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The Strategies for Increasing Grid-Integrated Share of Renewable Energy with Energy Storage and Existing Coal Fired Power Generation in China

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Abstract: The growing share of renewable energies needs more flexible services to balance their intermittency and variance. The existing coal fired units and electrical energy storage (EES) systems may play an important role in delivering flexible services. The value of their flexibility services, along with the value of renewable energies, has to be analyzed from the perspective of the power system, in which the capacity costs and operation costs of renewable energy power units, EES systems, and thermal power generation units have to be taken into consideration. An optimal model is built to analyze the renewable energy integration and the flexibility services delivered by the EES systems and thermal power units in a power system. Taking the existing thermal power units and EES systems in North China Power Grid as an instance, the overall cost of the grid is examined for the penetration of renewable energies and flexible service provision. The results show that the growing shares of renewable energies are affected by their capacity credits and flexibility sources in the grid, and that the potential of thermal power units to provide flexible services will be reduced due to the replacement of renewable energies for thermal power generation. The results also indicate that the thermal units may be dispatched to have priority to delivering flexible services for the renewable energy integration, and that the curtailment of renewable energies may be regarded as one type of flexible service. According to these results, policy and strategy recommendations are put forward to weigh the role of existing coal-fired units and EES systems in providing flexible services, and to improve their compensation mechanism and their coordination.

Keywords: coal fired power generation; electrical energy storage; renewable energy; policy recommendations; flexible services

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1. Introduction

The climate change primarily driven by greenhouse gas emissions from human activities is one of the world's great challenges. The transition to low carbon energy technologies and renewable energy sources is regarded as the main strategy to meet the decarburization target of 1.5 °C proposed by IPCC [1]. China attaches great significance to its sustainable development and response to climate change, and steadily strengthens the targets of its NDCs. The aims of NDCs were updated in 2020 and include striving to peak CO_2 emissions before 2030 and achieving carbon neutrality before 2060, lowering the CO_2 intensity of GDP by more than 65% by 2030 in comparison with that in 2005, and reaching the total installed capacity of wind and solar power of over 1200 GW by 2030, etc. [2]. By the end of 2020, the cumulative capacity of wind and solar power was about 535.21 GW, accounting for more than 24% of the total generation capacity in China, and it generated 727.6 TWh, accounting for 9.54% of total electricity generation [3]. In order to meet the relevant aims of NDCs, an average annual installed capacity of renewable energies will be more than

60 GW, whose variances and intermittence may have complex and context-specific impacts on the overall power system. However, over 20% penetration of renewable energy will result in the destabilization of the existing power system [4], which requires more flexible resources to mitigate their intermittence and variances.

The flexibility sources in China's power system are mainly gas-fired power stations and pumped-hydro energy storage stations, which grow slowly because of their operating costs and construction conditions [5,6]. However, a large number of coal-fired units were built in China to meet the electricity demand in the past decades, and now some of them can be retrofitted to deliver the flexibility services for the integration of renewable energies. The flexibility-retrofitted target of coal-fired units of 220 GW was set in the 13th Five-year Plan, but less than 27% of the target was achieved because the revenue from the deep-down regulations of flexibility-retrofitted coal fired units is low and less than expected [7], resulting in the failure to achieve as much as they are supposed to do in the current electricity market in China.

An EES system is another significant source to deliver flexible services, ranging from energy, capacity, and ancillary services in the power system. An EES system is regarded as one of the most potential technologies to balance the variances of renewable energies and the mismatch between supply and demand sides in the power system. Many literatures can provide a better understanding of the types of EES technologies, their similarity and differences, their roles, and costs for the integration of renewable energies and decarburization in the power grid, their support policy, and measurements [8–14]. The roles of EES systems are based on their performance, duration time, location, economic, and environmental impacts when they are deployed to integrate the renewable energy into the power system [15–19], and they are highly sensitive to the share of renewable energy in the grid, policy measures such as emission-taxes rates or penalty for the curtailment of renewable energies [20]. The potential values of EES systems can be defined through their applications in the power system including the bulk energy, ancillary services, customer services, etc., and their values vary due to utility and market structure, and valuation methodologies, ESS ratings [21].

Many analyses have been performed to optimize the operation of the given power system combined with EES systems according to certain criteria or economic indicators such as minimizing the total cost or maximizing the benefits [6,22–25]. EES systems can increase the value of renewable energies to some extent due to their high costs [26]. The cost of an EES system, its potential revenues from the operation of a power system, and its support policy are the main challenges to its applications [17,27–29]. However, recent power systems may have inherent capabilities to integrate large amounts of renewable energies, and if the power system is regarded as a whole to optimize and plan, the more renewable energies could be integrated, and an EES system may be one of future potential choices for flexibility services [30]. The flexibility of a power system is related to power generation technologies and electricity markets. The near-zero marginal costs of renewable energies and improper electricity market design can limit the initiatives to provide flexible services [31]. Thus, it is necessary to optimize the operation of the power system including the increasing share of renewable energies based on the flexible services delivered by EES systems, ensuring the balance between power supply and demand and the reduction of the total electricity cost [6,14,32].

