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Effect of market structure on renewable energy Development—A simulation study of a regional electricity market in China

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ABSTRACT

To achieve the carbon-neutral goal set for 2060, China has promoted renewable energy development for more than two decades. Meanwhile, China's electricity market is undergoing a new round of reform by introducing more market-oriented mechanisms and changing the market structure. This paper investigates the impact of three electric utility market structures experimented with in China on promoting renewable energy through a simulation model. The three market structures are vertical monopoly, weak monopoly (separation of power generators and grids), and monopolistic competition (Cournot-Nash competition). The model is calibrated with the actual data of the regional utility network in Beijing, Tianjin, and Tangshan areas. The simulation results show that the electricity market structure plays a vital role in renewable electricity, and the competition among utilities tends to benefit renewable energy development (wind power here). The study's conclusions are helpful to our understanding of further reforms in the electric utility industry and the long-term clean energy target in China.

1. Introduction

Over the past two decades, renewable energy has rapidly penetrated electric utilities worldwide. The global cumulative renewable energy power generation was 2805.5 GWh in 2019 through an average annual rate of more than 15% in the last ten years [1]. In China, renewable energy has grown faster than the global average. The cumulative power generation of renewable energy in China was 732.3 GWh in 2019 [1], which is 26.1% of the total in the world and increased by an average annual rate of more than 126.47% in the last ten years. However, China is also the world-leading fossil fuel producer and consumer; its coal production was 3.84 billion tons in 2019, accounting for 47.5% of the world's total. Adding to the import, China's coal consumption share in the world is 51.9% [2]. In contrast, renewable energy consumption was only 4.67% of the total energy consumption, and renewable energy output was only 8.5% of the entire power generation in China in 2019, despite its rapid growth [1]. Dealing with climate change, the Chinese government proposed the "carbon neutral" goal by 2060 in Sep. 2020. The goal is a challenge to traditional fossil fuel-powered electric utilities and a call for promoting clean and renewable electricity.

In developing renewable energies, China faces many unique challenges. In the electric utility industry, such challenges include power trade barriers across provinces [3], insufficient power grid construction [4,5], the technical difficulties of peak shaving in winter in some areas [6], and power demand fluctuation [7]. Institutional factors also contribute to the challenges. In China, the electricity dispatch mechanism, the rooms allowed for inter-firm competitions, and electricity pricing strongly impact electric utility renewable energies [8,9].

Economic reform in the past decades has led to the revamping of electric utilities in China. The Chinese electric utility industry's institutional structure and incentive systems have changed significantly from stringent administrative control under central planning to conceding more decision-making power to individual power generators and local grids. Although these reform measures are not necessarily targeted at promoting renewable energies, they may support the expansion of renewable energies through the change in the electricity market structure.

Different market structures or reform measures may have various incentives for renewable energy because of its unique generation technology and cost structure. Scholars have argued that electricity market design plays a considerable role in renewable energy integration into the

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Nomenclature

Abbreviation

BTT Beijing, Tianjin, and Tangshan

Index and Sets

i Number of generators
t Hour

Parameters

α_i^{up} The ramp-up rate of generator i (MW/hour)
α_i^{down} The ramp-down rate of generator i (MW/hour)
a_i, b_i, c_i Cost parameters of generator i (¥/MWh^2, ¥/MWh, ¥)
d The slope of the demand curve (MWh/¥)
L_t The maximum power demand at hour t (MWh)
P_t Profile of wind power (MW)
Q_i^{max} The maximum output of generator i (MW)
Q_i^{min} The minimum output of generator i (MW)
R_t^l Reserve without integrating wind power (MW)
R_t^w Reserve due to wind power (MW)
S_i Subsidy for power generation (¥/MWh)
T_i^{on} The minimum continuous running hours of generator i
T_i^{off} The minimum continuous shutdown hours of generator i

Variables

$\delta_{i,t}$ The binary variable that indicates whether generator i is online at hour t (0 or 1)
$\theta_{i,t-1}^{on}$ The continuous running hours of generator i at hour $t-1$
$\theta_{i,t-1}^{off}$ The continuous shutdown hours of generator i at hour $t-1$
mcp_t Market-clearing price of electricity at hour t (￥/MWh)
$Q_{i,t}$ The power output of generator i at hour t (MW)

grid [10]. On the other hand, as the competing force, conventional fossil fuel power generators react differently toward competition from renewable energy in various market structures. This study investigates the relationship between market structure and renewable energy development in the electric utility industry from a game-theoretic angle. We simulate strategic interactions among conventional fossil fuel and renewable energy firms in a local electricity market in China. The model is a stylized condensation of a complex electric utility market. Its calibration is based on the proportional reduction of the data collected from this power grid. Despite its simplicity, the model captures the interactions and outcomes between conventional fossil fuel power and renewable energy under the different assumptions of market structures or electricity dispatching mechanisms.

Our studies show that competition within the grid promotes more utilization of renewable energy. In an integrated electric utility grid of conventional fossil fuels and renewable energy, renewable energy also impacts the fossil fuel power in the grid. This study develops a quantitative approach to analyze the impacts of different electric utility market structures on renewable energy development in China's power market. The results indicate that encouraging competition promotes the speedy integration of renewable energies in the grid. Such a connection would be helpful for China's future power market design and other emerging economies' power market restructuring. Furthermore, our model is a proportional "miniature" of the power grid of Beijing, Tianjin, and Tangshan in China; the observations from the grid validate the simulation results. This paper provides a new methodological approach highlighting these economic issues while preserving the essential technological feature of a complicated electric power grid.

The remainder of the paper is organized as follows. Section 2 is the literature review. Section 3 describes some unique features and evolutions of the Chinese electricity market. Section 4 introduces our model, data source, and the model's algorithms. Section 5 presents the results and discussions. Section 6 is the concluding remarks.

2. Literature review

Electricity market concentration has been considered essential to impact on-grid power prices and different kinds of power generators' profit distribution, indirectly affecting renewable energy development. Many empirical studies have found that in electricity markets with a high concentration on the supply side, power generation firms will take advantage of market power to obtain high profits and increase power prices, such as England and Wales Electricity Market [11], California Independent System Operator [12,13], New Zealand Electricity Market [14], and Australian National Electricity Market [15]. For example [16], developed a static computational game-theoretic model empirically calibrated to eight Northwestern European countries. Based on the model, they compared different market structures, depending on the ability of firms to exercise market power, ranging from the perfect competition without market power to strategic competition where large firms exercise market power; they get the conclusion that a reduction in the market power of large producers may lead to lower power prices [17]. also pointed out that the Cournot competition leads to higher market prices than the perfect competition by estimating the power price level under an assumption of perfect competition and Cournot competition in three U.S. markets.

A few studies directly explored the impact of market concentration on renewable energy development [18]. investigated the effect of market concentration on residential solar photovoltaic price change in the United States. It is argued that in the initial stage of market concentration, the price may decline because of scale returns increase, but after concentrated markets have been formulated, the price increases due to market power. [19]; by investigating eight countries' factors affecting renewable energy, argued that a competitive market significantly impacts renewable energy development. A competitive market incentivizes players to intensify their competencies to maintain their positions. Still, it may unduly dent the profitability of renewable energy technologies when the technology is immature and lacks financial support.

Besides market concentration, market rules, such as market access, pricing mechanism, transaction rules, etc., which are closely related to market structure, also affect renewable energy. Some scholars argued that due to the volatility characteristics of renewable energy, the existing electricity market rules that are appropriate for conventional fossil fuel power generally have some deficiencies in deep renewable penetration scenarios [20–23], and thus there is the need for new market rules designed to meet the large scale of renewable energy integration [20]. Using a heuristic dynamic game approach [24], analyzed the impact of various electricity market rules (security constraints, pricing mechanism, and clearing price of wind power generators) on the interaction between market players. They concluded that a change in market rules about the clearing price of renewable energy could improve the investment incentives; by contrast, market rules may bankrupt renewable energy generators and decrease the investment incentives because of the collusive nature of fossil-based power generators. To resolve the mismatch between the rapid growth of renewable energy and outdated electricity market rules, some studies focus on new electricity market rules design [25–27]. [28] overviewed existing electricity market design options to meet the growing share of fluctuating renewable energy requirements. They concluded that capacity remuneration mechanisms could effectively reduce or even solve the problems of existing markets for integrating more renewable energies. However, it is argued that determining optimal market rules suitable for renewable energy development is still challenging [28].

