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Exploration on the Coordinated Development Path of Power Market and New Energy under Smart Grid System

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Abstract

This paper studies the coordinated development path of power markets and new energy in a smart-grid system. With the increase in the proportion of renewable energy, a centralized dispatch system for the power market will be gradually replaced by a flexible, data-driven multi-agent coordination model. The technical foundations of smart grids include the digitalisation of metering systems, real-time communication, and distributed control technologies. The coordinated development of market mechanisms, grid operations, and renewable-energy policies is essential for successful integration. Based on recent research on smart grids, electricity market modelling, renewable energy integration, and market design under high-renewable conditions, the four main paths have been identified in this article: market-based flexibility allocation, distributed energy participation, data-enabled forecasting and settlement, and institutional coordination among grid operators, regulators and renewable energy producers. Therefore, the paper concludes that smart-grid-enabled market reforms are needed to build a stable power supply system for renewables.

Keywords

Smart Grid; Power Market; Renewable Energy; Renewable Integration; Market Coordination; Flexibility.

1. Introduction

Decarbonisation, digitalisation and distributed generation are all causing the power sector to be restructured. Smart-grid technologies provide the technological foundation for this transformation through bidirectional information exchange, advanced monitoring, and real-time control of electricity systems. At the same time, the growing share of wind and solar power has introduced challenges such as generation variability, uneven geographical distribution, and periods of low or no output, all of which affect electricity markets.

The current problem is no longer whether renewable energy can connect to the grid, but how to establish market mechanisms that support large-scale integration of renewable energy safely, affordably and efficiently. Recently, some studies have indicated that the electricity market should better consider flexibility, storage, uncertainty and grid services to function effectively in a low-carbon environment [2, 3]. Therefore, a smart grid is both a new-generation system and a vehicle for market reform.

This paper investigates the joint development path of power markets and renewable energy in a smart-grid system. It will explore how market design, operational control and renewable energy deployment should develop together. This paper argues that effective coordination depends on four key elements: price signals that incentivise flexibility, data systems that support real-time decision-making, regulatory arrangements that encourage distributed participation, and planning mechanisms that integrate renewable energy with grid constraints.

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2. Smart Grid Basis

Smart grids are power systems that incorporate digital communication, automation, and real-time analytical capabilities for grid operation. The Department of Energy has proposed that the smart grid modernization program will boost system stability and resilience and increase the utilization of renewable resources through intelligent network monitoring [1]. Smart grids are also referred to as systems for promoting distributed energy cooperation, local control and market interaction in the academic community [5].

These characteristics improve the observability and controllability of the power system within market operations. Without intelligent-grid facilities, accurate measurements of distributed generation will not be available in a timely manner, and large-scale demand-response management cannot be realised. With the increase in the proportion of renewable energy, the grid will need to be developed into an adjustable platform for two-way electricity flow and market participation [2,5].

3. Market Coordination

3.1. Flexibility Pricing

The first pathway involves introducing pricing mechanisms that reward flexibility and scarcity in electricity markets. A 2024 review of power market models for the clean energy transition suggests that in the future, these markets will need to better reflect resource opportunity costs, storage, temporal resolution, uncertainty, and co-optimization of energy and grid services [3]. Therefore, new energy should not be considered an independent source of electricity but needs to be included in the market mechanism to reward balancing capacity, ramp-up and down ability, and reserve provision.

With flexible tariffs, batteries and demand response technologies will participate in market balancing for hybrid renewable energy systems more readily. It will reduce curtailment of renewable energy through economic incentives. Smart grids have collected a lot of operational data; therefore, at present, this pricing can be carried out more precisely than in the old system [3, 4].

3.2. Distributed Participation

A second way is the extended deployment of distributed energy resources. Smart-grid-enabled systems can make households, communities, microgrids and prosumers active participants in the market rather than passive consumers. Research on information systems for smart electricity grids has shown that the sustainability of such grids depends on the combined efforts of all parties and data-driven market operations [6].

Distributed participation can support the development of local flexibility markets, peer-to-peer electricity trading, and demand-response programmes. Distributed solar and storage can bid into the power market, and thus the power market will be more flexible and better deal with changes in renewable energy generation. As a result, a more coordinated system can emerge in which physical resources and market signals interact efficiently.

3.3. Market Design under High Renewables

As the proportion of renewable energy in power generation continues to increase, the construction model of a new electricity market will also change. Recent research on electricity spot markets with high renewable-energy penetration suggests that simulations, multi-agent modelling, and scenario analysis are increasingly important for developing stable market rules [7]. High-renewable systems have relatively higher requirements for handling forecast errors, reserve adequacy and intertemporal constraints.

