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Smart Grid as a Key Enabler for China’s Carbon Peaking and Carbon Neutrality Targets

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Abstract

In the context of the dual carbon goal, the intelligent transformation and upgrading of China’s power system, as an important field of carbon emissions, is of great significance for achieving the dual carbon goal. The traditional power system has been difficult to adapt to the current economic and social transformation of China’s high-quality development due to its low energy efficiency, large carbon emissions, lack of intelligence and other defects, which has become the bottleneck to achieve the dual carbon goal. The smart grid has the advantages of strong renewable energy consumption capacity, high proportion of clean energy generation and intelligent management, so promoting the intelligent upgrading of China’s power system can effectively promote the transformation of the power industry to low-carbon. This paper analyzes several challenges in the process of China’s smart grid construction. At the same time, combined with the actual situation of China and the existing domestic measures to deal with these challenges, the actual benefits of these measures are analyzed and discussed, providing a possible direction for the further construction of China’s smart grid.

Keywords

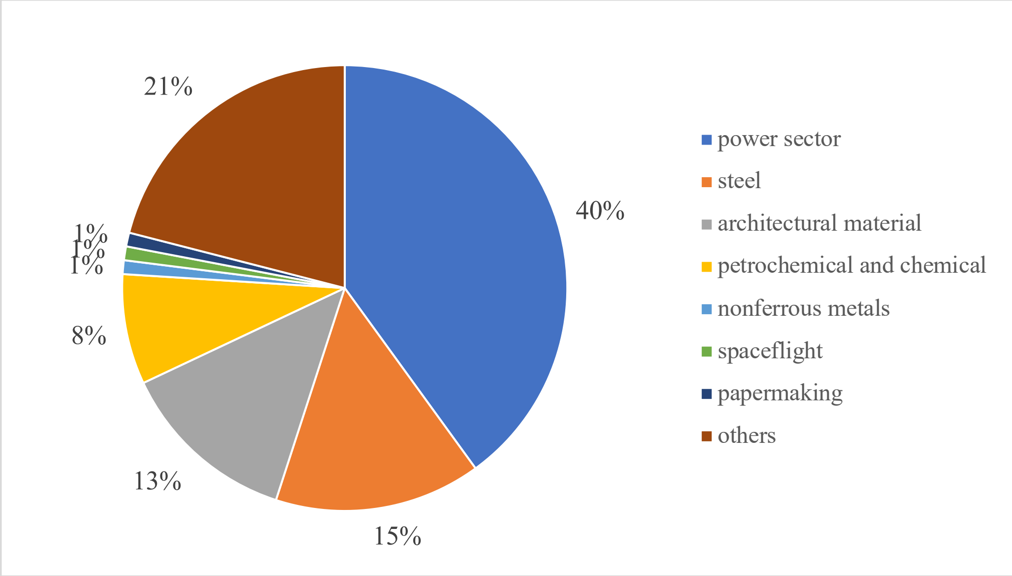
smart grid, double carbon target, carbon emission

1. Introduction

According to the data of the International Energy Agency, China’s carbon dioxide emissions reached 12.6 billion tons in 2024, accounting for one third of the world’s total, and energy related emissions increased by 0.4%. Therefore, building a clean, low-carbon, safe and efficient modern energy system is the prerequisite and core battlefield for achieving the “double carbon” goal (International Energy Agency, 2025). This extensive and profound systematic change is not only related to the fundamental transformation of energy production and consumption, but also will reshape China’s future industrial structure and economic pattern.

In the energy system, the power industry occupies a central position and is also the “main force” of carbon emissions. According to the statistics of the China electric power academy, the carbon dioxide emissions of China’s power industry account for more than 40% of the country’s total emissions, which is the highest in all single sectors (Chi, 2024), which can be seen in figure 1.

Figure 1 Proportion of carbon emissions of China's eight major industries in 2021 (Chi, 2024)



This data highlights the extreme importance of the power industry in the "double carbon" strategy - the success of its low-carbon transformation is directly related to the success of the overall goal. Decarbonization of the power system means that the power generation structure dominated by fossil fuels such as coal must be fundamentally changed, and the proportion of power generation from zero carbon renewable energy such as wind energy and solar energy must be significantly increased. Therefore, promoting the green revolution of the power industry is the top priority and the only way to achieve the goal of "double carbon".

However, the traditional power grid, which takes "source follows load" as the basic operation mode and centralized large-scale coal-fired/gas-fired power plants as the main power source, has exposed significant limitations in adapting to this revolutionary transformation. First, the traditional power grid has inherent deficiencies in accepting a high proportion of renewable energy. Wind power and photovoltaic power generation have the characteristics of intermittency, volatility and randomness. The traditional power grid lacks sufficient flexibility and regulation ability, which is difficult to ensure the safe and stable operation of the power grid, resulting in frequent "wind and light abandonment". Secondly, the traditional power grid is difficult to effectively respond to the growing demand for flexible loads. With the large-scale popularization of electric vehicles and the widespread use of smart appliances, the load side shows a stronger randomness and interactive demand, and the traditional one-way and passive power supply mode is unsustainable. Finally, in terms of operation efficiency, each link in the traditional power grid system is relatively independent, the ability of information perception is weak, and the level of intelligent decision-making is low, which makes it difficult to realize the refined allocation and optimal scheduling of resources. These inherent defects have made the traditional power grid a bottleneck restricting the realization of the "double carbon" goal.

