CASE STUDY

Assessing the impacts of large-scale offshore wind power in Southern China

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Abstract
As an important renewable energy resource, wind power has been greatly developed in Southern China to meet the increasing demands. In the context of power industry deregulation and hence electricity market development, wind power introduces new uncertainties for market participants and affects the long-term planning of the power system concerned. In this paper, we use a simplified Guangdong power system model to simulate the electricity market in Southern China from 2019 to 2028. To study the economic and reliability impacts of installing large-scale offshore wind farms, case studies are conducted to simulate two targeted scenarios, that is, with and without offshore wind power penetration. Based on the presented model, the well-established Monte Carlo simulation method is applied to assess the reliability of the Guangdong power grid by calculating the expected unsupplied energy (EUE). The experimental results show that the integration of offshore wind power farms will reduce the locational marginal prices (LMPs) as well as the weighted average spot price. The power flow on transmission lines with nodes connected to offshore wind farms will increase and the increase rate is higher in cases with higher demand. In addition, the increased EUE indicates that the integration of large-scale offshore wind power farms will impair the reliable operation of the power grid. The proposed system model delivers practical references to renewable energy evaluation and regional electricity market operations.

1 INTRODUCTION

Owing to the gradual exhaustion of fossil fuels and increasingly prominent environmental issues, more renewable energy resources (such as wind, hydro, and solar) are needed to ensure power systems can simultaneously satisfy the rapid growth of energy demand and achieve sustainable development. According to the Renewable Global States Report, renewable energy targets for the share of electricity generation by 2030 is 35% in China, 50% in California (United States), and 65% in Germany [1].

Compared with other renewable energy resources, the technology of wind power is relatively more mature and extensively used. In terms of construction, technology, and management, wind power has gradually evolved from a supplementary to an alternative energy resource. First, the global cumulative installation of wind power exceeded 591 GW in 2018, an increase of nearly 10% from 2017. Among the newly installed wind power capacities in 2018, approximately 91% were onshore while 9% were offshore. With regard to onshore wind, China took the lead with 21.2 GW installation followed by the United States (7.6 GW), Germany (2.4 GW), India (2.2 GW), and Brazil (1.9 GW) [1,2]. The share of newly installed capacity of offshore wind power units in the total newly installed capacity of all units worldwide increased from 1% in 2009 to 4% in 2018. Second, with the advancement of wind power technologies, the cost...
has gradually decreased in recent years. Levelized cost of electricity (LCOE) is a significant measure in the energy industry that defines the cost of different energy resources. In 2010, the LCOE of onshore and offshore wind energy was approximately $85 and $180/MWh, respectively. These values decreased to $50 and $115/MWh for onshore and offshore wind energy in 2018, respectively [1]. Third, the reliability and efficiency of wind power have been rapidly improved in recent years. In China, wind curtailment declined from 17.1% in 2016 to 11.9% in 2017 [3]. In addition, governments in different countries are working to improve the management of the wind energy industry and establish policy systems, particularly, for the offshore wind power energy resource. For example, the German government aims to achieve an offshore wind capacity of 20 GW by 2030. The French government started to conduct an offshore wind power auction in 2019. According to the “13th Five-Year Plan for Wind Power Development,” the cumulative installed capacity of offshore wind in China will achieve 5 GW by 2020. By then, it is estimated that the annual power generation of wind power will account for 6% of China’s total power generation [4].

Offshore wind power offers effective utilization of wind for coastal countries. There are several benefits of offshore wind power. First, it can help mitigate wind curtailment caused by onshore wind power. Most offshore wind farms are built near load centers; thus, enabling local consumption and reducing power transmission losses as well as transmission costs. In China, offshore wind resources are mainly located in well-developed Eastern coastal areas, which provide strong incentives for large-scale development of offshore wind power. Second, offshore wind resources are abundant, contain high average utilization hours, and produce electricity more efficiently than onshore wind resources. Third, as an environmentally and socially friendly energy resource, offshore wind power can reduce greenhouse gas emissions and increase employment opportunities.