Some studies on the planning and operation of the power system with a high proportion of renewable energies have been carried out, focusing on the importance of EES systems to provide flexible services and the security of power supply [30]. Based on the indices of flexibility services from source-load-storage sides, a power system with high penetration of renewable energy is optimized to minimize the investment cost or maximize the overall revenue of the power system [26,33]. Literature [34,35] propose a model to analyze the long-term storage requirements with a high proportion of renewable energies, and the model can value the EES system deployment and other options of flexibility services including thermal power units, biomass units, and the curtailment of renewable energies, based on their capacity value, balancing value, arbitrage value. But these studies mainly focus on the flexibility planning in a power system with high penetration of renewable energy, and fail to carry out the research in depth on the key issues during the transition to a high share of renewable generation, including the provision of flexibility services, EES applications and replacement of thermal power generation, etc. Besides, the value of the existing power plant portfolio cannot be captured in these analyses, and this would limit the related policy conclusions on the transition to a renewable-dominated power system. However, these analyses may provide the hints and foundation for the relevant follow-up research.

With the increasing share of renewable energies in China, more thermal power generation will be replaced and renewable energy will dominate in the power grid, but more flexible resources have to be required to balance their intermittence and variances during the transition process to a high proportion of renewable energies [31,33]. Flexibility services in a power system can be delivered by a mix of sources including demand response, generation side, and EES systems [36–38], but the deployment of existing coal-fired power units and EES systems is a feasible and realistic option to deliver flexibility services in China. The value of renewable energies to a power system may decrease with their increasing penetration level, which will have an important effect on the existing power generation portfolio [39]. Despite obvious benefits, for EES applications to integrate greater penetration of renewable energies [6,14,32,33], they have to be optimized with other flexible options in relation to the demand of a power system as a whole because of the complexity of valuing their operations in a power system [30,39]. However, few studies have been carried out in depth on the values of existing power plant portfolio and EES systems for flexible services in China, and it is necessary to establish effective strategies for the transition to a high share of renewable energies from China's coal-dominated power system based on the existing power generation portfolio and the effectiveness of EES applications. Therefore, this paper focuses on the integration optimization of EES systems and existing thermal power units during the transition of the power system to a high proportion of renewable energies in China, and analyzes the related strategies and policy recommendations.

The structure of this paper is organized as follows: Section 2 presents a planning model to minimize the total cost of the power system with the objective to optimize the capacities of EES systems, renewable energies, thermal power units, etc. Section 3 introduces a case study to analyze the cost and capacity changes of the above power generation sources during the transition to a high share of renewable energies, and the results are demonstrated and discussed. Section 4 shows the conclusions, the strategy, and policy recommendations.

2. Methodology

Increasing share of renewable energies necessitates more flexible services to address their variance and intermittency problems, meanwhile more renewable energies may gradually replace the existing conventional power units in the power system. However, these conventional power units may be important providers of flexible services despite their CO_2 emissions. The existing coal-fired unit can be retrofitted to run at 30% of its power rating without using oil [40–43], delivering flexible services. A large number of existing coal-fired power units in China can play a key role in integrating renewable energies. Besides an EES system may also be one of the most promising providers of flexibility services. The new requirements and changes during the transition to the growing proportion of renewable energies have to be met in the development and planning of a power system. Thus, based on the flexibility requirements in a power system, a planning model is built to analyze the capacity allocation of renewable energies and an EES system with the existing thermal power units, and their optimized operation in the transition to a high proportion of renewable energies.

2.1. Objective Function and Related Constraints

2.1.1. Objective Function

The total cost of a power system is minimized as the objective, including the capacity investment costs of renewable energies and EES systems, the costs of existing thermal power units, their operation costs which consist of their regular operation costs, and ancillary service costs such as the costs of balancing reserves and flexibility services. A high share of renewable energies may result in their declining value in a power system [39,44], and the curtailment penalty of renewable energies will not be included in the model. The power capacity and energy capacity of an EES system are its key characteristics [14,34], which can help the applications of an EES system in a power system. The objective function is formulated in Equation (1) [34,45,46]:

$$Cost_{sys} = \min(Cost_{inv,congen} + Cost_{inv,ren} + Cost_{inv,sto} + Cost_{oper,sys}) \tag{1}$$

$Cost_{inv,conven}$, $Costi_{nv,res}$, $Cost_{inv,sto}$ are respectively shown from Equation (2) to Equation (4).

$$Cost_{inv,congen} = \sum_{i=1}^{nc} c_{inv,coal} N_{i,coal} + \sum_{j=1}^{nj} c_{inv,gas} N_{j,gas} + \sum_{i=1}^{nc} c_{retr,coal} N_{i,coal} \tag{2}$$

$$Cost_{inv,ren} = \sum_{k=1}^{nw} c_{inv,wind} N_{k,wind} + \sum_{l=1}^{np} c_{inv,pv} N_{l,pv} \tag{3}$$

$$Cost_{inv,sto} = \sum_{m=1}^{nm} c_{inv,stoc} N_{m,sto} + \sum_{m=1}^{nm} c_{inv,stoe} E_{m,sto} \tag{4}$$

The operation cost of the power system, $Cost_{oper,sys}$, is comprised of the charge and discharge operation costs of an EES system, the regular operating costs of the existing conventional thermal power units, the flexibility operation costs including deep-down regulated costs, and startup costs. $Cost_{oper,sys}$ in the scheduling period T is given in Equation (5):

$$\begin{aligned} Cost_{oper,sys} = {} & \sum_{i=1}^{nc} \sum_{t=1}^{T} [u_{i,t} c_{i,op} G_{i,t} + us_{i,t} S_i] + \sum_{j=1}^{nj} \sum_{t=1}^{T} [u_{j,t} c_{j,op} G_{j,t} + us_{j,t} S_j] \\ & + \sum_{m=1}^{nm} \sum_{t=1}^{T} [c_{m,sto} (G_{m,stin} + G_{m,stout})] \end{aligned} \tag{5}$$

2.1.2. The Related Constrains

The optimization of the object function has to be subject to the following related constraints, including the balance constraints of power supply and demand, the power outputs of the power generation units, the charge and discharge constraints of EES systems, etc.