In order to overcome the disadvantages of traditional power grid, smart grid came into being, and is widely considered as the key platform to support energy transformation and realize low-carbon power system. Smart grid is a modern power transmission and distribution system integrating advanced sensing, communication, computing, control technology and grid infrastructure. Its core value lies in the high integration of power flow, information flow and business flow. Specifically, the smart grid presents great opportunities: it can accurately predict and flexibly consume a high proportion of renewable energy through a high degree of information and self-healing ability; Through advanced metering system and two-way communication, it can effectively interact with the user side (such as electric vehicles and smart homes), guide peak shaving and valley filling, and integrate distributed energy; By optimizing dispatching and distributed control, the energy conversion efficiency, transmission efficiency and utilization efficiency of the whole power system are significantly improved. Therefore, the smart grid provides a practical solution for building a new power system with new energy as the main body and ultimately driving the low-carbon transformation of energy consumption in the whole society through the whole chain of power generation side, transmission side and power consumption side.

This paper aims to explore the multiple advantages of smart grid compared with traditional power system in promoting the realization of the "double carbon" goal under the background of global climate change, systematically analyze the technical, economic and institutional challenges faced by the current construction of smart grid in China, and further explore feasible coping strategies and development paths, in order to provide theoretical reference and practical direction for smart grid to help China save energy and reduce emissions and achieve the grand goal of "double carbon" on schedule.

2. Theoretical Basis and Core Advantages of Smart Grid Enabling "Double Carbon" Goal

2.1 Correlation Mechanism Between Smart Grid and "Double Carbon" Goal

The support of smart grid for the goal of "double carbon" does not rely on the breakthrough of a single technology, but on the systematic remodeling and optimization of the whole link of power system "generation, transmission, distribution and utilization" through digital and intelligent means, forming a deep collaborative organic whole. Its correlation mechanism is embodied in a closed-loop, two-way interactive energy value chain.

On the generation side, the core task of smart grid is to solve the uncertainty and volatility problems caused by large-scale grid connection of renewable energy. By deploying meteorological monitoring stations, radar, satellite remote sensing and other equipment, combined with numerical weather prediction (NWP) and machine learning algorithm, it can achieve high-precision and ultra short-term power prediction of renewable energy output such as wind and light. These prediction data provide key decision-making basis for day ahead and real-time dispatching of power grid. At the same time, the intelligent dispatching system can coordinate and optimize the start-up, shutdown and output of various flexible resources (such as peak shaving gas units, pumped storage, electrochemical energy storage, etc.), so as to ensure the maximum acceptance of renewable energy while ensuring the stability of frequency and voltage of the power grid. In addition, the smart grid supports the "plug and play" of distributed generation (such as roof photovoltaic), and ensures its safe and friendly access to the distribution network through advanced grid connected inverter and protection control technology.

On the transmission side, smart grid focuses on improving energy transmission efficiency and grid security. It uses the wide area measurement system (WAMS) based on the synchronous phasor measurement unit (PMU) to realize the real-time, synchronous and high-speed monitoring of the power grid operation status, as if the power grid was equipped with "panoramic CT". Based on these massive data, the system can carry out dynamic power flow analysis, transient stability assessment and adaptive protection control, so as to optimize the load capacity of transmission lines, reduce network losses, quickly identify and isolate faults, and prevent the occurrence of large-scale blackouts. For example, the application of flexible AC transmission system (FACTS) technology can accurately control the power flow distribution of the line, solve the "choke" problem, and improve the capacity of trans regional renewable energy consumption.

On the distribution side, the smart grid has realized the transformation from passive operation and maintenance to active management. The traditional distribution network is a "blind pipe" system, fault location and recovery time-consuming. By installing intelligent switch, fault indicator and distribution automation (DA) system, the intelligent distribution network can automatically locate the fault section, and realize the rapid power supply recovery in the non fault area through network reconstruction, that is, "self-healing" function. At the same time, the distribution network management system (DMS) and the distributed energy management system (DERMS) work together to perform cluster control and optimal scheduling on a large number of distributed photovoltaic, energy storage, electric vehicle charging piles, etc. connected to the distribution network to avoid voltage overrun and equipment overload, and transform the distribution network from a simple power distribution network to an active energy management platform.