Despite these advantages, the economic and reliability impacts of large-scale offshore wind power need to be re-evaluated because there are several obstacles in practical situations. First, although the cost of offshore wind farms has reduced [1], it is still relatively high because offshore turbines need to be installed and operated at sea. Moreover, the production and installation of corresponding power cables can be very expensive [5]. Second, if a large-scale offshore wind farm is auctioned at an electricity market, it is highly possible that these wind farms will be bid on at the market price floor owing to their low operating cost. Therefore, the settlement price of the spot market will be significantly affected. Third, if the transmission lines between offshore wind farms and adjacent grids are insufficient, offshore wind power will experience similar problems of wind curtailment as onshore wind power. Finally, owing to the complete dependence of the generation of offshore wind power on natural conditions in coastal areas, its output is inevitably intermittent. Additionally, the maritime climate is harsh; the weather, waves, tides, and other factors are complex and variable. Offshore turbines are susceptible to damage in the event of severe weather such as typhoons and heavy rain, which not only cause economic loss but also significantly impair the stability of the power grid [6]. In these situations, the safety of the power grid within the entire load area will be challenged owing to the disappearance of the controllable power supply.

Studies on the influence of constructing wind power plants are extensive. For system stability analysis, Sorensen et al. discovered that offshore wind farms generated power with more prominent fluctuations than those of onshore wind farms [7]. The voltage fluctuations generated by offshore wind farms were also confirmed by Li et al. [8]. The corresponding stability was analyzed based on different countries. Giupuliga et al. analyzed the security of the Dutch offshore grid, demonstrating that loops in the offshore power grid are indirectly proportional to the use of the secure grid capacity in the market [9]. In ref. [10], through the study on wind power plants in California, Muljadi et al. revealed that the rapid growth of wind energy in the early stages of wind power development can pose a threat to the stability of the power grid and quality of the power supply owing to the lack of regulations. To alleviate these negative impacts, Garcia and Babazadeh indicated that more sophisticated communication devices and controllable generation units were needed by wind farms [11].

Studies on the impact of offshore wind farms on the electricity market have also been conducted. Although the operating cost of offshore wind farms is lower than those of other energy sources [9,12,13], Sun et al. proposed that it was difficult for wind power to be auctioned in an electricity market because of its random and intermittent characteristics [14–16]. Meanwhile, Gebrekiros et al. [17] analyzed the Nordic electricity market, and showed that offshore wind power boosted the cross-country electricity trade, and further augmented the integration of the day-ahead market in Europe. Mathew et al. [18] analyzed the wind power plants in the states of Gujarat and Tamil Nadu, India, and revealed that wind power plants had positive effects on the country’s economy by providing additional employment and serving as tourism attraction sites.

In this study, we make the following three key contributions:

(i) We design a system model to evaluate the policies of energy resources planning at the provincial level. It is noteworthy that we are among the first to analyze the impact of large-scale offshore wind power in Southern China in the context of China’s first spot electricity market and first cross-area market pilot (started from Guangdong).

(ii) In this study, we have proved that the integration of offshore wind power will significantly influence the economy of the electricity market and the reliability of the power system by conducting the simulation experiments from 2019 to 2028.

(iii) Our model delivers references on how renewable energy can be reasonably evaluated in policy design, that is, long-term energy policy design has to consider multiple factors (such as economy, reliability, and physical environment),
and adjust energy structure, transmission lines, and market mechanisms based on the electricity market and power grid.

This paper is organized as follows: Section 2 provides a brief introduction of the power system in Southern China and construction layout of offshore wind farms; Section 3 introduces the mechanism of the market clearing model and Monte Carlo method; Section 4 presents detailed information and steps of the simulation experiment; Section 5 presents the simulation results as well as corresponding analysis; finally, Section 6 concludes the paper.

2 | OFFSHORE WIND POWER PLANNING IN SOUTHERN CHINA

2.1 | Power grid in Southern China

In this paper, Southern China refers to five provinces including Guangdong, Guangxi, Guizhou, Yunnan, and Hainan, which are covered by China Southern Power Grid (CSG). CSG has a power supply area of more than 1,000,000 km² and is connected to the power grid of Hong Kong, Macao, and Southeast Asia. At the end of 2018, the total installed capacity within Southern China was 320 GW comprising 160, 120, 18.38, and 16.77 GW of thermal, hydro, wind, and nuclear powers, respectively (accounting for 48.2%, 37.4%, 5.6%, and 5.1%, respectively). In 2018, the total electricity consumption in Southern China was 1162.8 TWh with 217.5 TWh of electricity transmitted from “West to East.” Guangdong Province has always made the greatest contribution to power consumption in Southern China [19].