We have three takeaways from the above studies: First, the market structure will affect renewable energy development by influencing competitiveness or price change. Second, a perfect competition structure favors lowering power prices, but how different market structures affect renewable energy development is still being determined. Third, market concentration has a different impact on renewable energy development in various stages. As a result, the analysis of the effect of market structure on renewable energy needs to be improved. Promoting renewable energy development is a vital energy strategy choice. Therefore, the electric power system and the market should be adjusted accordingly. Especially, China's electricity market is experiencing a new round of reform; exploring the impact of market structure on renewable energy development is valuable for guiding policies. Meanwhile, the market structure changes in the electric utility in China over the last 30 years allow us to evaluate the relationship between market structure and government policies' effectiveness in promoting renewable energy.

3. The changes in China's electricity market structure and its impact on renewable energy

China's electricity market structure has experienced two significant changes in the past two decades. The first was dismantling the State Power Corporation on December 29, 2002. Two grid corporations, State Power Grid, China South Power Grid, and five large power generation corporations were set up. This change represents the end of vertical monopoly in the electricity industry and the emergence of a new electricity market. The electricity market reform in 2002 introduced competition on the power generation side and intended to improve energy efficiency through competition. The prominent achievements of this reform include the change in the administrative planning system and the separation between government administration and enterprise management. Accordingly, the diversified competition pattern of electricity market players has initially formed in the investment field, signaled by the establishment of the five large power generation corporations. However, in the on-grid power pricing mechanism, the real competition about on-grid power prices between power generators has not occurred; that is, local Chinese governments decide the on-grid power price.

The second significant change in the electricity system took place in 2015. This new round of electricity reform focuses on expanding market-oriented mechanisms, represented by the on-grid price and sale price is decided by competition instead of by administrative planning; competition is introduced in the newly added distribution business, retail electricity business, electricity production, and consumption are to be liberalized step by step.

Nurturing market mechanisms in the electric utility industry faces many challenges in China. One of the critical components of the change is allowing on-grid power pricing through competition. By 2018, the pilot work of the electricity spot market had been launched in eight provincial grid regions: Guangdong Grid, West Inner Mongolia Power Grid, Zhejiang Grid, Shanxi Grid, Shandong Grid, Fujian Grid, Sichuan Grid, and Gansu Grid. They are the institutional background for us to model the electricity market structure with Cournot–Nash competition among power generators in this study.

Over the past decades, the reforms in China's electric utility industry had evolved through three market structures: The first is the vertical monopoly period before the State Power Corporation dismantled it in 2002. In this period, the State Power Corporation managed all the generation, transmission and distribution links [8]. In this context, the State Power Corporation can control power supply to increase power price for obtaining ultra profits. The second is the weak monopoly period from 2002 to 2015 when the five big power generation companies were separated from the State Grid Corporation. In this period, power generation companies have freedom in their investment decisions, but they have no right to determine the on-grid power price, since the price and the amount of power generation are decided by governments. The third is the monopolistic competition period or Cournot–Nash competition period after 2015. In 2015, China launched a new round of electricity market reform to encourage competition among power generators. In this period, the power generation companies can determine their power generation amount at a specific ratio, thus influencing on-grid power prices to some extent. By the end of 2019, the amount of power generation from market competition reached 2087.2 GWh in 2019, amounting to 46.9% of the total power generation [29]. The scope of the on-grid power prices decided by competition is expanding. Meanwhile, a few power generation enterprises (the five big power generation groups) still significantly influence the electricity market. Their power generation accounted for 45.84% of the total power generation in China in 2019.[1] Hence, we call this period the "Cournot–Nash competition (monopolistic competition) period.

The vertical monopoly might hurt renewable energy. Specifically, the monopolists tend to decrease power output and hike the price to gain monopoly profit, discouraging high-cost capacity building through renewable energy. On the other hand, power generators are separated from grid corporations in the scenario of weak monopoly, and the competitive market of investment on the power generation side is formed. Such change leads to more power supply and lower power prices than vertical monopoly. Lowered power price attracts more demand, which pushes for more renewable energy investment. Moreover, the competition in investment leads to R&D in new technological fields (including renewable energy) by power generation corporations to obtain a "first-mover advantage." Hence, more renewable energy may be invested in and generated in a weak monopoly period scenario than in a vertical monopoly situation.

The most recent electricity market reform (Cournot–Nash competition period) is marked by the liberation of power production and on-grid power price and more investors of renewable energies in the market [1]. Moreover, because the marginal cost of renewable energy is less than fossil fuel-based power, a competitive market favors renewable energy. Among the three scenarios examined here, we hypothesize that renewable energy has the most potential development advantage in the Cournot–Nash competition period after 2015.

In the next section, we construct a simulation model to quantify the impact of China's market structure on renewable energy development. As previously argued, the simulations have direct empirical implications beyond simple illustrations. Through this set of simulations, we compare the competitiveness of wind power in different market structure scenarios and scenarios with or without government subsidy support. We also examined the cost-effectiveness of government subsidies for wind power under different market structures and wind power capacity utilization by comparing the scenarios.

4. A model of wind power in a power grid

4.1. Model construction

In this paper, we present a model of a power grid based on the regional grid consisting of Beijing, Tianjin, and Tangshan (BTT Grid). BTT Grid is an integral part of the North-China power grid, also the earliest power grid in North China, which has a history of nearly 40 years [30]. At the same time, the BTT power grid is located in the Bohai Rim Economic Circle, one of China's three major economic circles. In 2014, the power demand of the BTT Grid reached 360 TWh [31]. In recent years, the rapid development of renewable energy in BTT Grid makes it often used as a case for related research [31–33]. In real life, the

[1] Data source: Latest ranking of five power generation groups. https://www.sohu.com/a/391733493_651522. 2020.04.28. Last access: 2021.01.03.

BTT Grid has 160 generators, with a 63,824 MW total capacity in 2014. In our model, we reduce the capacity to 1/30 of the capacity of BTT Grid for the following two reasons: first, the structure of power units in this model can represent the actual power system well; second, the calculations are simplified by omitting some technical details of a full-scale grid. This reduced grid has five mainstream generators, each representing a power generator in the actual grid. The grid contains two firms with a 300-MW coal-powered generator, one firm with a 600-MW coal-powered generator, one with a 300-MW gas-powered generator, and one 250-MW windmill power plant. Each generator has different costs and efficiency parameters.

The model constructed in this study is summarized in Fig. 1. We generate unit commitment constraints based on the characteristics of various generators, such as maximum power output, minimum shutdown and turn-on time, and ramping rate. These unit commitment constraints are consistent under different market structures. After generating constraints, we construct objective functions based on the type of market structure and solve the result.

The power output $Q_{i,t}$ of generator i at hour t is subject to technological and market constraints. Among them, $i = 1, 2, 3$ indicates coal-powered generators, $i = 4$ indicates gas-powered generator, and $i = 5$ indicates wind power:

(i) Fossil fuel power generators' capacity constraints. The power output of fossil fuel generators subscript has lower and upper bounds.

$$\delta_{i,t}Q_i^{min} \leq Q_{i,t} \leq \delta_{i,t}Q_i^{max} \forall i = 1, 2, 3, 4 \tag{1}$$

Where $\delta_{i,t}$ indicates whether generator i is online at hour t, Q_i^{min} and Q_i^{max} are the minimum and maximum output power of generator i.

(ii) The minimum shutdown time constraints. Shutting down a fossil fuel power generator takes time. The generator cannot be turned on and shut down too frequently.

$$(\delta_{i,t-1} - \delta_{i,t})\left(\theta_{i,t-1}^{on} - T_i^{on}\right) \geq 0 \forall i = 1, 2, 3, 4 \tag{2}$$

$$(\delta_{i,t} - \delta_{i,t-1})\left(\theta_{i,t-1}^{off} - T_i^{off}\right) \geq 0 \forall i = 1, 2, 3, 4 \tag{3}$$

Here $\theta_{i,t-1}^{on}$ is the continuous running time of generator i at hour $t-1$, $\theta_{i,t-1}^{off}$ is the continuous shutdown time of generator i at hour t, T_i^{on} is the minimum continuous running time of generator i, and T_i^{off} is the minimum continuous shutdown time of generator i.

(iii) The ramping rate constraints of generators. Fossil fuel power generators can only increase or decrease their output gradually.

$$\delta_{i,t}Q_{i,t} - \delta_{i,t-1}Q_{i,t-1} \leq \alpha_i^{up} \forall i = 1, 2, 3, 4 \tag{4}$$

$$\delta_{i,t-1}Q_{i,t-1} - \delta_{i,t}Q_{i,t} \leq \alpha_i^{down} \forall i = 1, 2, 3, 4 \tag{5}$$

Here α_i^{up} is the maximum ramp-up rate of generator i, and α_i^{down} is the ramp-down rate of generator i.