On the power consumption side, the key of smart grid is to stimulate the flexibility potential of load side. As an interactive hub between users and power grid, advanced measurement system (AMI) not only realizes remote automatic meter reading, but also provides a technical basis for the implementation of demand side response (DR) projects such as time of use price and real-time price. Through price signals or incentive signals, smart grid can guide users to reduce power consumption during peak hours of the system, and increase power consumption during peak hours (such as charging electric vehicles), so as to smooth the load curve, reduce the use frequency of fossil energy units built to meet the transient peak load, and achieve systematic emission reduction. Furthermore, the vehicle to grid (V2G) technology regards the power battery of electric vehicles as a mobile distributed energy storage unit, which transmits power in reverse when required by the grid, providing valuable auxiliary services such as frequency modulation and standby for the grid.

To sum up, the smart grid has built an intelligent interactive ecosystem of "source grid load storage" through deep collaboration in all links, driving the power system from a rigid system dominated by fossil energy to a flexible, low-carbon system with renewable energy as the core.

On the distribution side, the smart grid has realized the transformation from passive operation and maintenance to active management. The traditional distribution network is a "blind pipe" system, fault location and recovery time-consuming. The smart distribution network improves the penetration of renewable energy by installing smart switches and fault indicators

2.2 Increase Renewable Energy Penetration

Increasing the proportion of renewable energy in energy consumption is the direct path to replace fossil energy and reduce emissions. The research on the technology path of smart grid in this area has become the focus of academia and industry, which can be summarized as the following aspects:

Advanced forecasting technology: This is the premise and foundation for the absorption of renewable energy. Early studies mainly relied on the NWP model of physical methods. In recent years, with the rise of artificial intelligence, data-driven machine learning methods have become the mainstream of research. For example, recursive neural network models such as long-term and short-term memory network (LSTM) and gating cycle unit (GRU) are widely used to capture the temporal variation of wind speed and irradiance because of their powerful processing ability for time series data (Cakir et al., 2022). Convolutional Neural Network (CNN) is used to process satellite cloud images and other spatial data to improve the prediction accuracy. Research shows that the hybrid forecasting model integrating NWP physical information and historical data can effectively overcome the limitations of a single model and reduce the root mean square error (RMSE) of short-term wind power forecasting to less than 15% (Fu and Wu, 2025). In addition, for the uncertainty of prediction, quantile regression, scenario generation and other technologies are introduced to support risk decision-making.

Flexible scheduling and operation control technology: Based on accurate prediction, how to optimize scheduling is the core challenge. The traditional deterministic scheduling model has been unable to adapt to the volatility of renewable energy. Therefore, stochastic optimization, robust optimization and other uncertain scheduling methods have been extensively studied. Stochastic optimization seeks the scheme with the lowest expected operating cost of the system by generating a large number of possible wind and solar output scenarios; Robust optimization focuses on dealing with the worst scenarios to ensure the safe operation of the system. At the same time, in order to improve the regulation ability of power grid, the modeling and calling of various flexible resources become the key. These include fast start-up and shut-down gas turbines, pumped storage power plants, and electrochemical energy storage systems with rapidly decreasing costs in recent years. The research focuses on the application strategy and capacity configuration optimization of these flexible resources in peak shaving and frequency modulation.

Distributed energy management and Microgrid Technology: in the face of massive and decentralized distributed photovoltaic, the traditional "one size fits all" management mode is unsustainable. Distributed energy management system (DERMS) emerges as the times require. It aggregates and coordinates thousands of distributed generators in the region through the communication network, so that it can participate in power grid dispatching as a "virtual power plant" (VPP). Microgrid technology is a typical paradigm to achieve "source network load storage" coordinated operation in local areas. It can optimize the operation when it is connected to the large power grid, or it can operate independently when the external power grid fails, which greatly improves the resilience of regional energy supply and the ability to absorb local renewable energy.

There are significant differences in the maturity and applicable scenarios of different technology paths. Power prediction technology has entered the mature stage of commercialization, but its accuracy bottleneck under complex terrain and extreme weather conditions still needs to be broken. The technology of electrochemical energy storage, especially lithium-ion batteries, has been relatively mature and began to be deployed on a large scale, but its full life cycle cost, long-term cycle life, safety risk and resource and environmental impact are still the key factors restricting its large-scale development. In contrast, demand side response, as a “virtual” and low-cost flexible resource, has great technical potential, but the business model and market mechanism are not perfect. The incentive and guarantee of user participation and response reliability are the current research difficulties.

In the future, it is difficult to solve all problems with a single technology path, so it is necessary to build a technology system integrating “high-precision prediction, uncertain scheduling, multi type energy storage collaboration, and extensive participation of demand side resources”. This system needs a powerful computing platform and intelligent algorithm as the brain to realize the fusion processing and real-time decision-making of massive heterogeneous data.

2.3 Optimizing Asset Management and Improving Energy Efficiency

Improving energy efficiency is described as the “fifth energy” after coal, oil, gas and renewable energy. Through digital transformation, smart grid has opened up a new path for the lean management of grid assets and the systematic improvement of energy efficiency.