2.2 | Construction layout

Guangdong Province contains 4114 km of coastline and 419.3 km² of sea area. The theoretical reserves of wind energy resources in the coastal waters are approximately 100,000,000 kW. The sea area of Guangdong Province has a high average wind speed, intensive wind power density, high utilization hours, low turbulence intensity, and abundant wind resources with good quality [20]. Therefore, Guangdong has already devoted itself to the promotion of offshore wind power construction for a few years. According to the “Guangdong Province Offshore Wind Power Development Plan (2017–2030),” Guangdong plans to construct 23 offshore wind power sites: 15 sites in 35 m shallow waters with a total installed capacity of 9.85 GW (4.15 GW in Eastern Guangdong, 1.5 GW in Pearl River Delta, and 4.2 GW in Western Guangdong); 8 sites in 35–50 m deep waters with a total installed capacity of 57 GW (distributed in the sea areas of Eastern and Western Guangdong) [20].

Furthermore, according to the “Hainan Province 13th Five-Year Energy Planning” [21], Hainan will accelerate the construction of wind power, especially offshore wind power. The total installation of wind power will reach 650 MW by the end of 2020 with 350 MW of offshore wind power. Guangxi Province plans to establish wind power plants of 4.5 GW including new constructions and continued constructions. An additional 3 GW will be operational by 2020 [22].

Figure 1 shows a general construction layout of power consumption, West–East power and offshore wind in Southern China. Figure 2 shows the location and installed capacity of offshore wind farms that would be constructed and operated from 2019 to 2028.

2.3 | Wind power in market

The Chinese government encourages clean energy generators to participate in the electricity market. Owing to the secure and stable operation of the power grid, wind power should be organized based on the resource conditions within the region when the annual power generation plan is formulated. If the full supply of clean energy exceeds the newly increased power demand in areas containing abundant energy resources and high penetration of wind power, measures should be taken to facilitate direct transactions between clean energy generators and users [23].

3 | ELECTRICITY MARKET MODEL

3.1 | China electricity market reform

In 2015, the Communist Party of China Central Committee and State Council issued No. 9 Document on power system reform. The overall idea was to explore marketization, build an advanced energy system, and reduce carbon emissions. In terms of power trading systems, it indicated the need to guide market entities to conduct multi-party transactions, encourage the development of long-term stable trading mechanisms, and improve the cross-regional electricity market [24]. To build a competitive market structure effectively, “Notification on Pilot Construction of Spot Electricity Market” issued by National Development and Reform Commission of China in 2017 proposed that the establishment of spot market should be accelerated to further deepen the electricity market reform. In accordance with the will of the local government and preliminary preparations, the Southern (started from Guangdong), West Inner Mongolia, Zhejiang, Shanxi, Shandong, Fujian, Sichuan, and Gansu were selected to be the first batch pilots based on the status of power supply, demand, network structure, and marketization [25]. As the only cross-area pilot, the spot market in the Southern (starting from Guangdong) performed well and officially ran on May 14, 2019, with the settlement results delivered on May 20, 2019.
3.2 | Market clearing model

3.2.1 | Electricity market

Proposed in “Southern (Started from Guangdong) Power Spot Market Implementation Plan (Manuscript)” formulated by the Guangdong Development and Reform Commission and the Economic and Information Committee in 2018, the trading mechanism of day-ahead and the real-time spot energy market with full-scale bidding in Guangdong Province would be fully established by the end of 2019 [26]. In 2019, the trial settlement has been successfully operated in Guangdong electricity spot market. The marketplaces of Guangdong electricity market can be divided into wholesale and retail markets. The overall
framework of the wholesale market combines electric energy and ancillary service markets. The energy market includes medium- and long-term electricity energy markets based on the contracts for differences together with a full-time day-ahead and real-time spot energy markets [27]. Meanwhile, the implementation of the electricity retail market is completed by a power transaction agreement between the electricity sales company and the user.

The trading of power spot is conducted in the day-ahead and real-time markets. In the day-ahead electric energy market, generators report the segmented electricity quantities and the corresponding prices. Through security-constrained economic dispatch (SCED), the output of each generator and nodal prices are obtained. In the early stage of market construction, the demand side only needs to quote the quantity; however, later, users need to quote both price and power quantity [27]. The real-time energy market uses SCED for ultra-short-term optimization based on the day-ahead market to minimize the cost of power generation under balanced load conditions.

