system, coordinate and promote the rapid development of new-type energy storage technologies across various application scenarios on the source, grid and load sides.

Fully leverage the important role of electrochemical energy storage in ensuring power supply security and enhancing system regulation capabilities. In addition to integrating storage into spot markets for energy, assess the reliability services storage and “renewable energy + storage” hybrids can provide and open up compensation mechanisms for these services to include storage. This should include provision of inertia, voltage control, frequency regulation, ramping and peak-serving capacity. Fully integrate system demand and technical-economic viability to coordinate the layout of grid-side independent storage and grid function-replacement storage, ensuring reliable power supply. Actively promote the construction of an integrated power generation, transmission, consumption, and storage system, flexibly develop electrochemical energy storage at the user side, and enhance power supply reliability and energy quality for users.

(3) Promote the coordinated operation of new-type energy storage and power systems to thoroughly enhance the power system’s balancing and regulation capabilities.

Establish and improve dispatch operation mechanisms to fully leverage the dual regulation functions of electrochemical energy storage in terms of power and electricity. Promote renewable energy-based hydrogen production, develop advanced solid-state hydrogen storage materials, and focus on breaking through large-scale, low-cost, and high-efficiency electro-hydrogen conversion technologies and equipment. Conduct large-scale demonstration applications of hydrogen production and comprehensive utilization. Promote the large-scale application of new energy storage technologies such as electrochemical storage and compressed air storage. Optimize the development model of new energy storage technologies, fully leverage the advantages of electricity storage, thermal storage, gas storage, cold storage, and hydrogen storage, achieve the organic integration and optimized operation of various types of energy storage, and address the issue of seasonal mismatch between renewable energy generation and electricity demand during the medium to long term, thereby promoting major breakthroughs in the real-time balancing mechanisms and means of the power system.

V. Policy Recommendations

1.Accelerate the deployment of major related scientific research facilities and bases to innovate cutting-edge technologies and promote high-quality development of the renewable energy sector.

The wind and solar new energy industry in China has entered a critical phase characterized by simultaneous large-scale development and high-quality enhancement. Confronted with complex application scenarios and challenges related to high penetration of systems, it is essential to implement systematic policies that stimulate endogenous industry momentum, accelerate technological innovation, and enhance industry competitiveness.

First, promote technological application and model innovation to facilitate the large-scale deployment of mature technologies and upgrade the industrial chain. Encourage the greater multi-dimensional integration of "new energy +" with other sectors such as industry, transportation, construction, and information technology. Wind and solar should be integrated into high-standard green shipping and green industrial clusters like zero-carbon parks. Top-level planning across departments should be strengthened to ensure coordination, and land and resource allocation optimized, thus providing a solid foundation for the development of new energy. Accelerating the creation of a comprehensive lifecycle device recycling system is also necessary, and recovery technologies for rare metals and critical minerals should be advanced to enhance the resilience and security of the global industrial and supply chains.

Second, expedite the deployment of major new energy infrastructure to promote key technological breakthroughs and application demonstrations. Significant innovation should be stimulated and pilot platforms should be established for wind resource development, including breakthroughs in lightweight wind turbine blades, deep-sea floating wind power, and high-altitude wind turbines. Artificial intelligence, digital twins, and other next-generation information technologies should be rapidly introduced into the integration with energy systems, and AI-powered accurate forecasting, smart operation, and maintenance is worthy to be empowered. Major demonstration projects can be tailored to local conditions, such as integrated multi-energy and ecological restoration bases in the "decertified" regions and offshore energy centers that serve as energy supply and conversion hubs in the costal areas.

Third, improve the support and coordination mechanisms for innovation elements to build an open and inclusive global energy technology cooperation ecosystem. Talent, funding, and collaboration systems can be enhanced by supporting leading enterprises and universities in establishing pilot platforms and transformation centers. Strategic scientists, leading technological talents, and innovative teams should be cultivated, and female researchers should be encouraged to engage in energy innovation through special funds and reward mechanisms. Construct a multi-level financial support system to leverage green credit, green bonds, and transition finance to steer social capital toward frontier technologies in renewable energy.

2.Invest in the development of a main-distribution-microgrid power network, explore innovative power dispatch modes, and continuously enhance the grid's capacity to cost-effectively accommodate renewable energy.

Strengthen power grid development to support wind and solar energy in becoming the dominant source of both total and newly installed capacity. By 2030, wind and PV power is expected to account for more than 60% of total installed capacity, and generate more than 35% of total electricity.

First, leverage the role of large-scale power grids in optimizing resource allocation, promote the quality upgrading and healthy development of the main grid structure, and support the efficient development and utilization of high proportions of renewable energy. Priority should be given to establishing the "desertified" base in Northwest China and developing renewable energy bases in the major river basins of Southwest China. This includes accelerating the construction of inter-provincial and cross-regional transmission corridors, with a target of delivering no less than 50% of electricity from clean energy sources. New models of renewable energy only power transmission should be explored to enable higher share of solar and wind power to be transmitted and consumed. The modernization and upgrade of DC transmission systems as well as the optimization of grid architecture should be promoted through employing advanced power transmission technologies and establishing a layered, zoned, flexible development, adaptable backbone grid. This will enable the power grid to serve as a critical foundation for the development of new distribution systems and distributed smart/micro grids.