From preventive maintenance to predictive maintenance: the traditional power grid follows the preventive maintenance based on fixed time cycle, which may lead to “excessive maintenance” or “insufficient maintenance”. Smart grid collects real-time health status data of equipment through advanced sensors such as vibration, temperature, partial discharge and oil chromatogram deployed on key equipment such as transformers, circuit breakers and cable joints. Combined with the load data provided by the advanced measurement system (AMI), and using big data analysis and artificial intelligence (such as machine learning and deep learning) algorithms, the remaining life of equipment can be predicted and early warning of faults can be realized. Literature shows that this predictive maintenance strategy can reduce the failure rate of key equipment such as transformers by more than 20%, reduce the maintenance cost by 15%-30%, and minimize the loss of power failure caused by sudden equipment failure (Panda and Panda, 2023).

Line loss management and operation optimization: non-technical line losses (such as electricity theft) and technical line losses (such as resistance loss) are the main manifestations of low grid efficiency. The advanced distribution network management system (ADMS) based on AMI can accurately locate abnormal power consumption areas and effectively combat power theft by comparing the real-time data of Transformer Outlet Power and user power consumption. At the same time, through real-time network reconfiguration and reactive power optimization based on power flow (such as adjusting the switching of capacitor banks), the topology and power flow distribution of power grid can be dynamically changed to minimize the technical line loss in the process of power transmission. Research shows that intelligent line loss management can reduce the overall line loss rate of the distribution network by 1-2 percentage points, which means huge energy conservation and emission reduction benefits for a country with annual power consumption of trillions of kilowatt hours.

From “post failure maintenance” to “preventive maintenance” and then to “predictive maintenance”, this is not only the upgrading of technology, but also the fundamental paradigm shift of operation and maintenance concept and management mode. The core value of this transformation is that it changes the operation and maintenance decision from based on experience and fixed procedures to based on data and objective facts, and realizes the “transparent” management of asset health status. The benefits of emission reduction are twofold. On the one hand, the equipment operates in the best condition, directly reducing energy consumption; On the other hand, due to the significant reduction of equipment failures and unplanned downtime, the ability to accept renewable energy has been enhanced, indirectly supporting the low-carbon operation of the system.

However, the full realization of predictive maintenance still faces challenges: first, the data barrier, and the difficulty of data fusion between different professional systems (such as production MIS, GIS, SCADA); The second is the generalization ability of the model. Whether the AI model trained for specific equipment can be applied to similar equipment of different manufacturers and different operating environments; Finally, the technical economy. The initial investment cost of large-scale deployment of high-precision sensors and communication networks still needs to be further reduced.

2.4 Enabling New Load and Demand Side Response

With the electrification and intelligence of energy consumption terminals, the load side is changing from a passive energy receiver to a "producer consumer" who can actively interact with the grid. Smart grid is an enabling platform for this transformation.

Demand response: Dr is the main means to mobilize load side flexibility. Academic research divides it into price type DR and incentive type Dr. price type Dr includes time of use price (TOU), real-time price (RTP) and peak price (CPP), which guide users to spontaneously adjust their electricity consumption behavior through price signals. Incentive Dr, through the project contract, stipulates that users can reduce a specific amount of load when the power grid needs to obtain compensation (Cavus et al., 2025). A large number of empirical studies have proved that in the industrial field, Dr can effectively reduce peak load by 5% -15%; In the residential area, the air conditioning load can be reduced by 10%-20% through intelligent thermostats, intelligent water heaters and other equipment (Liu et al., 2025).

Electric vehicles and V2G: the large-scale development of electric vehicles is not only a challenge to the power grid (disorderly charging aggravates the peak valley difference), but also a huge opportunity (orderly charging and V2G). The research mainly focuses on two levels: orderly charging and V2G. Orderly charging controls the charging time and power through the intelligent charging pile or cloud platform, and guides the charging behavior to the low load period of the grid. V2G technology goes further, allowing electric vehicles to discharge to the grid during shutdown. Literature summarizes several V2G pilot projects around the world, proving that the electric vehicle cluster can provide FM services comparable to traditional units, and the response time can reach the second level (Boateng et al., 2025). However, the business model of V2G, its impact on battery life and related standards are still the current research hotspots.

Smart home and building energy management system: smart home connects household appliances through Internet of things technology, and building energy management system (BEMS) integrates building energy equipment such as air conditioning, lighting, energy storage, etc. They can be linked with the Dr signal of the power grid to automatically adjust the operation mode of the equipment and realize the overall optimization of building energy consumption on the premise of ensuring user comfort (Refaat et al., 2025).

The integration of large-scale flexible loads has a dual impact on power system stability. From a positive perspective, they are high-quality and flexible resources with wide distribution and low cost. They are ideal tools to balance the fluctuation of renewable energy, and can delay or replace the expensive investment in power grid upgrading. However, from the perspective of risk, if there is no effective guidance and control, millions of electric vehicles start charging rapidly at the same time in the evening peak, or the air conditioning load rises sharply in extreme weather, which will cause huge pressure on local power distribution facilities and even cause failures.