In this market structure, the electricity prices in spot market are determined by the locational marginal prices (LMPs). Market clearing is performed after every 15 min such that the LMPs are obtained. Meanwhile, the average nodal price is calculated using the average clearing price in four cycles per hour. The spot market settlement price for each generator is the LMP at the node it connects, whereas the settlement prices for users and the retailers in the wholesale market are determined using the unified settlement electricity price (weighted average electricity price of the whole market) [27].

Generators under a provincial level dispatch and above in Guangdong Province are categorized as Classes A and B. Class A units only have the basic power generation plan, but do not have the qualification to transact directly with the demand side while Class B units refer to the generating units that are qualified for direct transactions with the demand side. Class B units can simultaneously have both the base power and the market power [28].

### 3.2.2 Security-constrained economic dispatch

SCED model is the basis of the operation of spot electricity market. It demonstrates the most economical dispatch for all generators to serve the forecast load, fulfill system reserve and other requirements under physical security constraints. The output of this model is similar to the output of each online generator, LMPs, and reserve prices for each reserve category [29]. The constraints include unit operating constraints, power balance constraints, and transmission security constraints.

The objective function is modeled using Equation (1) as follows:

$$
\min F = \sum_{i=1}^{T} \sum_{i=1}^{n} C_i [P_{Gi}(t)],
$$

where $T$ is the number of periods during dispatching; $n$ is the number of generators; $P_{Gi}(t)$ is the active power of generator $i$ during time $t$; $C_i [P_{Gi}(t)]$ is the operating cost of generator $i$ during $t$, and its expression is usually a quadratic function.

$$
C_i [P_{Gi}(t)] = a_i P_{Gi}^2 (t) + b_i P_{Gi}(t) + c_i,
$$

where $a_i, b_i$, and $c_i$ are the coefficients of the quadratic function.

Unit operating constraints can be expressed using the inequality constraints (3) and (4), which consider the capacity of each unit as follows:

$$
P_{Gi \text{ min}} \leq P_{Gi}(t) \leq P_{Gi \text{ max}},
$$

$$
Q_{Gi \text{ min}} \leq Q_{Gi}(t) \leq Q_{Gi \text{ max}},
$$

where $P_{Gi \text{ min}}$ and $P_{Gi \text{ max}}$ are the minimum and maximum active power outputs of generator $i$; $Q_{Gi \text{ min}}$ and $Q_{Gi \text{ max}}$ are the minimum and maximum reactive power outputs of generator $i$ at time $t$, respectively.

Power balance constraint is expressed in Equations (5) and (6),

$$
P_{Gi}(t) - P_{Bi}(t) - V_i(t)
\times \sum_{j=1}^{n} (G_{ij} V_j(t) \cos \theta_{ij} + B_{ij} V_j(t) \sin \theta_{ij}) = 0
$$

$$
Q_{Gi}(t) - Q_{Bi}(t) - V_i(t)
\times \sum_{j=1}^{n} (G_{ij} V_j(t) \sin \theta_{ij} - B_{ij} V_j(t) \cos \theta_{ij}) = 0,
$$

where $P_{Bi}(t)$ and $Q_{Bi}(t)$ are the active and reactive loads at node $i$ at time $t$; $G_{ij}$ and $B_{ij}$ are the conductance and susceptance between nodes $i$ and $j$; $\theta_{ij}$ is the phase angle difference of nodes $i$ and $j$; $V_i(t)$ and $V_j(t)$ are the voltages at nodes $i$ and $j$ at time $t$, respectively.

Transmission security constraints include flow constraints and node voltage constraints. Flow constraints can be expressed as inequality constraints (7) as follows:

$$
I_{ij \text{ min}} \leq I_{ij}(t) \leq I_{ij \text{ max}},
$$

where $I_{ij}(t)$ is the real power flow over a transmission line for the transmission security constraint between nodes $i$ and $j$ at time $t$; $I_{ij \text{ min}}$ and $I_{ij \text{ max}}$ are the corresponding lower and upper limits of the power flow, respectively.

Node voltage constraints can be modeled using following inequality constraints (8) as follows:

$$
V_{i \text{ min}} \leq V_i(t) \leq V_{i \text{ max}},
$$

where $V_{i \text{ min}}$ and $V_{i \text{ max}}$ are the minimum and maximum voltage limitations at node $i$, respectively.
3.2.3 | Locational marginal price

LMP, also known as nodal price, is defined as the marginal cost required to increase a unit load at a certain node under system constraints. Congestion occurs when the demand for power transmission exceeds the capacity of the transmission network; therefore, the low cost power cannot be transmitted to the load in the restricted transmission area. Instead, the high cost power must be operated [30]. In this case, the market clearing price of the restricted area is higher than that of the unconstrained area. Therefore, LMP can be used to measure the system energy prices and congestion costs.