1. The balance constraints of power supply and demand.

$$\sum_{i=1}^{nc} u_{i,t} \cdot G_{i,t} + \sum_{j=1}^{nj} u_{j,t} \cdot G_{j,t} + \sum_{k=1}^{nw} G_{k,t} + \sum_{l=1}^{np} G_{l,t} + \sum_{m=1}^{nm} G_{m,stout} = D_t + \sum_{m=1}^{nm} G_{m,stin} \tag{6}$$

2. The constraints of renewable energy generation.

$$cr_{k,wind} \cdot N_{k,wind} = G_{k,t} + CU_{k,t} \tag{7}$$

$$cr_{l,pv} \cdot N_{l,pv} = G_{l,t} + CU_{l,t} \tag{8}$$

$$G_{k,t} \le N_{k,wind};\ G_{l,t} \le N_{l,pv} \tag{9}$$

3. System reserve constraints.

$$\sum_{i=1}^{nc} u_{i,t} \cdot N_{i,coal} + \sum_{j=1}^{nj} u_{j,t} \cdot N_{j,gas} + \sum_{m=1}^{nm} G_{m,stout} + \sum_{m=1}^{nm} G_{m,stout,rsrv} + \sum_{m=1}^{nm} G_{m,stin,rsrv} = D_t + \sum_{m=1}^{nm} G_{m,stin} + Rs_t \quad (10)$$

4. The charge and discharge constraints of EES systems.

$$Stolev_{m,t} = Stolev_{m,t-1} + G_{m,stin} \cdot \eta_{m,stin} - G_{m,stout}/\eta_{m,stout} \quad (11)$$

$$Stolev_{m,t} \le E_{m,sto} \quad (12)$$

$$G_{m,stout} + G_{m,stout,rsrv} \le N_{m,sto} \quad (13)$$

$$G_{m,stin} + G_{m,stin,rsrv} \le N_{m,sto} \quad (14)$$

$$G_{m,stout} + G_{m,stout,rsrv} \le Stolev_{m,t-1} \quad (15)$$

$$G_{m,stin} + G_{m,stin,rsrv} \le E_{m,sto} - Stolev_{m,t-1} \quad (16)$$

5. The operation constraints of thermal power units.

$$u_{i,t} \cdot \gamma_{i,coal} \cdot N_{i,coal} \le G_{i,t} \le u_{i,t} \cdot N_{i,coal} \quad (17)$$

$$u_{j,t} \cdot \gamma_{j,gas} \cdot N_{j,gas} \le G_{j,t} \le u_{j,t} \cdot N_{j,gas} \quad (18)$$

$$-r_{ido} \le u_{i,t}G_{i,t} - u_{i,t-1}G_{i,t-1} \le r_{iup} \quad (19)$$

$$-r_{jdo} \le u_{j,t}G_{j,t} - u_{j,t-1}G_{j,t-1} \le r_{jup} \quad (20)$$

$$us_{i,t} = u_{i,t} - u_{i,t-1} \quad (21)$$

$$us_{j,t} = u_{j,t} - u_{j,t-1} \quad (22)$$

$$u_{i,t-1} - u_{i,t} \le 1 - u_{i,dur} \quad (23)$$

$$u_{j,t-1} - u_{j,t} \le 1 - u_{j,dur} \quad (24)$$

2.2. Solving Method about the Model

The above model involves the on/off states of existing thermal power units and their fuel consumption. Their on/off states are represented by binary variables, and their curves of fuel consumption cost are usually convex. The model belongs to a MINLP problem. The optimization analyses of a MINLP problem have been carried out by some literatures [47–49]. In order to reduce the computational complexity of the model, the curves of fuel consumption cost are linearized and the model becomes a MIP problem, which can be programmed and solved in GAMS. The flowchart for the solving method about the model is shown in Figure 1.

GAMS is a high level modeling system for mathematical programming and optimization, and it consists of a language compiler and a range of associated solvers [50], such as Cplex, Scip, etc. Based on these solvers and their options, the above model can be solved.