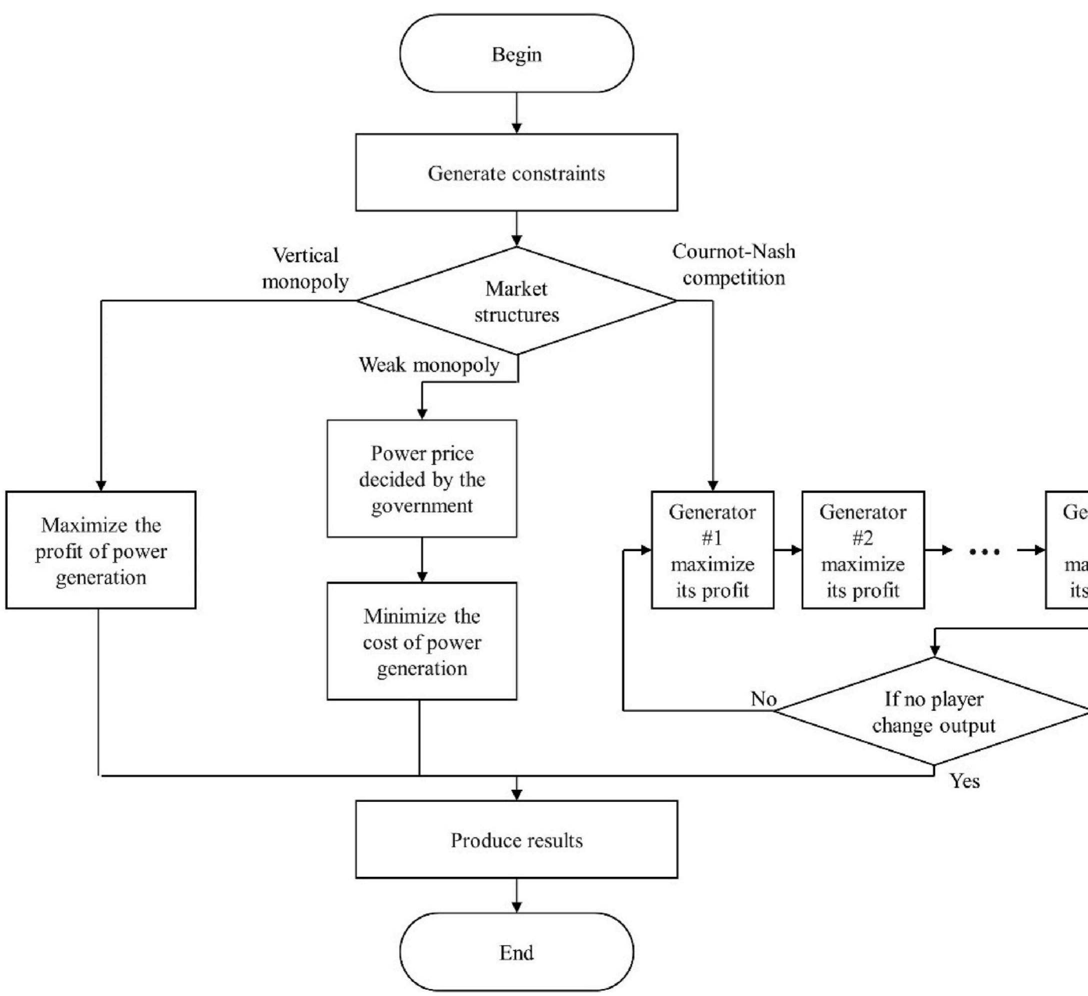

Fig. 1. Algorithm flowchart of the model.

(iv) Wind power supply constraint. It is lower than the wind power profile.

$$0 \le Q_{i,t} \le P_t \forall i = 5 \tag{6}$$

Here $Q_{5,t}$ is the power output of wind power at hour t, and P_t is the profile of the wind power generator.

(v) Capacity redundancy constraint. It is set to guarantee the security of the network.

$$\sum_{i=1}^{5} \left(Q_i^{max} - Q_{i,t}\right) \ge R_t^l + R_t^w \tag{7}$$

Here R_t^l is the capacity redundancy without integrating wind power in the power grid and is set at 5% of power demand. R_t^w is the additional capacity redundancy reserved for wind power and is set at 10% of the wind power capacity here [9].

(vi) Power balance constraint. The generated electricity cannot be stored and must always meet the electricity demand.

$$L_t - d \times mcp_t = \sum_{i=1}^{5} Q_{i,t} \tag{8}$$

Here mcp_t is the market-clearing price of power at hour t, L_t is the maximum power demand at hour t when the power price mcp_t is at a hypothetical 0, and d is the slope of the demand curve, which is set to 0.5 (MWh/¥) here [34].

Under the given technologies, the various electricity market structures dispatch electricity from power generators to consumers differently. As discussed in the previous section, the electricity market of China has experienced three phases in the past decades: vertical monopoly (Scenario A), weak monopoly (power generators separated from power grid corporations, Scenario B), and Cournot–Nash competition (introducing market-style competition, Scenario C). Scenario A reflects the institution where a single authority controls the electricity system. It is a mix of a market economy (monopolistic pricing) and state ownership of the electricity industry. Scenario B reflects the early reform measures of the electricity industry in China. The government sets the price of electricity but allows power generators to compete with one another to improve internal efficiency. Scenario C reflects the most recent structure of the electricity industry in China. Power generators are given the right to decide their electricity output to some extent and compete for market share.

From an engineering standpoint, the three scenarios in BTT Grid have the same technological structure and constraint conditions. The differences are the objectives of the dispatchers and generator managers (decision-makers). The objective functions represent the targets of managers under different market structures. In these three scenarios, power generators' decision variables are power output $Q_{i,t}$. The objective functions for the 24-h day supply of electricity in Scenarios A, B, and C are as follows:

A. Vertical monopoly: Under this scenario, the generation, transmission and distribution of power are controlled by one monopolist. Therefore, the monopolist can determine the power price by controlling power supply. The objective function of the monopolist is to maximize the profit of all power generators:

$$Max \sum_{t=1}^{T} \sum_{i=1}^{5} \left[mcp_t Q_{i,t} - \left(a_i Q_{i,t}{}^2 + b_i Q_{i,t} + c_i\right) + S_i Q_{i,t}\right] \tag{9}$$

Where T is the total number of hours, a_i, b_i, c_i are the cost parameters of generator i, S_i is the subsidy for power generation. The values of the coefficients of cost functions differ across generators and are given in Table 1.

Table 1
Technical parameters of the generators used in BTT Grid.

Units	Capacity (MW)	Coefficient of power generation cost		
		a (¥/MWh^2)	b (¥/MWh)	c (¥)
Coal-fired power #1	300	0.06	103.21	8098.40
Coal-fired power #2	600	0.06	72.68	13332.07
Gas-fired power	300	0.54	58.59	5535.30
Wind power	250	0	0	17274.31

Data source： [35]; [36]; [37]

B. Weak monopoly (Power generators separated from grid corporations): Under this scenario, governments decide power price, and thus decide the demand and supply of power. Therefore, the objective of the monopolist is to minimize the cost of power generation:

$$Min \sum_{t=1}^{T} \sum_{i=1}^{5} \left(a_i Q_{i,t}{}^2 + b_i Q_{i,t} + c_i - S_i Q_{i,t}\right) \tag{10}$$

C. The Cournot-Nash competition (new round of electricity market reform): Generators are split into independent market players. They can only decide their own power generation and pursue their own profit maximization. The market determines the power price. In the Cournot-Nash competition, the objective function of each generator, i.e., profit, is as follows:

$$Max \sum_{t=1}^{T} \left[mcp_t Q_{i,t} - \left(a_i Q_{i,t}{}^2 + b_i Q_{i,t} + c_i\right) + S_i Q_{i,t}\right] \tag{11}$$

Solving the Cournot–Nash equilibrium in Scenario C is mainly divided into three steps. The first step is to calculate the market equilibrium in the monopoly scenario and take the resulting output as the initial value. In the second step, each generator acts in turn, changing its output to maximize its profit while the other companies stay at the previous output level. In the last step, iterate through the second step until the output of each generator no longer changes.

As a result, objective functions (9), (10), or (11), subject to constraints (1)–(8), forms a unique dispatching mechanism of the BTT Grid. We will test the performance of wind power in this grid and the policy impacts on wind power under different dispatching mechanisms. The model calibration of electricity generation is based on the technical parameters of the generators used in the BTT Grid (Table 1). Liu's study is a good source of these technical specifications of fossil fuel power generators written in Chinese [34]. The wind power output data are collected from a wind power farm in Gansu Province, where the wind condition is like the BTT Grid. Although the parameters in Table 1 are based on the current power generators, the parameters change over time would be minimal.