LMP is defined using Equation (9) as follows:

\[
LMP_{k,t} = \lambda_t - \sum_{l=1}^{L} \left( \tau_{j,l}^{\max} - \tau_{j,l}^{\min} \right) G_{l-k} - \sum_{s=1}^{S} \left( \tau_{j,s}^{\max} - \tau_{j,s}^{\min} \right) G_{s-k},
\]

(9)

where \( \lambda_t \) is the shadow price of the power balance constraint (energy price); \( \tau_{j,l}^{\max} \) and \( \tau_{j,l}^{\min} \) are the shadow prices corresponding to the forward and reverse constraints of the transmission line; \( \tau_{j,s}^{\max} \) and \( \tau_{j,s}^{\min} \) are the shadow prices corresponding to the forward and reverse constraints of the power flow interfaces; \( G_{l-k} \) and \( G_{s-k} \) are the sensitivities of the line and interface, respectively.

3.3 | Monte Carlo simulation

The reliability of the power grid is evaluated by calculating the expected unsupplied energy (EUE), which is the expected amount of electricity not supplied owing to inadequate power generation and transmission capacity [31]. For the proposed method, we apply Monte Carlo simulation to generate random scenarios with different system loads and unit outputs [32]. We assume that the system load follows a normal distribution and the variance can be estimated using historical data [33]. Similarly, we assume that the wind speed in every hour follows a Weibull distribution based on the acquired average wind speed data. We subsequently use randomly generated numbers to derive simulated results, and the corresponding EUE can be obtained for each scenario.

4 | SIMULATION EXPERIMENT

To assess the impacts of integrating large-scale offshore wind power from 2019 to 2028, we establish a simplified model of Guangdong spot electricity market through existing data and network topology. System loads and Class B generators’ bids are two important variables for the simulation system. In our experiment, we predict system loads for each year via historical data and thereafter, we allocated to every node proportionally. New thermal and offshore wind units are classified into Class B, whereas other types of generators including hydropower and nuclear generators are classified into Class A. The declared bids of generators can be divided into up to five bands, and each band contains the quantity of power (MW) and corresponding price (¥/MWh). In addition, the West–East electricity is assumed to be one third of the system load according to previous records. We simulate a typical day in each season from 2019 to 2028 for both with and without considering offshore wind power, such that there are 80 cases in total. Spot market simulation is cleared after every 15 min to obtain the LMPs, unit output, and power flow. Figure 3 shows the process of simulation.

4.1 | Demand forecast

Based on the annual power consumption of Guangdong Province from 2009 to 2018 [34–37], we forecast the amount from 2019 to 2028 via linear regression. The principle of linear regression is the least square method, which aims to minimize the sum of errors between the obtained data and the actual data. Both Statistical Product and Service Solutions (SPSS, statistical software) and sklearn are used and the average growth rate (%) of annual power consumption forecast value for the next 10 years are [3.41, 4.29, 4.11, 3.95, 3.80, 3.66, 3.53, 3.41, 3.30, and 3.19]. In our experiment, we take the demand for one day in the autumn of 2018 as the basis and multiply with relevant ratio to get the load of every node for each case.
TABLE 1  Forecast value of installed capacity from 2019 to 2028 in Guangdong Province

| Year | Total capacity (10 MW) | Thermal | Hydropower | Nuclear | Wind | Solar |
|------|------------------------|---------|------------|---------|------|-------|
| 2019 | 11,614                 | 8467    | 1291       | 1411    | 445  | 424   |
| 2020 | 12,470                 | 8700    | 1570       | 1600    | 600  | 600   |
| 2021 | 12,736                 | 9171    | 1397       | 1637    | 531  | 532   |
| 2022 | 13,162                 | 9524    | 1315       | 1749    | 574  | 586   |
| 2023 | 13,678                 | 9876    | 1323       | 1862    | 617  | 640   |
| 2024 | 14,195                 | 10,229  | 1331       | 1974    | 661  | 694   |
| 2025 | 14,711                 | 10,581  | 1339       | 2087    | 704  | 748   |
| 2026 | 15,228                 | 10,934  | 1347       | 2200    | 747  | 802   |
| 2027 | 15,743                 | 11,286  | 1355       | 2312    | 790  | 856   |
| 2028 | 16,259                 | 11,638  | 1363       | 2425    | 833  | 910   |

4.2  | Installed capacity estimate

4.2.1  | Forecast value

In our experiment, we forecast the installed capacity of diverse energy resources from 2019 to 2028 in Guangdong Province via linear regression using historical data from 2009 to 2018, as presented in Table 1.