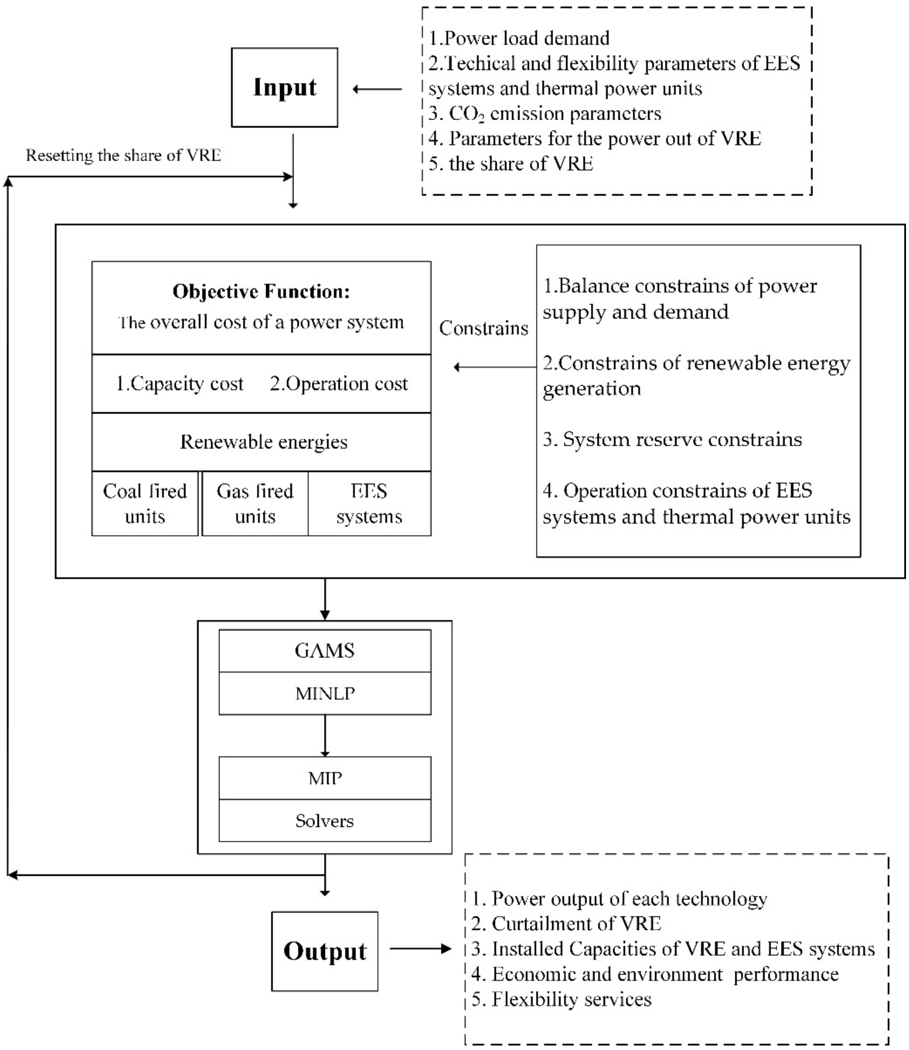


Figure 1. The flowchart for solving method about the model.

3. Case Study

3.1. Description of the Studied Power System

The certain regional grid of the North China Power Grid is taken as the studied power system. The capacity of existing conventional thermal power units is 60,820 MW, including the coal-fired power generation capacity of 50,425 MW, and the capacity of combined-cycle gas turbines of 10,359 MW. The capacity of CHP units among these existing thermal power units is about 31,806 MW. The detailed capacities of these existing power units are given in Table 1. The conventional thermal power units can provide flexible services by lowering their minimum load, increasing their ramping rate, and shortening their startup time [40,41]. CHP units can deliver less flexible services during the heating season, and their flexibility services can be increased by decoupling the generation of electricity and heat. The regional power system is rich in renewable energies, and the available hours of wind and solar PV power generation in the grid are respectively more than 2700 h and 1700 h.

Table 1. Capacities of the existing thermal power units in the studied regional grid.

Type	Total Capacity/MW	CHP Capacity/MW
Coal-fired units	50,425	21,411
CCGT units	10,395	10,395

For the simplicity of analysis, this case study concentrates only on the flexible services delivered by the EES systems and the existing conventional thermal power units, and examines their impacts on the capacity allocation of renewable energies and an EES system and their operation on the basis of the typical daily demand loads of the studied power system during the transition to a high proportion of renewable energies.

3.2. Assumptions and Input Data

Due to the difficulty of data access and the complexity of analysis, the annual load demand of the regional grid is analyzed based on its typical daily historical loads. The demand loads on a typical day per month in the regional grid are shown in Figure 2, and the related capacity factors of renewable energies [51] are shown in Figure 3.

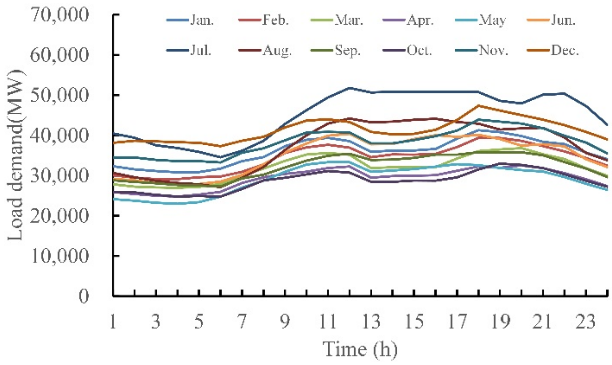
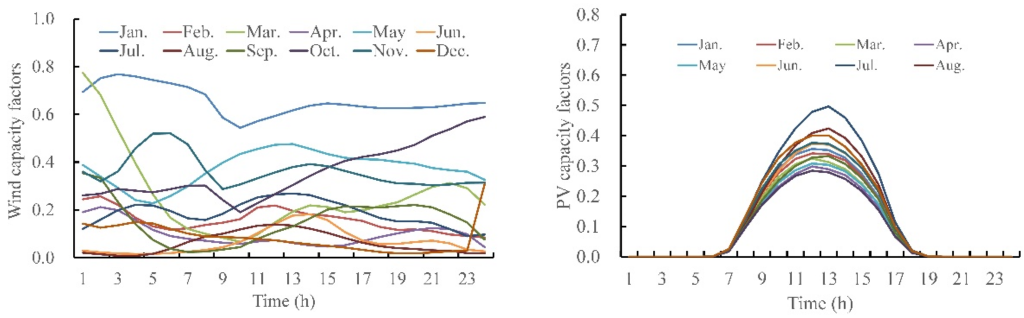


Figure 2. 12-month load profiles of the regional power system based on a typical day.