4.2. Data source

The data on fossil fuel prices are the market prices in 2014 from the Price Department of China National Development and Reform Commission. In Scenario B, where the government sets the power price, the power price was based on the average selling prices from various generators in 2014 (for instance, the price of coal-fired power is 418.77 ¥/MWh, wind power is 572.06 ¥/MWh and gas power is 647 ¥/MWh), the data is collected from the *National Annual Price Supervision Report of Electricity Enterprises over the year 2013*-2014 b y the Chinese National Energy Administration. The data on electric power demand is collected from the North China Energy Regulatory Bureau. Fig. 2a shows the maximum power demand L_t when the power price mcp_t is at a hypothetical 0. The data on wind power generation is collected from Ref. [38] (Fig. 2b). Finally, the Chinese government grants subsidies to wind power generation on corporate income tax and value-added tax. According to the authors' survey of wind power companies and relevant

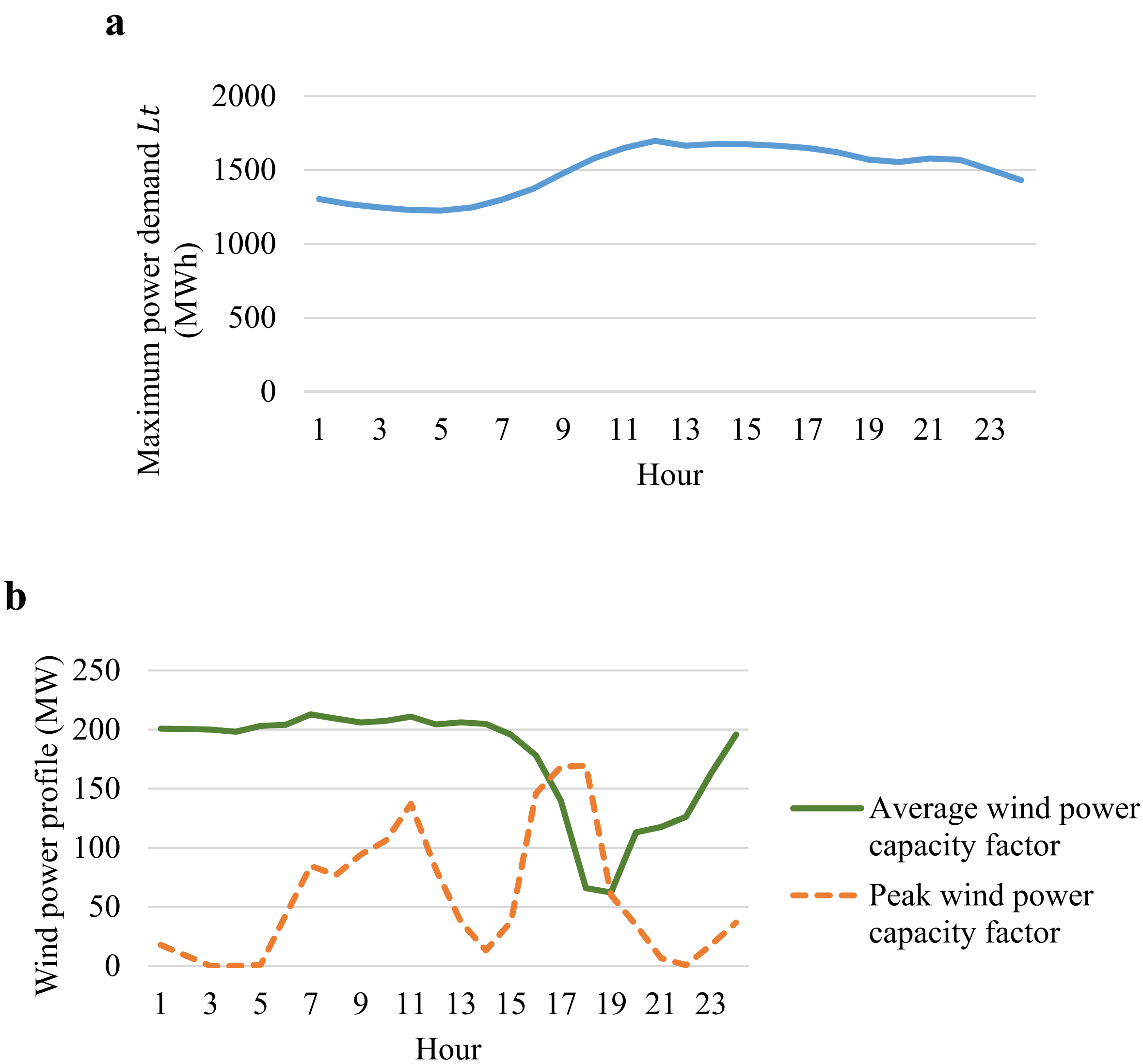

Fig. 2. Power demand and wind power profile.
Data source: the North China Energy Regulatory Bureau and [38].

regulations [39,40], the size of wind power subsidy is calibrated to 110 ¥/MWh.

4.3. Scenario design and algorithm for solving the model

To examine the performance of wind power in the simulated BTT Grid under different market structures, we conduct two sets of simulations under three market structure scenarios (A, B, and C). The first set includes government subsidies for wind power. The second set is a counterfactual case without government subsidies. In the past decades, the Chinese government has subsidized wind power in the BTT Grid through the following five measures: (i) preferential value-added tax; (ii) preferential corporate income tax; (iii) preferential land leasing; (iv) R&D credits; and (v) sale price subsidies (see http://www.nea.gov.cn/). These policies decrease the investment and operational costs of wind power.

In average wind power capacity factor scenarios, 2 (with or without subsidies) x 3 (A, B, and C) = 6x rounds of simulations, the upper bound of wind power output fluctuates every hour and the average upper bound of wind power (i.e., wind power capacity factor) is 23% [41]. This assumption is based on the statistics of the annual wind force in Northern China. The yearly average of the wind power capacity factor is calculated from hourly data.

In addition to the cases mentioned above, we increased the wind power capacity factor to 70% and repeated all six rounds of simulations. 70% capacity factor reflects the maximal wind power generator utilization in Northern China. Therefore, we calculate 12 cases in total: 2 (with, without subsidies) × 3 (Scenarios A, B, C) × 2 (average wind power capacity factor, peak wind power capacity factor).

The above constrained optimization problem was formulated as a Mixed Integer Nonlinear Program in MATLAB with the YALMIP package [42] and solved with the mathematical programming solver SCIP [43]. The source programming code, the parameter database of the model, and the solution outputs are available upon request.

5. Results and discussions

5.1. Wind power output under different electricity market structures

We obtain 12 optimal solutions for the 12 cases described in Section 4. Real-time 24h electricity outputs from different power generators are presented in stack-bar diagrams. Fig. 3 shows the results of electricity output in Scenario B, with subsidies and the average wind power capacity factor. In this figure, the vertical axis is the total electricity output and individual output (in MW) from five different power generators in Fig. 3. The top line reflects the real-time electricity demand fulfilled by

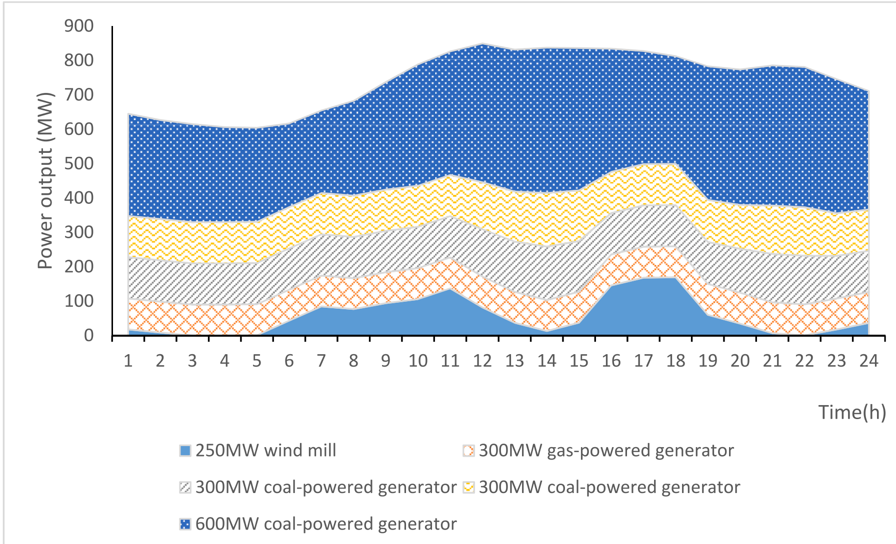

Fig. 3. Illustration of the results from a case. Note: The power output in Scenario B (power generators separated from grid corporations), with subsidies and average wind capacity factor.

the total supply from the five power generators. For easy reading of wind power, we place it right above the horizontal axis (in the colored figure, it is solid blue). To save space and for easy comparison, we present the figures of electricity outputs in 12 cases, similar to Fig. 3, in the Appendix.