4.2.2  | Adjustment value

The prediction results of wind power based on past decade data actually represents the value of onshore wind power capacity because only onshore wind turbines were constructed before 2019. Therefore, linear prediction cannot accurately reflect the capacity of turbines in the future. Combined with the planning documents [20,38,39] together with current data, the prediction results are adjusted, as presented in Table 2.

4.3  | Bids inference (price and quantity)

4.3.1  | Output calculation

The wind data adopted in this study is based on a 24 h average daily wind speed at a location with planned offshore wind farms, including Zhuhai, Jieyang, Yangjiang, and Zhanjiang. The offshore wind turbine selected is Mingyang Intelligent MySe 5.5-155-IB. Its cut-in wind speed is 3 m/s, the cut-out wind speed is 25 m/s, and the rated power is 5.5 MW. The output of a single generator can be calculated as follows:

$$W_r = W_{turbine} \times \eta_{\text{mechanical}} \times \eta_{\text{electrical}}$$

where $W_{turbine}$ is the power output of the wind turbine; $\eta_{\text{mechanical}}$ is the efficiency of the gearbox and alternator; $\eta_{\text{electrical}}$ is the efficiency of the frequency converter. The output power of the wind turbine is relevant to wind speed, and the expression is as follows:

$$P_{turbine} = \frac{1}{2} \rho v^3 S C_p$$

where $\rho$ is the air density; $v$ is the wind speed; $S$ is the swept area, and $C_p$ is the Betz coefficient.

According to the output formula of the wind turbines, the daily output of a single unit can be obtained. Therefore, the total output per day of a wind farm can be calculated by multiplying the output power of a single unit by the planned capacity.

4.3.2  | Price decision

Considering the output characteristics and low operating costs of wind turbines, all units in wind farms are quoted in a unified way, and the quotation for each wind farm is the floor price (in this experiment, the floor price is set at 150 ¥/MWh and

TABLE 2  Adjustment value of installed capacity from 2019 to 2028 in Guangdong Province

| Year | Total capacity (10 MW) | Thermal | Hydropower | Nuclear | Offshore | Onshore | Solar |
|------|------------------------|---------|------------|---------|----------|---------|-------|
| 2019 | 12,441                 | 8743    | 1291       | 1411    | 127      | 445     | 424   |
| 2020 | 13,976                 | 9595    | 1570       | 1600    | 245      | 488     | 478   |
| 2021 | 15,198                 | 10,101  | 1397       | 1637    | 1000     | 531     | 532   |
| 2022 | 15,675                 | 10,221  | 1315       | 1749    | 1230     | 574     | 586   |
| 2023 | 16,481                 | 10,589  | 1323       | 1862    | 1450     | 617     | 640   |
| 2024 | 17,229                 | 10,970  | 1351       | 1974    | 1670     | 660     | 694   |
| 2025 | 18,162                 | 11,365  | 1339       | 2087    | 1920     | 703     | 748   |
| 2026 | 19,009                 | 11,774  | 1347       | 2200    | 2140     | 746     | 802   |
| 2027 | 19,901                 | 12,198  | 1355       | 2312    | 2390     | 790     | 856   |
| 2028 | 20,778                 | 12,637  | 1363       | 2425    | 2610     | 833     | 910   |
the cap price is 1000 ¥/MWh). In terms of thermal generators, the quotation in each band refers to the average value of similar generators at the same access point.

4.4 Monte Carlo

In our experiment, we assume that the load follows a normal distribution and we set the standard deviation to be 10% of the total demands. We then fit wind speed using historical data based on Weibull distribution. Subsequently, we calculate the relevant total output for each offshore wind farm. In our experiment, EUE is equal to the total load less the total output. The total load is equal to the sum of demands within Guangdong Province, demands from an external node (e.g., HK), and a pumping load. The total output is equal to the sum of the output of Class A units, Class B units, and West-East Power.