(**a**) (**b**)

Figure 3. 12-month capacity factors of renewable energies based on a typical day: (**a**) 12-month wind capacity factors; (**b**) 12-month PV capacity factors.

The existing conventional thermal power units have different potentials to deliver the flexibility services according to their startup time, ramping rate, and minimum load rate, and these parameters are selected according to the literature [52,53]. CHP units have less potential during the heating months to provide flexible services because the heat demand has to be met from their heat and electricity generation to maintain a certain load rate, which limits their ability to regulate the power output. Thus, it is assumed that a CHP unit has the potential to keep 30% of its full load during the non-heating season and 40% of its full load during the heating season after its flexible retrofits. The EES system of Lithium-ion batteries is assumed to be deployed in the regional grid, and the related key parameters of thermal power units and EES systems [45,54,55] are shown in Table 2. The coal consumption rates of the existing coal fired units may vary according to *the norm of energy consumption per unit product of the general coal-fired power set* [56], which is one of the standards of the People's Republic of China.

Table 2. Costs of the existing thermal power units, Wind power and PV units, EES systems.

Type	Investment Cost (CNY/kW)	Operating Cost (CNY/kW)	Rtrofitted Cost (CNY/kW)
Coal-fired units units	3200	0.18	500
CCGT units	2500	0.4	500
Wind power units	7600	0.00	–
PV units	4600	0.00	–
The EES systems of Lithium-ion batteries	1200 (1 h)	0.00389	–

Besides, it is assumed that the capacity of wind power units is the same as that of solar PV units, and the curtailment of their generation is free because of its decreasing value with its increasing penetration. Transmission network constraints are also assumed to be met. Then the impact of the flexibility demand of the regional grid on the capacity allocation of renewable energies and an EES system, along with the existing thermal power units, will be analyzed based on their optimal operation under different shares of renewable energies.

3.3. Simulation Results and Analysis

3.3.1. Integration of Renewable Energies and Total Cost of the Power System

Based on the flexibility retrofits of the existing thermal power units, the integration of renewable energies and the total cost of the power system are shown in Figure 4. The total cost of the power system increases with the growing shares of renewable energies including solar PV and wind power. According to Equation (1), the total cost consists of the capacity costs of renewable energies and EES systems, the flexibility-retrofitted costs of existing thermal power units, and their operating costs. The flexibility-retrofitted capacities of the existing thermal power units and the related costs are fixed by the above assumption. The capacities of renewable energies and the EES system have to increase with the growing share of the renewable energies, as shown in Figure 5, resulting in an increase of their costs. Because the operating cost of renewable energy power units is near zero and the operating cost of the EES system is relatively low, the overall operating cost of the power system decreases with the growing integration of renewable energies replacing the generation of existing thermal power units, although part of them run in off-designed load rate to provide the flexibility services for the renewable energy integration which may lead to higher fuel consumption and cost.

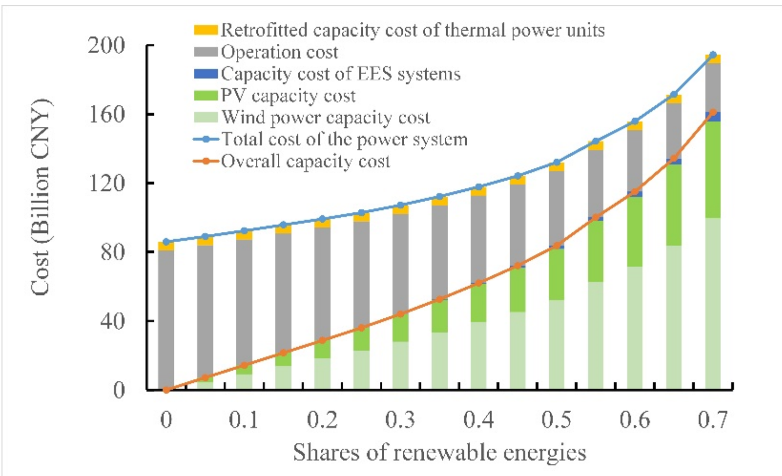


Figure 4. The correlation among the integration shares of renewable energies, the related cost portfolio, and the total cost of the power system.

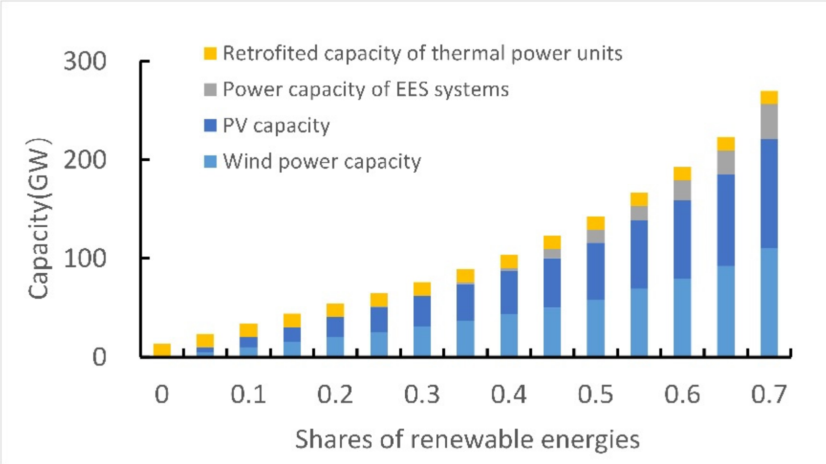


Figure 5. The correlation of the power capacity portfolio among the integration shares of renewable energies.