Therefore, future research and technology application must be committed to transforming the "challenge" of the load side into the "opportunity" to support the stable operation of the system. This requires the development of more refined, adaptive, market-based load aggregation and control strategies. At the same time, it is necessary to establish a fair, transparent and reliable incentive mechanism, and attach great importance to user privacy protection and participation experience, so as to realize the sustainable and large-scale development of load side resources.

2.5 Comparison of Advantages and Disadvantages between Smart Grid and Traditional Grid

Table 1: Comparison of advantages and disadvantages between traditional power grid and smart grid

	Traditional power grid	Smart grid
generation	Fossil fuel based	Mainly renewable energy
equipment	Low efficiency and potential safety hazard	Stronger performance and better stability
Payload service	Difficult to adapt to flexible loads	Intelligent control to meet demand

Table 1 shows fundamental differences between the traditional grid and the smart grid in the three core dimensions of power generation source, equipment performance and load service capacity, highlighting the significant advantages of the latter as the core of the future energy system.

On the power generation side, the traditional power grid mainly relies on fossil fuels, which is not only facing the pressure of resource depletion, but also accompanied by serious environmental pollution. The smart grid takes renewable energy as the main source of power generation, fundamentally promoting the clean and low-carbon energy structure, which is in line with the global goal of sustainable development, although it puts forward higher management requirements for the large-scale access of intermittent renewable energy.

In terms of power grid equipment and operation, the traditional power grid shows the characteristics of low efficiency and many potential safety hazards. Its system response is slow and its self-healing ability is poor, which is easy to lead to fault expansion and long-term power failure. In contrast, relying on advanced sensing, measurement and control technologies, smart grid has achieved stronger system performance and better operation stability, has powerful self-healing function, can quickly isolate faults and restore power supply, and greatly improves the reliability and security of power supply.

In response to user demand, the traditional one-way and rigid “one size fits all” mode of power grid is difficult to adapt to the access of flexible loads such as electric vehicles and distributed photovoltaic, and the management mode is extensive. The smart grid, through digital and intelligent technology, realizes the two-way interaction between the grid and users, can carry out refined demand side management, intelligently meet and guide the diversified power demand, and lays a solid foundation for the development of new energy formats in the future.

To sum up, smart grid, through its cleanness, self-healing and intelligence, comprehensively overcomes the inherent shortcomings of traditional grid in terms of sustainability, security and stability and service flexibility, representing the inevitable direction of grid technology development.

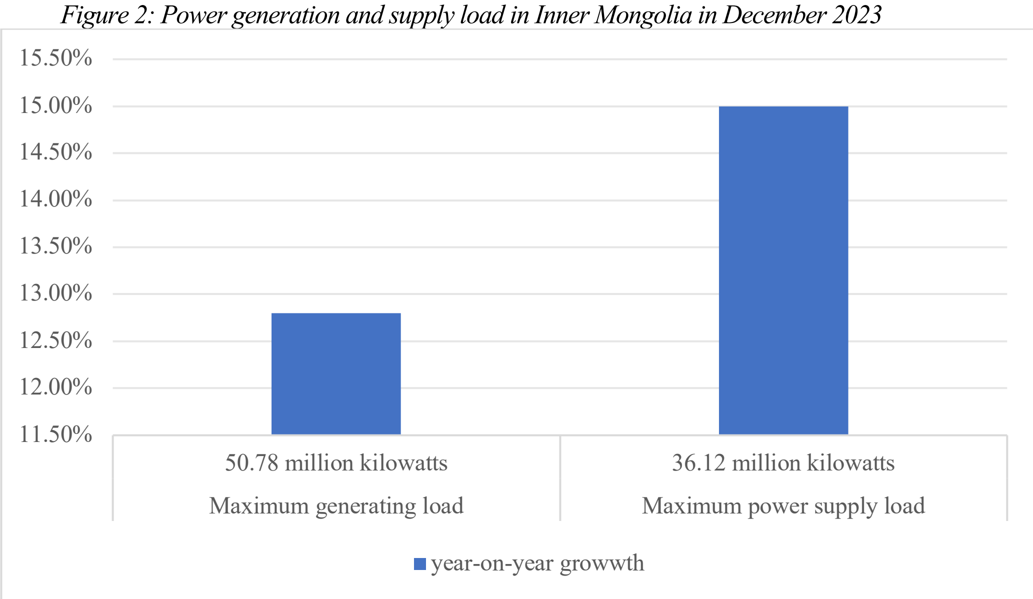
3. key Challenges of China’s Smart Grid Construction under the Goal of “Double Carbon”: Literature Perspective

3.1 Technical Challenge: System Stability of High Proportion of Renewable Energy

The increasing proportion of renewable energy has fundamentally changed the dynamic characteristics of power system and brought unprecedented technical challenges. The literature generally points out that the core problem lies in the intermittency, volatility and low inertia of renewable energy power generation.