For each of the 80 cases, we use Monte Carlo simulation to generate random scenarios, and record the simulated results. EUE and the proportion of EUE in the total load are calculated to analyze the reliability impact by predicting the possible inadequate power generation. Negative EUE will be set to 0 when calculating average EUE for each case because EUE estimates the situations where excessive load cannot be satisfied.

5 RESULTS ANALYSIS

The market simulation model is cleared after every 15 min, and the results of every hour are collected for further analysis.

5.1 Economic impact

To assess the economic impact, LMP, weighted average spot price, and power flow of both 220 and 500 kV transmission lines were considered.

5.1.1 LMP

To clearly analyze the impact on different nodes, we selected several nodes connected to offshore wind farms and nodes not connected to offshore wind farms to make comparisons. For the following figures, the inter-frames between adjacent years represent 24 h a day (i.e., [1:00, 2:00, …, 24:00]).

Nodes connected to offshore wind farms

In terms of nodes connected to offshore wind farms, (for instance, Pingdi, Bajitou, Wentao, and Shuangzhai I), we compared LMPs under conditions with and without integrating offshore wind power. Figures 4–11 are the LMPs of two representative nodes (i.e., Bajitou and Wentao) for each season from 2019 to 2028, respectively.
The simulation results show the following:

(a) The integration of offshore wind power will directly decrease LMPs of the nodes connected to offshore wind farms. As shown in Figures 4–11, in each season of the next decade, the LMPs have different degrees of reduction compared with those of no offshore wind power, and the reduction rate increases annually (except for the Pingdi node).

(b) It is also clear that after 2020, the LMPs are basically at the floor price for every season because offshore wind farms bid at floor price; thus, they are given priority during market clearing. As the installed capacity of offshore wind power increases, the LMPs of relevant nodes will be greatly reduced to the floor price.

Nodes not connected offshore wind farms

In terms of nodes without offshore wind farm integration, (for instance, Tieshan, Baocheng, Tanjie, and Yaogang), we compared LMPs under the conditions of with and without integrating offshore wind power. Figures 12–19 show the LMPs of two
The simulation results show the following:

(a) After integrating offshore wind power, the LMPs of the nodes not connected to offshore wind farms were slightly reduced, but the reduction rate was less than those of the nodes connected to offshore wind farms.

(b) For nodes not connected to offshore wind farms, electricity prices were rarely pulled down to the floor price. This is because these nodes are not connected to offshore wind farms and market clearing is mainly operated through the competition among thermal generators.

(c) During the same period, the electricity price of the same node in summer and autumn was higher than that in spring and winter, and the cap price frequently occurred during the peak periods in summer and autumn. Owing to the high load during summer and autumn, when the output of the low-quote units on the power generation side cannot satisfy the demand, the high-quote units must be executed to generate electricity, resulting in higher LMPs.

5.1.2 Weighted average spot price

The weighted average spot price is a direct measurement of electricity price change in the spot market, which is calculated based on the supply of electricity at each node. Figures 20–23 represent the weighted average spot price for each season from 2019 to 2028, respectively.
The simulation results show the following:

(a) As shown in Figures 20–23, when the growth rate of stable power generation on the generation side of the system cannot match with the growth rate of the load on the demand side, the weighted average spot price will increase yearly.

(b) For both the cases of integrating and not integrating offshore wind power, the weighted average spot price in each season gradually increases yearly (except for a short time in winter).

(c) For both the cases of integrating and not integrating offshore wind power, considering the high demand in summer and autumn, the weighted average spot price is generally higher than that in spring and winter.

(d) For a significant proportion of the following 10 years, in the cases of integrating and not integrating offshore wind power, the peak of the weighted average spot price is mostly concentrated in the 18:00–22:00, which basically overlaps with the peak period of power consumption.

(e) After integrating offshore wind power, the weighted average spot price of each season has been reduced to diverse degrees, and the reduction rate increases yearly. This is in line with the previous analysis of the LMPs of a single node, meaning the integration of large-scale offshore wind power will directly decrease the LMPs in Guangdong Province.

5.1.3 220 kV power flow

For the following figures, the inter-frames between adjacent years represent a single season. We selected four representative 220 kV transmission lines, two of which contain nodes connected to offshore wind farms (i.e., Huahu-Xiangyun I and Chaoyang-Haojiang I) while the other two does not (i.e., Liangying-Tieshan and Qujiang220-Tianjie). Figures 24–27 represent the power flow for the selected transmission line in 2019 and 2028, respectively.