Fig. 3 and figures in the Appendix indicate that hourly wind power outputs vary more substantially than fossil-fuel power. This phenomenon is mainly due to the daily variation of wind in the field, calibrated into the model based on statistical information. On average (capacity factor is 23%), wind power generation occurs at full capacity during all hours. Wind power integrates into BTT Grid seamlessly, according to the simulations. Observations from the actual operation of the BTT Grid are consistent with our simulations.

In the average capacity factor cases, little or no wind power is curtailed (see Table 2). In the peak capacity factor cases, a high proportion of wind power is curtailed in the vertical monopoly (Scenario A) (see Table 2). However, wind power curtailment does not occur in weak monopoly (Scenario B) and the Cournot-Nash competition (Scenario C) scenarios. This is because a vertical monopoly suppresses the output of the total power generation and marks up the price to a vertical monopoly, suppresses the total power generation output and marks up the price to maximize industry profit. Despite its near-zero marginal cost, wind power may not be dispatched because fossil-fuel power firms hit lower generation bounds. The simulations show that market structure directly affects wind power generation; a more open market benefits integrating renewable energy. This result is consistent with the previous studies [44]; Jamasb and Pollit, 2005). Because the marginal cost of wind power is lower than fossil-based power, a more competitive market provides a better environment for wind power and other renewable energies.

Table 2
Wind power generation and wind curtailment rate in different cases.

Average wind power capacity factor (23%)		
	(MWh)	wind curtailment rate (%)
Vertical monopoly (w/o subsidy)	1376.96	0.32%
Vertical monopoly (w/subsidy)	1381.39	0
Weak monopoly (w/o subsidy)	1381.39	0
Weak monopoly (w/subsidy)	1381.39	0
Cournot (w/o subsidy)	1381.39	0
Cournot (w/subsidy)	1381.39	0
Peak wind power capacity factor (70%)		
Vertical monopoly (w/o subsidy)	3046.58	27.9%
Vertical monopoly (w/subsidy)	3231.58	21.4%
Weak monopoly (w/o subsidy)	4225.95	0
Weak monopoly (w/subsidy)	4225.95	0
Cournot (w/o subsidy)	4225.95	0
Cournot (w/subsidy)	4225.95	0

Table 3
Power generation in different cases (MWh).

Average wind power capacity factor (23%)					
	250 MW wind	300 MW gas	300 MW coal	300 MW coal	600 MW coal
Vertical monopoly (w/o subsidy)	1376.96	2160.00	2972.01	2972.01	7775.60
Vertical monopoly (w/subsidy)	1381.39	2160.00	2972.01	2972.01	7775.60
Weak monopoly (w/o subsidy)	1381.39	2399.35	6167.59	6167.59	12771.49
Weak monopoly (w/subsidy)	1381.39	2399.35	6167.59	6167.59	12771.49
Cournot (w/o subsidy)	1381.39	5120.28	6686.65	6686.81	7292.81
Cournot (w/ subsidy)	1381.39	5120.28	6686.65	6686.81	7292.81
Peak wind power capacity factor (70%)					
	250 MW wind	300 MW gas	300 MW coal	300 MW coal	600 MW coal
Vertical monopoly (w/o subsidy)	3046.58	2160.00	2880.00	2880.00	6556.21
Vertical monopoly (w/subsidy)	3321.58	2160.00	2880.00	2880.00	6556.21
Weak monopoly (w/o subsidy)	4225.95	2160.00	5358.46	5358.46	11784.55
Weak monopoly (w/subsidy)	4225.95	2160.00	5358.46	5358.46	11784.55
Cournot (w/o subsidy)	4225.95	4615.18	6185.87	6186.14	6732.24
Cournot (w/ subsidy)	4225.95	4615.20	6185.98	6186.17	6732.04

5.2. Impacts of wind power on BTT grid under different market structures

Wind power responds to market structures differently (see Table 3). In vertical monopoly (Scenario A), wind power crowds out coal power (in this context, gas power has reached its minimum power generation limit). This implies that if decision-makers intend to maximize the power system's profits, they should promote wind power for its low marginal cost, suppressing fossil fuel generators with higher marginal costs. In contrast, in the scenario of weak monopoly (Scenario B), wind power generation also crowds out gas power, besides coal. Breaking vertical monopoly is favorable for wind power, thus strengthening the argument on the role of market structures. Lastly, Cournot–Nash equilibrium (Scenario C) is like Scenario B. In this aspect, wind power supplies electricity at full capacity, while fossil fuel firms generate less electricity because of their higher operational costs.

The above results also imply that although opening up the market is favorable for wind power output, wind power alone cannot meet an increased power demand (competition lowers the price, increasing the electricity demand) in a short time. Fossil-powered generators must run at their full capacity peak-load periods. The demand fluctuation is why fossil-based power generation increases rather than wind power in Table 3.

5.3. Power generators' profits under different market structures

Table 4 contains the various power generators' profits in 12 cases. The results show that the profits of power generators (regardless of whether they generate wind, gas, or coal power) are higher in the vertical monopoly scenario than in other scenarios. Meanwhile, the power generators' profits in the weak monopoly scenario (power generators separated from grid corporations) are lower than in the Cournot-Nash competition scenario. This result indicates that deepening electricity market reform is the electricity market valuable for renewable energy development and for improving all kinds of power generators' benefits.

Another interesting finding is the following. In the vertical monopoly scenario with wind power subsidies, the profits of gas-powered and coal-fired generators are slightly lower than in the cases without subsidies. But in the weak monopoly (power generators separated from grid corporations) and Cournot-Nash competition scenarios, the profits of gas-powered and coal-fired generators are the same. This pattern is because the subsidy decreases the marginal clearing price of the power system in the vertical monopoly scenario (Table 5). The wind power subsidies do not change the marginal clearing price of the power system because wind power has reached its maximum without subsidies in the weak monopoly and Cournot-Nash competition scenarios.

Table 4
Profits of firms in different cases (thousand ¥/day).

	250 MW wind	300 MW gas	300 MW coal	300 MW coal	600 MW coal
Average wind power capacity factor (23%)					
Vertical monopoly (w/o subsidy)	2223.74	3328.84	4595.53	4595.53	12182.35
Vertical monopoly (w/subsidy)	2380.71	3328.04	4594.47	4594.47	12180.22
Weak monopoly (w/o subsidy)	789.82	1551.97	2581.88	2581.88	5346.67
Weak monopoly (w/subsidy)	941.78	1551.97	2581.88	2581.88	5346.67
Cournot (w/o subsidy)	997.96	2681.04	3832.21	3832.38	4308.45
Cournot (w/ subsidy)	1149.91	2681.04	3832.21	3832.38	4308.45
Peak wind power capacity factor (70%)					
	250 MW wind	300 MW gas	300 MW coal	300 MW coal	600 MW coal
Vertical monopoly (w/o subsidy)	4830.31	3280.92	4374.53	4374.53	10081.45
Vertical monopoly (w/subsidy)	5494.16	3231.42	4308.53	4308.53	9949.45
Weak monopoly (w/o subsidy)	2417.50	1033.29	1421.70	1421.70	3419.98
Weak monopoly (w/subsidy)	2882.35	1033.29	1421.70	1421.70	3419.98
Cournot (w/o subsidy)	2695.75	2171.69	3183.88	3184.09	3528.26
Cournot (w/ subsidy)	3160.61	2171.70	3183.88	3184.07	3528.27

5.4. Investment's effects on wind power shadow prices in different market structures

Table 6 reports wind power's shadow prices (the profit obtained from power unit capacity increase) in the optimal solutions of 12 cases. It shows that market structure also affects wind power through its shadow price changes in various cases. In both the average and peak capacity factors, the shadow prices of wind power are positive in all three scenarios (A, B, and C). The results show that the profits of wind power generators will increase with the increase of wind power capacity in the three scenarios. However, the shadow prices are very different across market structures. The shadow price in Scenario A is the lowest, implying that the benefits of wind power investment are lower than those in Scenario B and Scenario C. Additionally, the shadow price of wind power in Scenario B is lower than in Scenario C. They point to a higher power market opening up is more favorable for wind power. In the vertical monopoly scenarios (Scenario A), although wind power has obtained higher profits (Table 4), the monopolist has little willingness to increase power supply by investing in new wind power generators (Table 6). This is because the monopolist must maintain a higher power price to increase its total profits. Investing in wind power generators and increasing the power supply will reduce the power price, which is not conducive to high monopoly profits for monopolists. On the other hand, in the Cournot-Nash competition scenarios (Scenario C), although the profits of wind power are lower, wind power generators are willing to increase their profits by expanding the power supply.