System balance and reserve capacity: the “relying on the weather” characteristics of wind and solar energy make the net load (total load minus renewable energy output) curve of the power system more steep and difficult to predict. This requires that the system must be equipped with a large number of quick start reserve capacity and regulation capacity. The extreme weather event in Inner Mongolia in December 2023 is a typical case.

Figure 2: Power generation and supply load in Inner Mongolia in December 2023



As shown in Figure 2, this event led to a sudden drop in wind power output, which was at the peak of heating power consumption, resulting in a 12.8% year-on-year surge in the maximum power generation load of the grid, and the supply and demand situation was extremely tense. Such events are frequently cited in academic research to illustrate the severe test of system resilience and adequacy in a high proportion of renewable energy systems.

Frequency and voltage stability: traditional synchronous generators store a large amount of kinetic energy in the rotor, which can provide natural inertia for the power grid and slow down frequency changes. While wind power and photovoltaic are connected to the grid through power electronic devices, the inertia support provided by them (if any) is essentially different from the traditional synchronous machine, resulting in reduced equivalent inertia of the system, faster frequency change, and higher requirements for frequency modulation resources. At the level of distribution network, the access of a large number of distributed photovoltaic may lead to the line voltage exceeding the limit and the voltage rise problem.

Existing research focus: current research mainly focuses on coping with these challenges through technical means such as large-scale energy storage, cross regional DC interconnection (using the complementary effect of large power grid), and thermal power flexibility transformation (Wang et al., 2025).

Although the existing research has achieved fruitful results, there are still significant research gaps on the following key scientific issues:

Power grid resilience under complex extreme weather: the existing studies are mostly focused on single meteorological factors, and the research on “worst case” superimposed by multiple extreme conditions such as “no wind, no light, extreme cold/extreme heat” is insufficient. It is necessary to develop the resilient grid planning and operation theory considering the weather power coupling, and study the black start and rapid recovery strategies in extreme scenarios.

Long term/seasonal energy storage technology: lithium ion batteries are suitable for hour level energy transfer, but to solve the imbalance of renewable energy output in days, weeks and even seasons, it is necessary to explore the economy and system integration scheme of long-term energy storage technologies such as hydrogen energy storage and compressed air energy storage (CASE).

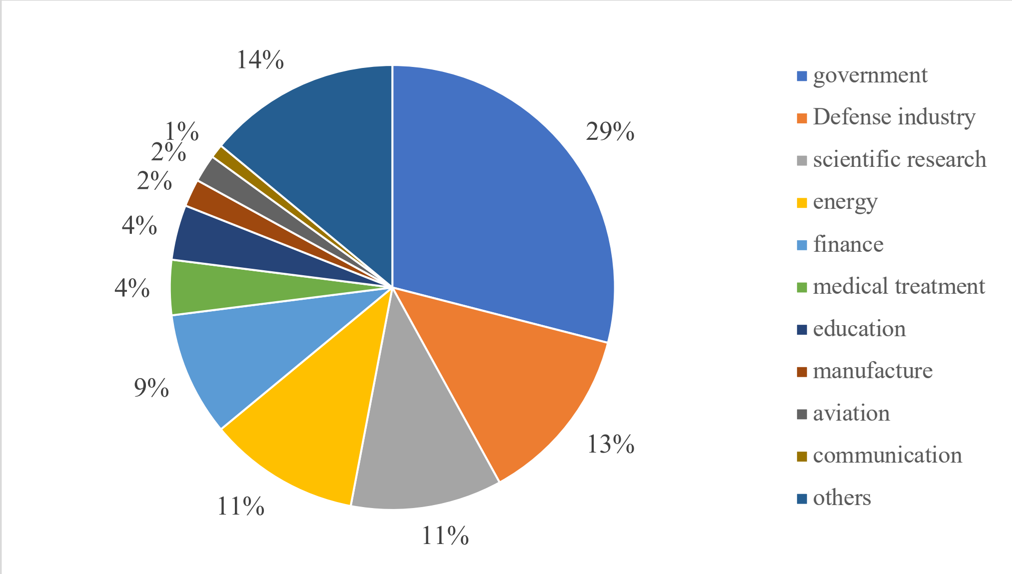
Collaborative optimization of the whole link of source network load storage: the current optimization model focuses on local links such as “source network” or “source load”, and lacks a unified modeling and collaborative optimization framework that can comprehensively consider the flexible resources, market mechanism and security constraints of the whole link.

3.2 Security Challenges: Increasingly Severe Network Security Threats

The “smart” of smart grid is built on the highly interconnected information network, which makes its attack surface expand rapidly, from the traditional physical security to the severe network security field.