The simulation results show the following:

(a) The integration of offshore wind power increased the power flow of 220 kV transmission lines with nodes connected to offshore wind farms. During the same year, the increase rate in summer and autumn was higher than that in spring and winter, and in the same season, the increase rate of 2028 was higher than that of 2019.

(b) As shown in Figures 24–27, the power flow of the transmission line that was connected to offshore wind farms was significantly increased after integrating offshore wind power. However, there is no consistent increase or decrease rule in the change of power flow of transmission lines that are not connected to offshore wind farms.

(c) Owing to the priority given to wind turbines in market clearing, more low-quote offshore wind units will be executed in summer and autumn due to higher loads; thus, the power flow of corresponding transmission lines is significantly improved after integrating offshore wind power. There is no need to expand the current 220 kV transmission lines because the capacity limit is substantially higher than the value of power flow.

5.1.4 500 kV power flow

For each case, we estimated whether the congestion occurs on all 500 kV transmission lines. The results showed that the con-
gestion only occurs in the Huizhou–Dayawan transmission line for a short duration, which reveals the planning of offshore wind power for the next decade will not cause serious congestion. Therefore, there is no need to expand several 500 kV transmission lines from the perspective of supporting offshore wind farms.

5.2 Reliability

To assess the impact on reliability, EUE and the proportion of EUE in the total load are considered. For the following figure, the inter-frames between adjacent years represent the four seasons in a year (sequentially as spring, summer, autumn, and winter). Figure 28 represents the EUE and the proportion of EUE in the total load from 2019 to 2028, respectively.

The simulation results show the following:

(a) As illustrated in Figure 28, after integrating offshore wind power, EUE is increased by over 50% in most scenarios, and the increase rate in summer and autumn is higher than those in spring and winter.

(b) The proportion of EUE in the total load also increases after integrating offshore wind power, but there is no significant difference between seasons and years.

(c) EUE represents the average electricity not supplied owing to inadequate power supply for the random scenario. The integration of offshore wind power increases EUE because of the intermittent and unstable wind power output, and the impact increases as total load increases. Therefore, measures such as encouraging demand response, promoting ancillary services, and building peaking power plants including pumped-storage plants are beneficial to relieve the unreliability of power supply brought by large-scale offshore wind power.

6 CONCLUSION

As the focus of energy development in Southern China, the installed capacity of offshore wind power will increase annually, which will significantly influence the electricity market. In this paper, we used a simplified Guangdong power system model to simulate the electricity market from 2019 to 2028, and then analyze the impacts of integrating large-scale offshore wind power in Southern China represented by Guangdong Province. The experimental results show the following:

(i) The integration of offshore wind power will directly decrease Guangdong’s LMPs owing to the floor bidding price and market clearing priority of offshore wind farms. The price drops of nodes not connected to offshore wind farms are less than those of nodes directly connected to offshore wind farms, which is mainly because thermal power will still take the leading role in the next 10 years.

(ii) When the growth rate of the stable power generation capacity of the system cannot keep up with that of the system demand, the weighted average spot price will increase yearly. During some seasons and time periods when the load is high, the LMPs will even be raised to the market price cap.

(iii) The integration of large-scale offshore wind power (nearly 26 GW) in the next 10 years will increase the power flow on 220 kV transmission lines that are connected to offshore wind farms; however, this will not cause severe network congestions on these lines. The expansion of the corresponding transmission lines is unnecessary based on current construction plans.

(iv) The planning of offshore wind power from 2019 to 2028 will not cause serious congestions on 500 kV transmission lines.

(v) The reliability of the Guangdong power grid will be affected as the EUE increases after integrating large-scale offshore wind power because of its intermittency, and the impact increases as total load increases. The relevant measures such as improving demand-side management and ancillary service as well as building peak power plants can be implemented to improve the reliability.

Consequently, the development of large-scale offshore wind power has economic and environmental benefits, and can be promoted through competition due to priority in market clearing. While the construction plans of offshore wind power or other energy resources still need to be adjusted according to market operating conditions. Long-term energy policy design has to consider multiple aspects including energy structure, transmission lines, and market trading mechanism, which also need to be adjusted based on the operation of electricity market and power grid. Future studies will focus on how to design and improve energy policy including renewable energy to establish a more sustainable energy system.

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