The ratio of renewable energies available to the total power demand and their curtailment are shown in Figure 6. The ratio of renewable energies available to the total power demand increases with their growing share integration. When their integrating share reaches about 0.25, their curtailment begins. The curtailment of renewable energies occurs under the operating constraints of the power system and its total cost on the basis of the flexibility services provided by the EES system and the existing thermal power units. The curtailment increases with the growing share of renewable energies. Since the capacity costs of renewable energies and the EES system outweigh the decrease in the operating cost of the power system, their combined effect leads to an increase in the total cost.

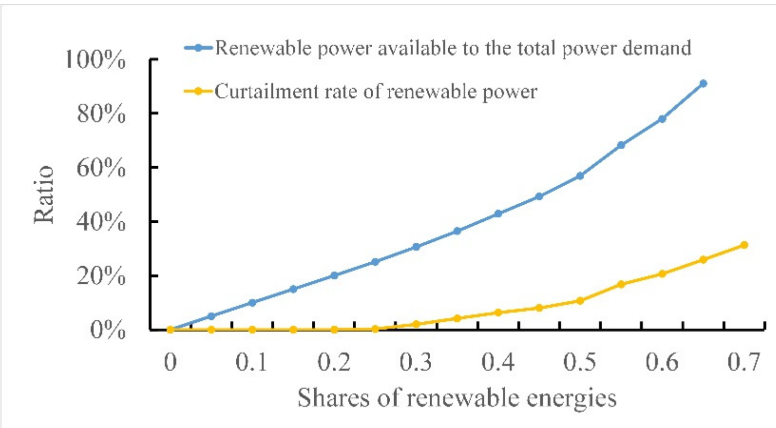


Figure 6. The curtailment rate of renewable energies with their integration shares.

3.3.2. Flexibility Services for Renewable Energy Integration

The increasing share of renewable energy integration requires more flexibility services to balance their variances and intermittence, and these flexible services are provided through the existing thermal power units and the EES system in the power system. The EES system delivers flexibility services by its charge and discharge operation. The existing thermal power units provide flexible services by regulating their power output between their maximum and minimum power outputs, and sometimes they may be shutdown provisionally. When the load rate of a thermal power unit is regulated down below 50% of its rated power output, the type of flexibility services is regarded as the deep-down regulation, and the operation of above 50% of its rated power output belongs to its regular operation. The flexibility services of power output from the EES system and existing thermal power units are shown in Figure 7, and the ratio of solar PV and wind power output available to the overall demand of the power system and their curtailment is also shown in Figure 8. The flexibility-regulated power output increases with the growing share of renewable energies. The ratios of solar PV and wind power output available to the overall demand of the power system increase with their growing shares. The curtailments of solar PV and wind power output, respectively, begins at nearly 25% of renewable energy integration, but the curtailments are too small to be shown in Figure 8. Then the curtailments increase with the growing share of renewable energies.

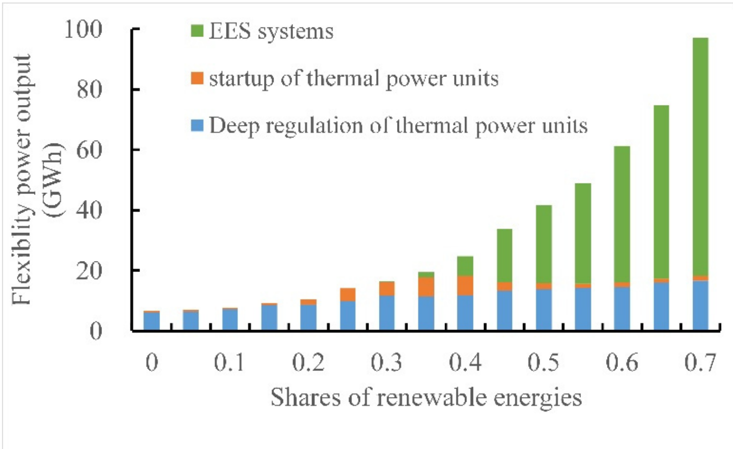


Figure 7. The flexibility sources with the integration share of renewable energies.

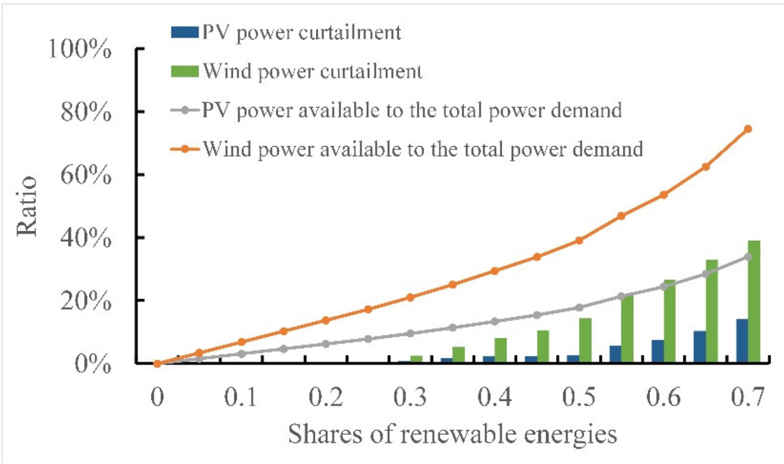


Figure 8. The wind and PV curtailment ratios with the integration share of renewable energies.