Second, efforts should focus on new-type distribution grids to support emerging industries and expand the capacity of distribution networks integrated with solar and wind energy and distributed renewable energy and storage. Invest in advancing distributed smart grids from demonstration stage to widespread deployment, enabling the efficient grid integration and absorption of decentralized renewable energy. Distributed smart grid should be built to support the large-scale development and local consumption of distributed energy resources, ensuring compatibility, coexistence and development integrated with the main grid. The construction of microgrids should be accelerated, with a well-balanced configuration of generation, load, and storage to enhance local peak shaving and self-balancing capabilities. Projects that integrate power generation, grid infrastructure, loads, and storage should be actively promoted, and tailored to local conditions and characteristics. These efforts should focus on the development of zero-carbon industrial parks and key application areas such as public buildings, residential communities, electric vehicle charging stations, railways, highways, and other infrastructure and transportation hubs. New multifunctional models for the development and utilization of renewable energy should be explored to reach integrated energy solutions across multiple sectors. Develop a hosting capacity methodology that reveals the value of different DERs to the bulk power and distribution systems, and accordingly, assess the net benefits of different scenarios of distributed energy resource deployment, and to develop location-specific incentives for DERs. By 2030, the capacity and operational flexibility of the distribution grid are expected to significantly increase, with the ability to accommodate approximately 1 billion kilowatts of distributed renewable energy and 24 million charging piles. These advancements will contribute to a high level of electrification and the transition to non-fossil energy consumption.

Third, promote the transformation of renewable energy supply and consumption models for coordinated development of large renewable energy projects, distributed renewables and storage, and flexible demand. The construction of a new-type power system involves the transformation from traditional “passive” one-way radial networks to “active” two-way interactive systems. Functionally, the grid should evolve from a single-purpose power delivery system into a platform that enables efficient generation-network-load-storage coordination of resources. It involves the construction of bottom-up scheduling and balancing mechanisms, and strengthening of self-balancing capability of distribution networks. A new model of active distribution grid operation, featuring coordination across main grids, distribution networks and microgrids, should be developed to meet the demands of large-scale electric vehicle charging and other emerging loads. The grid should also enable the innovation of new business models such as VPPs, load aggregators and vehicle-to-grid interaction, and support large-scale grid integration of distributed renewable energy. Achieving this will require an effective coordination among renewable energy targets, grid planning, operations, markets, and resource development.

3.Develop a diverse energy storage system encompassing multiple technologies and application scenarios to improve the coordination between different types of energy storage and power systems and support the efficient integration and utilization of high shares of renewable energy.

Promote the efficient utilization across diverse technologies and application scenarios, and support the development of energy storage systems from the generation (source), grid (network), and consumption (load) sides, and build a new-type power system with renewable energy at its core. By 2030, electrochemical energy storage is expected to account for 20% of the system’s total flexibility capacity.

First, accelerate the large-scale deployment of electrochemical energy storage, compressed air energy storage, and other emerging storage technologies. Optimize the development of diverse energy storage solutions by leveraging the complementary advantages of electricity, thermal, gas, cold, and hydrogen storage. Promote the integrated operation and optimal coordination of multiple storage types to address mid- and long-term seasonal imbalances between renewable energy output and electricity demand. These efforts will enhance the real-time balancing capability and security of the power system during periods of high net demand, and drive major breakthroughs in system balancing mechanisms and technologies. Develop a generation and storage resource investment plan through fully utilizing advanced modeling techniques. This plan should involve the management of resources under various weather conditions, including reliability risks associated with thermal generators. It should also reflect real cost data to highlight the cost advantages of renewables and storage for both capacity and energy. Additionally, update the capacity credit scheme by shifting from a thermal-generation-focused approach to a technology-neutral framework that rewards performance during periods of grid stress.

Second, based on the practical needs of the power system, promote the integrated and rapid development of electrochemical energy storage across diverse application scenarios on the source, grid, and load sides. Demonstrate at scale batteries' ability to provide synthetic inertia and voltage support at scale, and accelerate the large-scale deployment and optimized layout of energy storage systems to support the energy transition. On the generation side, promote rational deployment of system-friendly hybrid ("renewable energy + storage") power stations and energy storage at renewable energy bases and transmission hubs to enhance the reliability and substitutability of renewable power. On the grid side, coordinate the development of independent and functionally integrated energy storage to improve grid stability and ensure reliable electricity supply. On the user side, encourage flexible deployment of distributed energy storage to support self-consumption of renewable energy and enhance demand-side response capabilities.

Third, promote the coordination between energy storage and the power system to considerably enhance the system's balancing and regulation capabilities. Pilot electrochemical storage and "grid forming inverters" as stability resources in areas with high shares of renewable energy. Establish and refine scheduling and operational mechanisms to fully leverage the dual regulatory functions of electrochemical energy storage in both energy and power dimensions. Continue deploying pilot projects for promising long-duration storage technologies to determine its commercial feasibility and system value.

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