Lastly, we observed that the capacity factor affects wind power performances in different cases. Due to its small share in the BTT Grid and capacity factor constraints, wind power outputs are at their upper bounds in the average capacity factor cases. However, different market structure settings and subsidies affect wind power output in the peak

Table 5
The marginal clearing price in vertical monopoly with 23% of capacity factor[a].

Time	Price (¥/MWh) Vertical monopoly (without subsidies)	Vertical monopoly (with subsidies)	Time	Vertical monopoly (without subsidies)	Vertical monopoly (with subsidies)
1	1356.30	1356.30	14	1736.97	1736.97
2	1320.77	1320.77	15	1733.70	1733.70
3	1297.92	1297.92	16	1719.52	1719.52
4	1280.26	1280.26	17	1702.72	1702.72
5	1276.71	1276.71	18	1672.79	1672.79
6	1266.09	1266.09	19	1628.10	1628.10
7	1300.37	1291.51	20	1612.80	1612.80
8	1423.35	1423.35	21	1637.51	1637.51
9	1531.12	1531.12	22	1629.18	1629.18
10	1633.47	1633.47	23	1558.99	1558.99
11	1705.07	1705.07	24	1486.51	1486.51
12	1756.49	1756.49	average	1541.30	1540.93
13	1724.42	1724.42			

[a] The conclusions of power generation with a 70% capacity factor are similar.

Table 6
The impact of market structure on shadow prices of wind power (¥/MW).

	Average wind power capacity factor (23%)	Peak wind power capacity factor (70%)
Vertical monopoly (w/o subsidy)	557.69	861.03
Vertical monopoly (w/ subsidy)	1159.27	1826.91
Weak monopoly (w/o subsidy)	3160.95	9669.99
Weak monopoly (w/ subsidy)	3275.95	9779.99
Cournot (w/o subsidy)	3661.60	9222.986
Cournot (w/subsidy)	4269.41	11076.76

capacity factor cases (Table 3). Government subsidies are vital to ensure that wind power remains profitable in the accounting book, as shown in Tables 4 and 6

6. Conclusion and policy implication

In this study, we analyzed the impact of the electricity market structure on renewable energy development. We took wind power in a simulated regional power grid as a case study to identify our theoretical argument. Based on the practice of China's electricity market reform, the market structure in this study is referred to as three scenarios: vertical monopoly, weak monopoly (power generators separated from grid corporations), and Cournot-Nash competition. Meanwhile, we considered the impacts of wind power subsidies on results. Our simulation studies find that the different market structures have important implications for renewable energy in a stylized grid model.

Among three electricity market structure scenarios, i.e., the vertical monopoly, the weak monopoly (in which power generators are separated from grid corporations), and the Cournot-Nash competition), wind power output is the least in vertical monopoly with peak wind power generation (70% capacity factor) since power demand in this scenario is the least because of high power price; thus, a high level of wind power curtailment occurs. In the weak monopoly (power generators separated from grid corporations) and Cournot-Nash competition scenarios, lower power price leads to higher power demand, higher wind power output, and no wind power curtailment.

Different electricity market structures have varied effects on the profitability of wind power generators. The simulation results are consistent with our economic intuition. In vertical monopoly (Scenario A), the profits for wind power generators are the maximum among the three scenarios because power generators obtained extra monopoly profit. In a weak monopoly (Scenario B), in which power generators are separated from grid corporations, the profits for wind power generators are less than in the Cournot-Nash competition (Scenario C). The outcome indicates that opening the electricity market is more favorable to wind power.

We should point out that wind power's profit per unit investment is considerably lower than coal-fired power generators, with or without subsidies. Moreover, the marginal profits obtained from unit wind power capacity increase significantly differ across market structures. The results suggest that opening the electricity market incentivizes the willingness to invest in wind power.

From a policy perspective, the results in this study show that a freer electric utility market promotes renewable energy in the electric utility industry. Currently, China's electricity market-oriented reform is on the way; the degree of China's electricity market openness is still in question. The study here is helpful to the policymakers in the electric utility industry of China in their decisions regarding the future electricity market structure. The simulation study here points out an indicative view toward a much more complicated real-world power system involving fossil fuels and renewable energy. We realize that the stylized model and the engineering details here have room for improvement, and the game-theoretic simulations can be more sophisticated. These are among our continued research efforts.

CRediT authorship contribution statement

Xiaoli Zhao: Conceptualization, Methodology, Writing, Validation, Resources. **Chuyu Sun:** Writing, Data curation, Software. **Zewei Zhong:** Writing, Software. **Suwei Liu:** Methodology, Software. **Zili Yang:** Conceptualization, Methodology, Writing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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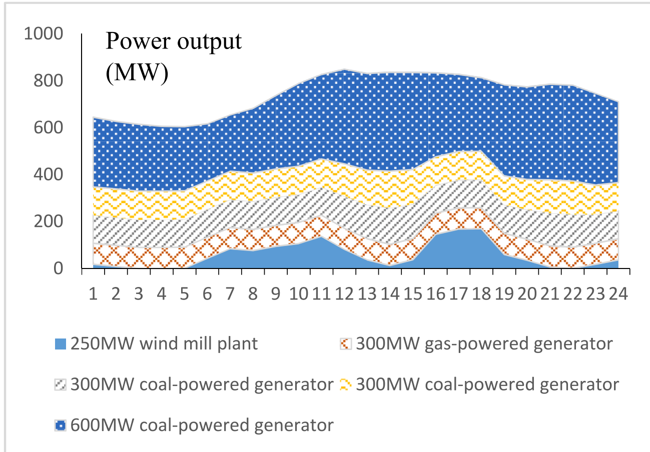
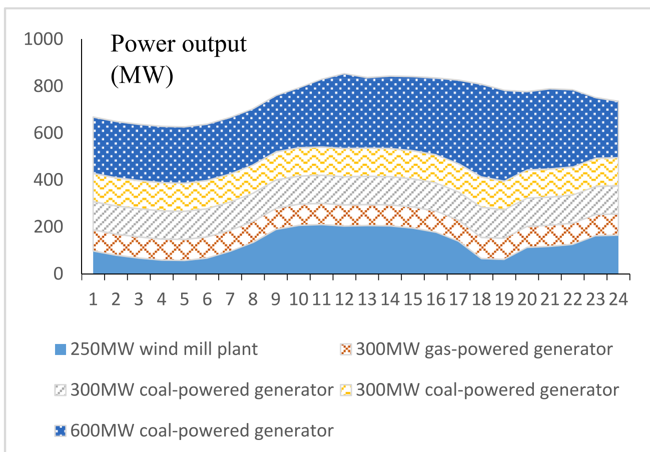
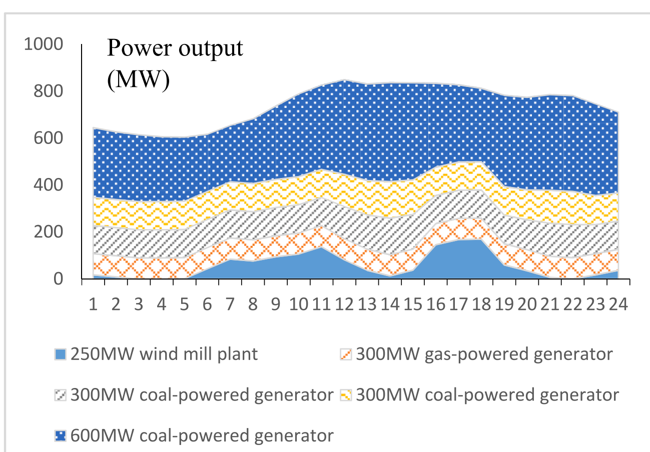
Appendix. Power Outputs in Various Cases



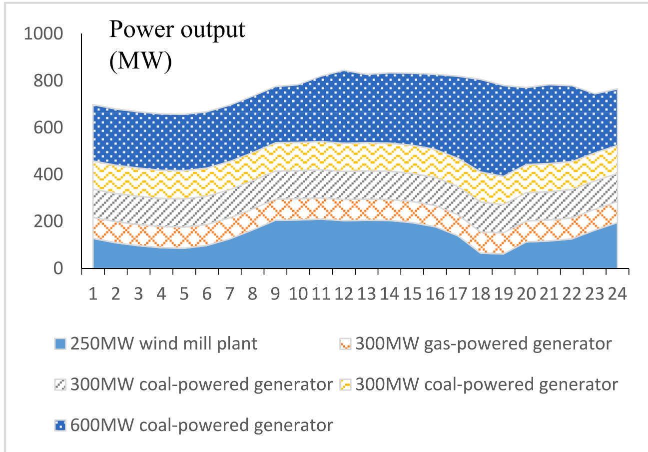
01. Scenario A*no subsidy wind *average wind power.