Flexibility services for renewable energy integration can be provided by the existing thermal power units before 25% of renewable energy integration, beyond which the flexibility services from the EES system gradually play an important role in the renewable energy integration, since the increasing proportion of renewable energies replaces part of the power generation for the existing thermal power units and these conventional units cannot provide enough flexibility services for the integration of renewable energies. The flexibility services from their deep-down regulation are more than those from their startup regulation (as shown in Figure 7), and the related costs are shown in Figure 9.

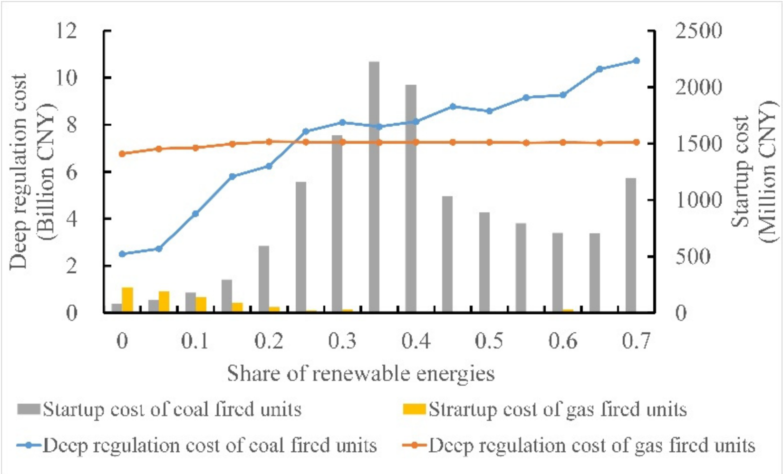


Figure 9. The flexibility cost portfolio with the integration share of renewable energies.

3.3.3. The Net Operating Benefits of the Power System

The net operating benefits of the power system consist of energy savings and CO_2 emission reductions. The benefit from CO_2 emission reductions is included in the model as part of the operating costs of the existing thermal power units. The net operating benefits of the power system increase with the growing share of renewable energies, as shown in Figure 10, mainly because the power outputs of the existing thermal power units are replaced by renewable energies with no fuel consumption and no greenhouse gas emissions. Figure 11 shows the power outputs of all units and the related coal consumption of the existing thermal power units in this regional grid under the different integration shares of renewable energies. Some of the existing thermal units in the grid run in regular operation, and some of them provide flexible services including the startups and deep-down regulations. As the integration proportion of renewable energies in the grid increases, the power generation of these thermal power units in regular operation will be replaced gradually. The coal consumption of the thermal units delivering flexibility services shows a slow growth trend. So, the benefits of the fuel saving and greenhouse gas emission reductions are nearly from the replacement of the generation of the thermal power units in regular operation.

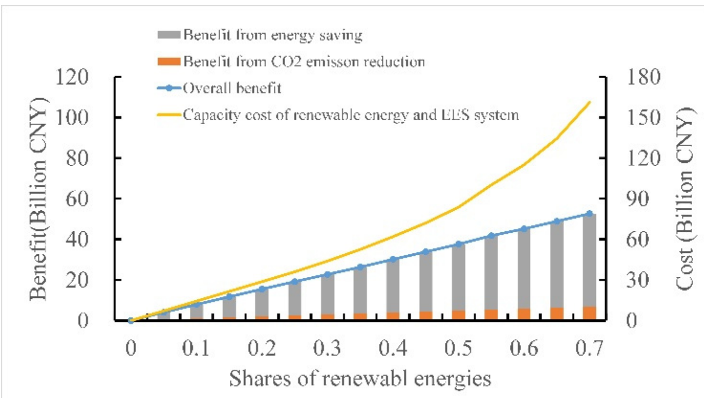
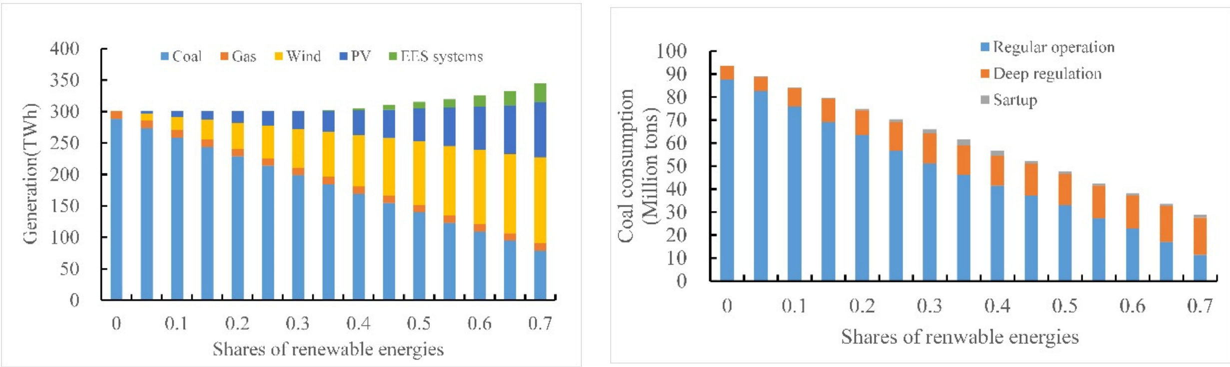


Figure 10. The net operating benefits with the integration share of renewable energies.