New network attack mode: the new attack mode for smart grid summarized in the literature is worrying. Advanced persistent threat (APT) aims at long-term and slow penetration of specific power grid enterprises, aiming to steal core data or wait for the opportunity to launch a fatal blow. False data injection (FDI) attacks mislead dispatchers to make wrong decisions and even cause cascading failures by tampering with the measured data of sensors or SCADA systems. Large scale attacks on smart meters may lead to user data leakage, electricity fraud, and even be used as botnets to launch distributed denial of service (DDoS) attacks (Efatinasab et al., 2025). The blackouts of Ukraine power grid in 2015 and Venezuela power grid in 2019 have been confirmed to be related to cyber attacks. At the same time, cyber attacks on key facilities around the world have surged by 300% in the past five years. Figure 3 shows that the power system has become an important target of attacks because of its high interconnection with other facilities, which has sounded the alarm for the global power industry (Zhang et al., 2025).

Figure 3: Main target industries of network attack in 2023



Existing protection strategies: Currently, China mainly follows the provisions on security protection of power monitoring system issued by the national development and Reform Commission, the core of which is to establish a protection system of "security zoning, network dedicated, horizontal isolation and vertical certification" (National Development and Reform Commission, 2025). This system has played an important role in isolating the internal network from the public Internet.

The traditional border protection strategy has limitations in the face of high-level and internal attacks. Future research gaps and directions include:

"Zero trust" security architecture: This paper studies the "zero trust" architecture for power control system. Its core idea is "never trust, always verify". It carries out dynamic and fine-grained identity authentication and authorization for all access requests to minimize the risk of attack horizontal movement.

Post Quantum Cryptography: with the development of quantum computing, the public key cryptography system currently widely used faces the risk of being cracked. It is urgent to prospectively study the post quantum cryptography algorithm which can resist the attack of quantum computing, and explore its application in embedded devices of smart grid.

System recovery model under network attack: it is necessary to establish a coupling model between network attack and physical power grid fault, and study how to quickly locate damaged nodes, isolate malicious code and realize self-healing and recovery of power system after targeted network attack.

3.3 Market and Policy Challenges: Building a Unified and Efficient Electricity Market

A market and policy environment that matches the development of technology is the catalyst to give full play to the value of smart grid. However, the reform of China's electricity market is still in the deep water. Academic research has unanimously pointed out the following major problems:

Inter provincial barriers: This is the core sticking point that hinders the cross provincial consumption of renewable energy. In order to protect local thermal power enterprises, protect local taxes and employment, some provinces have set up hidden barriers through administrative means, such as restricting the input of new energy power from other provinces, and setting unfair transmission prices or limits in inter provincial transactions (Xia et al., 2025).

The market mechanism is not perfect: the connection between the medium and long-term market, the spot market and the auxiliary service market is not smooth enough. The spot market price signal can not fully reflect the degree of power scarcity and congestion in different time and space. Emerging market varieties such as capacity market and demand response market are still in the exploratory stage, unable to provide a stable return on investment expectation for flexible resources.

Barriers to participation of emerging players: emerging market players such as distributed photovoltaic, user side energy storage, and load aggregators face barriers such as high barriers to entry, complex trading mechanisms, and settlement difficulties when participating in market transactions, and the value of their flexibility is difficult to be reflected through marketization (Wang and Wang, 2023).

In order to promote the power market to better support the “double carbon” goal, future research should focus on the following frontier topics:

Coupling mechanism of green power market and carbon market: deeply study the price transmission mechanism, transaction coordination mode and policy convergence point of the two markets to form the superimposed incentive to promote emission reduction and truly reflect the environmental value in the electricity price.

Design of spot market for high proportion of new energy: explore the introduction of new market varieties such as clearing model with probability information and climbing products to better manage the uncertainty of renewable energy.

Theory and mode of distributed energy participating in market transactions: study the business model, technical support system, credit evaluation method of distributed energy aggregators and the cooperative operation mechanism with the distribution system.

4. Discussion and Future Research Direction

4.1 Interconnection of Cross Domain Challenges

The technical, security, market and policy challenges faced by the construction of smart grid are not isolated from each other, but constitute a complex and interconnected challenge ecosystem. A profound understanding of its interconnectivity is the prerequisite for formulating systematic solutions.

For example, the imperfect market mechanism (challenge 3.3) will directly inhibit the development and application of energy storage and demand response technologies. If the energy storage power station cannot obtain reasonable income through arbitrage of peak valley price difference or participation in auxiliary service market, its investment enthusiasm will be greatly reduced. Similarly, if the compensation for users’ participation in demand response is too low, their willingness to respond will inevitably decline. This in turn exacerbates the technical challenge under the high proportion of renewable energy (challenge 3.1), because the system loses these valuable flexibility resources and becomes more vulnerable. On the other hand, network security (challenge 3.2) is the basic guarantee for the implementation of all digital technologies and market-oriented transactions. A fragile network environment will make advanced collaborative control technology and transparent market transactions unable to be carried out safely, thus restricting technological breakthroughs and market construction at the same time.