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Therefore, coordinated market development requires more flexible market products, including shorter settlement intervals and higher-resolution price signals. These mechanisms help align investment incentives with operational requirements and support the integration of renewable energy into smart-grid systems.

4. Renewable Energy Integration

4.1. Forecasting and Dispatch

Wind and solar power have been developing rapidly, and now more accurate forecasts are required for their joint development. The digital infrastructure of a smart grid supports short-term forecasting, state estimation and adaptive dispatch. A recent review of smart grids and renewable energy integration shows that, to address the integration problem, flexibility of the grid, storage systems, interoperability and demand-side management should all be strengthened [8, 9].

However, forecasting is not the entire problem. Forecasting must be closely integrated with dispatch decisions and market-settlement mechanisms. Updated forecasts should be incorporated into market bids and into the scheduling of flexible loads and energy-storage resources. A smart grid will reduce information lag and increase the entire system's observability.

4.2. Storage and Hybrid Resources

Energy storage is suitable for reducing fluctuations in renewable energy generation and providing supporting services. As the clean energy transition market model evolves, storage will be employed to improve the flexibility of both energy and grid services through joint optimisation of the two [3]. A hybrid renewable-storage system will reduce curtailment and stabilize price fluctuations.

Thus, new-energy development and market reform have been linked. The more flexibility is favoured by the market, the more appealing a storage is. With more storage units added, it will be easier to manage the fluctuations in renewable energy sources in a smart grid. Therefore, the coordination is based on a feedback loop of market incentives and technical feasibility.

5. Coordinated Pathways

5.1. Policy and Regulation

The first pathway is regulatory coordination. Align the grid code, market rules, renewable energy subsidy system and data-sharing standard to enable fair and open participation of renewable energy. If the policy supports generation but lacks flexibility, the system will be constrained. Policies that encourage market participation without supporting grid reinforcement may undermine system reliability. Effective coordination requires both [9].

5.2. Digital Infrastructure

The second pathway is digital infrastructure development. A system consisting of smart meters, forecasting platforms, communication protocols, and settlement mechanisms should be established to make renewable and distributed energy resources market-ready [10, 12]. Therefore, the smart grid will be a supporting system for integrated development, not just an add-on [1,5]. Advances in digital infrastructure make finer-grained measurements possible, thereby improving power system monitoring for both real-time operation and long-term planning [10].

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5.3. Flexible Resources

The third pathway is the deployment of flexible resources. Demand response, storage, flexible industrial loads, electric vehicles and hybrid power plants can all reduce fluctuations. Market mechanisms can assign economic value to these resources, allowing them to be compensated for the flexibility services they provide [11]. Otherwise, the expansion of new-energy development will be unstable and not reduce carbon emissions.

5.4. Data-driven Governance

The fourth pathway is data-driven governance. Electricity markets operating within smart-grid systems generate large volumes of operational data, which can support forecasting, monitoring, anomaly detection, and policy evaluation. Research on smart electricity markets has shown that information systems can provide a shared decision-making environment for market participants, including grid operators, consumers, regulators, and renewable energy producers [6].

6. Related Challenges

There are also several challenges to the coordinated development pathway. First, renewable uncertainty will make market clearing and reliability management more difficult. Second, data interoperability and cybersecurity remain essential but are difficult to standardize across different systems and market participants. Third, price signals can only work well if the participants believe in the rules and have good technical facilities. Fourth, grid congestion may reduce the benefits of market incentives for renewable energy [2-3, 8].

Another challenge is the limited large-scale deployment of projects beyond the pilot stage. Some areas have implemented smart-grid trials; however, to build a large-scale smart grid, institutional reform and cross-sector cooperation are still required. Therefore, joint development should be regarded as an all-encompassing system of policies rather than a single one.

7. Conclusion

Joint development of power markets and renewable energy under a smart grid system requires technical, economic and institutional reforms. Smart grids provide the digital visibility and operational control necessary for renewable energy integration, while market mechanisms create price signals that incentivize flexibility, energy storage, and participation by distributed energy resources. Together, these components will reduce curtailment, enhance stability, and promote the transition to a green power system.

The above is the general conclusion: smart-grid-based market reform needs to be an all-encompassing system. If the rules of the market, grid operation and renewable energy planning can all be harmonised, then renewable energy will be integrated into the power system smoothly and power markets will be more stable. These coordinated pathways provide a practical plan for the energy transition in a high-renewable environment.

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