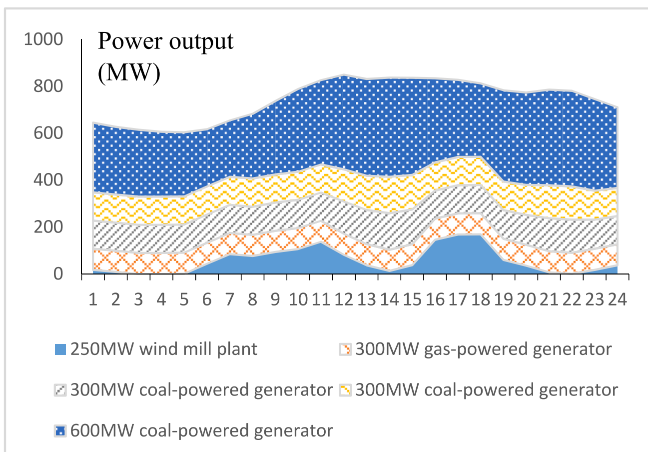
02. Scenario A*no subsidy wind *peak wind power.



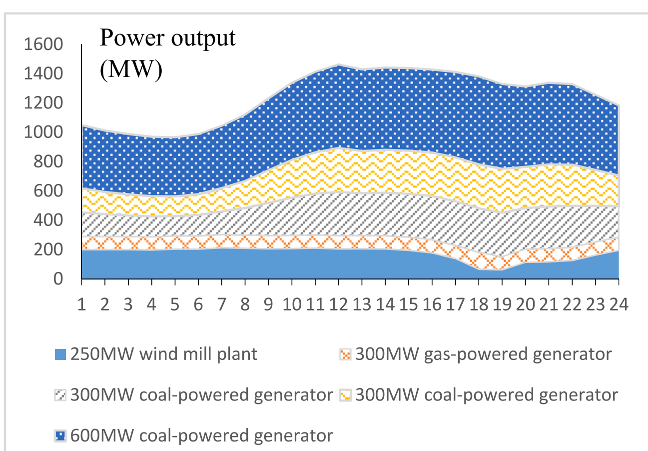
03. Scenario A*subsidy wind *average wind power.



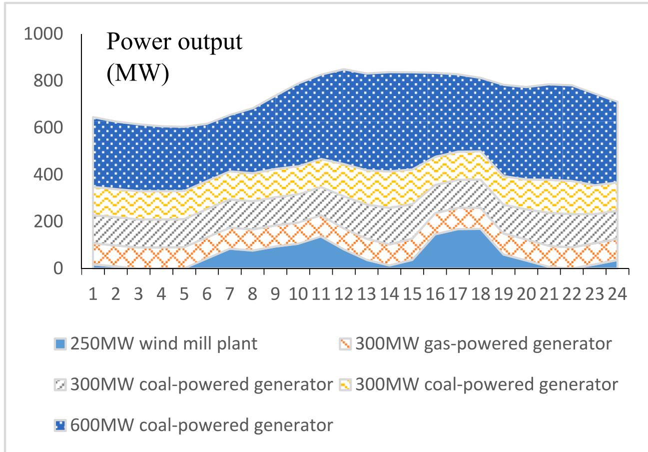
04. Scenario A*subsidy wind *peak wind power.



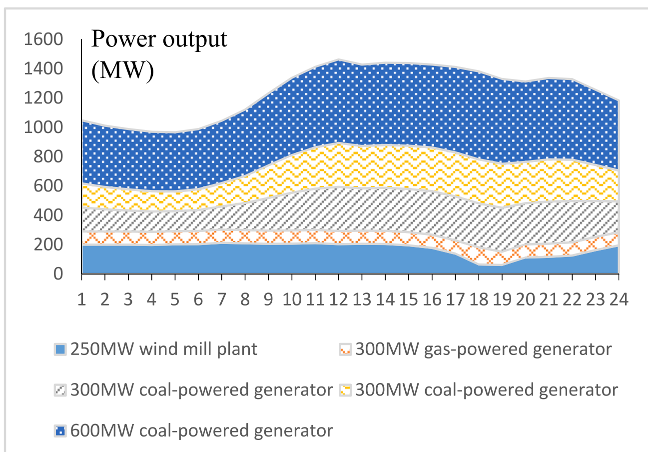
05. Scenario B*no subsidy wind *average wind power.



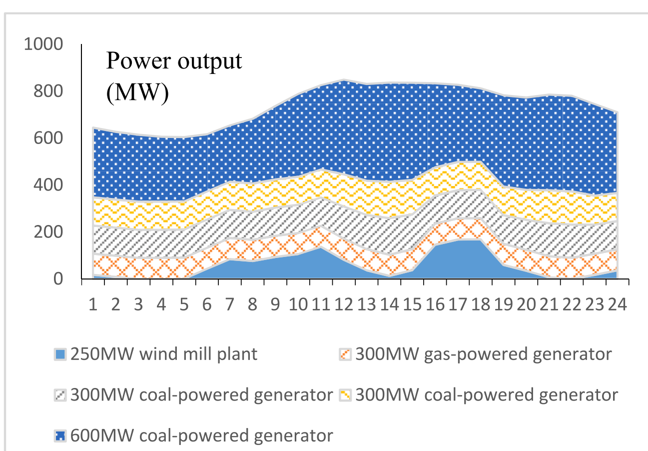
06. Scenario B*no subsidy wind *peak wind power.



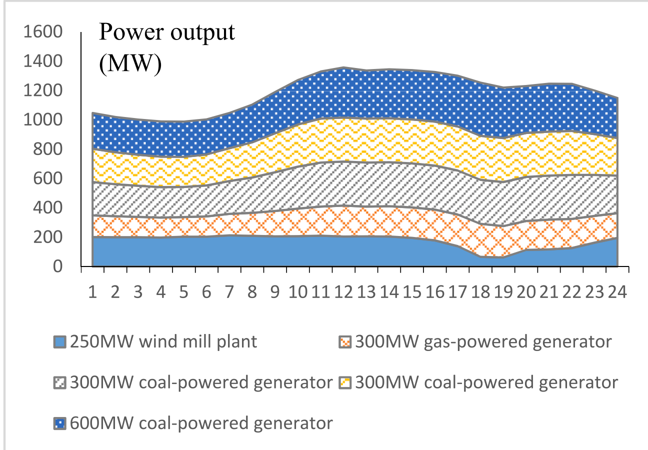
07. Scenario B*subsidy wind *average wind power.



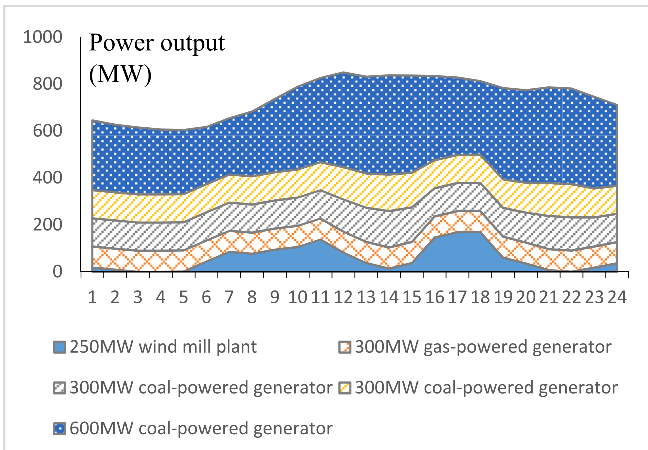
08. Scenario B*subsidy wind *peak wind power.



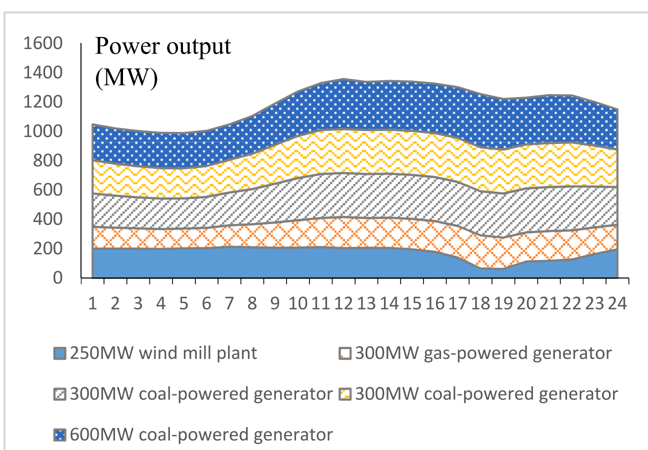
09. Scenario C*no subsidy wind *average wind power.