Therefore, any solution of “treating head pain and foot pain” can achieve half the result with twice the effort. We must adopt systematic thinking and recognize that technological breakthroughs need market traction and policy escort, market construction needs technical support and security, and policy formulation needs to consider the feasibility of technology and market as a whole.

4.2 Suggestions for Future Research Directions

Based on the overview of the current situation and the analysis of the challenge of interconnection, this paper puts forward the following key research directions in the future, in order to provide academic guidance for the healthy development of China’s smart grid.

Technical level:

Power system digital twin: build a digital twin system with synchronous mapping, virtual real interaction and iterative optimization with the physical power grid, and use it as a powerful platform for power grid planning, simulation, intelligent operation and maintenance and personnel training.

Artificial intelligence driven ultra short term power prediction: develop the next generation AI prediction model integrating multi-source data (such as satellite, radar, ground-based cloud images) and physical information, shorten the prediction time to 15 minutes and improve the accuracy to more than 95%.

Full life cycle assessment of new energy storage technologies: carry out a systematic assessment of the technical economy, environmental friendliness and carbon footprint of technologies such as flow battery, compressed air energy storage and sodium ion battery, so as to provide a scientific basis for the selection of technical routes.

Market level:

Collaborative clearing model of the national unified electricity market: study the joint clearing algorithm and congestion management mechanism that can efficiently coordinate the intra provincial market and inter provincial and inter regional markets, medium and long-term transactions and spot transactions.

Distributed energy aggregator business model: explore the distributed energy aggregator business model for different scenarios such as residents and businesses, and clarify its rights and obligations, income distribution and risk sharing mechanism.

Design of capacity compensation mechanism: study the capacity market or capacity compensation mechanism suitable for China's national conditions to ensure that the system has sufficient reliable capacity during the energy transition period and ensure the safety of power supply.

Policy and security level:

Industrial policy system to support smart grid technology innovation: study a comprehensive industrial policy toolbox covering R&D funding, tax incentives, standard setting, demonstration projects, etc.

Green electricity traceability and trading system based on blockchain: using the decentralized, tamper proof and traceable characteristics of blockchain technology, build a transparent and credible green electricity consumption traceability system to stimulate users' enthusiasm for purchasing green electricity.

Application of network security insurance in the field of power: explore the introduction of network security insurance into the power industry, disperse and transfer network risks through market-oriented means, and use the risk control ability of insurance companies to urge enterprises to improve the safety level.

Cross cutting areas:

Energy information society system coupling model: establish an interdisciplinary model that goes beyond the traditional power system analysis, and integrate energy technology, information dissemination, user behavior, and socio-economic factors into a unified framework for more realistic policy simulation and impact assessment.

Comprehensive energy system planning considering the uncertainty of user behavior: in the regional comprehensive energy system planning, behavioral economics and social psychology theories are introduced to quantify the uncertainty of user behavior and improve the robustness of the planning scheme.

5. Conclusion

This review systematically demonstrates the irreplaceable core position and grasping role of smart grid in the process of realizing the "double carbon" goal in China. It is not a simple technological upgrading, but a comprehensive and all-round profound revolution in the power system through digital and intelligent empowerment. Its core value is to systematically improve the penetration of renewable energy, realize the lean management of grid assets, and fully stimulate the flexibility potential of load side, so as to build a clean, low-carbon, safe and efficient new power system.

This paper summarizes the three core advantages of smart grid: in terms of enhancing the penetration of renewable energy, it depends on advanced prediction, flexible scheduling and distributed management technology system; In terms of optimizing asset management, the paradigm shift from preventive maintenance to predictive maintenance has been realized, and energy efficiency and reliability have been significantly improved; In terms of enabling new loads, challenges are transformed into opportunities through technologies such as demand response and V2G. However, the road to the future is full of thorns. This paper sorts out three key challenges from the perspective of literature: facing the problem of system stability and toughness caused by the high proportion of renewable energy connected to the grid; In terms of security, it encounters severe network security threats caused by high interconnection; In terms of market and policy, it is urgent to build a national unified, efficient and fair power market system to optimize resource allocation.

More importantly, these challenges are intertwined and affect each other. The solution lies in the synergy of technological breakthrough, policy innovation and market construction. We call on academia, industry and government departments to break the barriers in the field, carry out deeper interdisciplinary and interdisciplinary cooperative research, and jointly focus on cutting-edge directions such as digital twins, advanced AI prediction, new energy storage, unified market design, and zero trust security architecture. Only through collaborative innovation and systematic promotion can we overcome the obstacles on the way forward, give full play to the huge potential of smart grid, help China achieve the grand goal of "double carbon" as scheduled, and contribute Chinese wisdom and strength to the global response to climate change.

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Conflicts of Interest

The authors declare no conflict of interest.

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