10. Scenario C*no subsidy wind *peak wind power.



11. Scenario C*subsidy wind *average wind power.



12. Scenario C*subsidy wind *peak wind power.

References

[1] Global Energy Review & Outlook, State Grid Energy Research Institute Co. LTD. China Electric Power Press, 2020, 2020, p. 11 (In Chinese).
[2] British Petroleum, Statistical Review of World Energy 2021, *70th edition*, 2021.
[3] X. Zhao, F. Wang, M. Wang, Large-scale utilization of wind power in China: obstacles of conflict between market and planning, Energy Pol. 48 (2012) 222–232.
[4] X. Zhao, S.F. Zhang, R. Yang, M. Wang, Constraints on the effective utilization of wind power in China: an illustration from the northeast China grid, Renewable and Sustainable Energy Reviewers 16 (2012) 4508–4514.
[5] X. Lu, M.B. McElroy, W. Peng, S.Y. Liu, C.P. Nielsen, H.K. Wang, Challenges faced by China compared with the US in developing wind power, Nat. Energy 1 (2016) 1–6.

[6] X. Du, The cause and countermeasure analysis of the phenomenon of abandoning wind and solar in China, Industry and Technology Tribune 16 (2016) 85–87 (in Chinese).
[7] C. Dong, Y. Qi, W. Dong, X. Lu, T. Liu, S. Qian, Decomposing driving factors for wind curtailment under economic new normal in China, Appl. Energy 217 (2018) 178–188.
[8] X. Zhao, L. Wu, S. Zhang, Joint environmental and economic power dispatch considering wind power integration: empirical analysis from Liaoning Province of China, Renew. Energy 52 (2013) 260–265.
[9] X. Zhao, H. Chen, S. Liu, X. Ye, Economic & environmental effects of priority dispatch of renewable energy considering fluctuating power output of coal-fired units, Renew. Energy 157 (2020) 695–707.
[10] R. Christiane, R. Madlener, Regulatory options for local reserve energy markets: implications for prosumers, utilities, and other stakeholders, Energy J. 37 (2016) 39–50.
[11] F.A. Wolak, R.H. Patrick, The Impact of Market Rules and Market Structure on the Price Determination Process in the England and Wales Electricity Market, National Bureau of Economic Research Working Paper Series No. 8248, 2001.
[12] S. Borenstein, J.B. Bushnell, F.A. Wolak, Measuring market inefficiencies in California's restructured wholesale electricity market, Am. Econ. Rev. 92 (2002) 1376–1405.
[13] F.A. Wolak, Measuring unilateral market power in wholesale electricity markets: the California market, 1998–2000, Am. Econ. Rev. 93 (2003) 425–430, 0.
[14] S. Poletti, Market Power in the New Zealand electricity wholesale market 2010–2016, Energy Econ. (2020), 105078.
[15] L. Marshall, A. Bruce, I. MacGill, Assessing wholesale competition in the Australian national electricity market, Energy Pol. 149 (2021), 112066.
[16] W. Lise, V. Linderhof, O. Kuik, C. Kemfert, R. Östling, T. Heinzow, A game theoretic model of the northwestern European electricity market—market power and the environment, Energy Pol. 36 (2006) 2123–2136.
[17] J. Bushnell, E.T. Mansur, C. Saravia, Market Structure and Competition: A Cross-Market Analysis of US Electricity Deregulation. Scholarship, 2004.
[18] E. O'Shaughnessy, Non-monotonic effects of market concentration on prices for residential solar photovoltaics in the United States, Energy Econ. 78 (2019) 182–191.
[19] A. Darmani, N. Arvidsson, A. Hidalgo, J. Albors, What drives the development of renewable energy technologies? Toward a typology for the systemic drivers, Renew. Sustain. Energy Rev. 38 (2014) 834–847.
[20] S. Bigerna, C.A. Bollino, P. Polinori, Renewable energy and market power in the Italian electricity market, Energy J. 37 (2016) 123–144.
[21] S. Djørup, J.Z. Thellufsen, P. Sorknæs, The electricity in a renewable energy system, Energy 162 (2018) 148–157.
[22] M. Waite, V. Modi, Price determination limits in relation to the death spiral, Energy J. 7 (2019), 150-20.
[23] C. Hiroux, M. Sagan, Large-scale wind power in European electricity markets: time for revisiting support schemes and market designs? Energy Pol. 38 (2010) 3135–3145.
[24] M. Shafie-khah, P.M. Moghaddam, K.M. Sheikh-El-Eslami, Development of a virtual power market model to investigate strategic and collusive behavior of market players, Energy Pol. 61 (2013) 717–728.
[25] M. Cepeda, D. Finon, How to correct for long-term externalities of large-scale wind power development by a capacity mechanism? Energy Pol. 61 (2013) 671–685.
[26] P.C. Bhagwat, K.K. Iychettira, J.C. Richstein, E.J. Chappin, L.J. de Vries, The effectiveness of capacity markets in the presence of a high portfolio share of renewable energy sources, Util. Pol. 48 (2017) 76–91.
[27] C. Byers, T. Levin, A. Botterud, Capacity market design and renewable energy: performance incentives, qualifying capacity, and demand curves, Electr. J. 31 (2018) 65–74.
[28] A. Bublitz, D. Keles, F. Zimmermann, C. Fraunholz, W. Fichtner, A survey on electricity market design: insights from theory and real-world implementations of capacity remuneration mechanisms, Energy Econ. 80 (2019) 1059–1078.
[29] CPSDAR, Analysis Report of China Power Supply Development, State Grid Energy Research Institute Co. LTD. China Electric Power Press, 2020, p. 7 (In Chinese).
[30] W. Wang, Discussion on power generation market of Beijing-Tianjin-Tangshan power grid, Electr. power (2000) 58–61 (in Chinese).
[31] X. Chen, M.B. McElroy, C. Kang, Integrated energy systems for higher wind penetration in China: formulation, implementation, and impacts, IEEE Trans. Power Syst. 33 (2018) 1309–1319.
[32] X. Chen, H. Zhang, Z. Xu, C.P. Nielsen, M.B. McElroy, J. Lv, Impacts of fleet types and charging modes for electric vehicles on emissions under different penetrations of wind power, Nat. Energy 3 (2018) 413–421.
[33] Z. Luo, Z. Hu, Y. Song, Z. Xu, H. Lu, Optimal coordination of plug-in electric vehicles in power grids with cost-benefit analysis—Part II: a case study in China, IEEE Trans. Power Syst. 28 (2013) 3556–3565.
[34] S.W. Liu, Research on incentive mechanisms of renewable energy generation based on game theory, in: Chinese) Graduation Dissertation for Master Degree, North China Electric University, 2017.
[35] X. Zhao, S.H. Wang, The economic evaluation of wind power generation based on the benefits of reducing carbon dioxide emission (in Chinese), Electr. power 47 (2014) 154–160.
[36] National Energy Administration, Center for Renewable Energy Development, renewable energy data manual. Staff report. http://www.cnrec.org.cn/cbw/zh/2016-09-20-512.html, 2016.
[37] China Electric Power Press, Annual Development Report of China Electric Power Industry, 2016. Staff Report.
[38] X.L. Wang, T. Xu, S.Y. Ma, Research on wind power absorption capacity of Beijing-Tianjin-Tangshan power grid in 2015, Energy of China 36 (9) (2014) 39–42 (In Chinese).
[39] Ministry of Finance of the People's Republic of China, Finance and Taxation [2015] 74, 2015.
[40] National People's Congress, Enterprise Income Tax Law of the People's Republic of China, 2007.
[41] D. Cyranoski, Beijing's windy bet, Nature 457 (2009) 372–374.
[42] J. Löfberg, YALMIP: a toolbox for modeling and optimization in MATLAB. Taipei, in: Proceedings of the CACSD Conference, 2004.
[43] A. Gleixner, M. Bastubbe, L. Eifler, The SCIP Optimization Suite 6.0, 2018. Optimization Online, http://www.optimization-online.org/DB_HTML/2018/07/6692.
[44] J.B. Bushnell, E.T. Mansur, C. Saravia, Vertical arrangements, market structure, and competition: an analysis of restructured US electricity markets, Am. Econ. Rev. 98 (2008) 237–266.