(**a**) (**b**)

Figure 11. The power generation and energy consumption with the integration share of renewable energies: (**a**) the power generation portfolio; (**b**) the energy consumption portfolio.

However, with the growing shares of renewable energies, less number of thermal power units can provide flexible services and the EES system has to be required to deliver the flexible services for the integration of renewable energies. According to Figures 6 and 8, the curtailment of renewable energies may be regarded as one of the flexible services for their integration. Despite the power generation of renewable energies with no or fewer operation costs, their capacity costs are still higher than those of conventional thermal power units. With the growing share of renewable energies, the benefits from their replacement of the existing thermal power units will be offset by the increase in their capacity costs.

3.3.4. Discussions and Further Analyses

GAMS has been applied in solving a broad range of power system optimization problems [34,35,54,57]. According to the solvers in GAMS, their preprocessing, and general options, the above power system optimization problems can be solved effectively to mitigate or avoid some undesirable possibilities. But there are a few limitations in the methodology and its assumptions. First, the capacities of wind power and solar PV units are supposed to have the same capacities in the above assumptions. In fact, they may have different capacities due to their respective resources, cost, and capacity credits. Second, the impacts of the power demand side and sector coupling on the provision of flexibility services and the related costs in the grid, are not reflected in the model. Third, the operating benefits could result from energy saving and its related pollutants such as CO_2, SO_2, NO_x, etc. due to the integration of renewable energies in the grid. But only the benefit of CO_2 emission reductions is taken into account in the methodology and above analyses.

However, this study emphasizes the fundamental rules about the integration of renewable energies and the required flexibility services despite the above limitations, which might have an effect on or weaken the validity of these rules. The principles of renewable energy integration and the flexibility services from the existing thermal power units and the EES system still can be highlighted.

4. Conclusions and Policy Recommendations

4.1. Conclusions

This study shows that the growing shares of renewable energies are affected by their capacity credits and flexible sources in the grid which are the key factors for their integration into the power system. The existing thermal power units and EES systems are the most promising providers of flexibility services due to their construction conditions, operation costs, and technical development. The value of their flexible services, along with the value of renewable energies, has to be analyzed from the perspective of the power system. Due to the flexibility-retrofitted costs of the existing thermal power units and their related operating costs are lower than the deployment costs of EES systems, the thermal units may be dispatched to have priority to deliver flexible services for the integration of the renewable energies in the power system, and these existing thermal units may help the renewable energies to be integrated even up to 25% of total electricity generation.

The increasing share of renewable energies needs more flexible services to balance their variances and intermittence, but they also replace part of the existing thermal power units, and the number of the thermal units providing flexible services will be reduced. When the flexible services from the thermal units is not enough to support the growing shares of renewable energies, the EES system will be employed to deliver flexible services. Besides, this study also indicates that the curtailment of renewable energies may be regarded as one type of flexible service for their integration based on the reasonable dispatch of the power system at its minimum total cost.

4.2. Policy and Strategy Recommendations

4.2.1. To Strengthen the Role of Existing Coal-Fired Units in Providing Flexibility Services

In order to promote the provision of flexible services for the renewable energy integration in the power system, a *Notice on Encouraging Renewable Energy Power Generation Enterprises to Build or Purchase Peak Shaving Capacity to Increase the Grid-connected Scale of their renewable power generation* was issued in 2021 by The National Development and Reform Commission (NDRC), National Energy Administration (NEA) [58]. This policy encourages the renewable energy power generation enterprises to take their initiatives to deploy EES systems or peak regulation sources, which may help to advance the development of EES systems and ensure flexible service provisions for renewable energy integration.

There are a great number of coal-fired units in operation in China, and they have the potential to deliver much more flexible services for the integration of renewable energies. EES systems may be another promising flexible source for the renewable-dominating power system. However, their high capacity costs and new development uncertainty except the pumped-hydro energy storage stations might have an effect on their deployment for the integration of renewable energies. Due to the capacity and operation costs, and construction conditions of the flexibility sources in China, the existing thermal power units, especially the existing coal-fired units are the better candidates to deliver the flexibility services. Thus, much more attention should be paid to the existing coal fired units to deliver flexible services during the transition to a high share of renewable energies.

4.2.2. To Improve the Compensation Mechanism for the Exiting Thermal Power Units and EES Systems Delivering Flexibility Services

The exiting thermal power units and EES systems are the important providers of flexibility services for renewable energy integration. At present, the flexibility services provided by the thermal power units only include the deep-down regulations, startup, and shutdown regulations. However, the operation regulation of above 50% of its rated power output for the integration of renewable energies should also have to be included. Delivering flexibility services will lower the load rates of the thermal power units, resulting in an increase in their fuel consumption. Meanwhile, the growing shares of renewable energies and their replacement may also cut down the benefits of these thermal units from the power generation. Besides, the deployment of EES systems may significantly increase the fixed costs of renewable energy power generation enterprises, but there is a lack of a cost recovery mechanism for the capacity costs of EES systems. The charging and discharging dispatch of an EES system is closely related to the revenue from renewable energies. If the EES system participates in the power market as an independent market entity, it will also face the same challenges.

The value of flexibility services delivered by the EES system and coal fired units, cannot be fully captured by the existing market mechanism. The new incentives have to be further designed from the respective public goods and externalities, to compensate for the costs and benefits of the providers of flexibility services, guaranteeing that the existing thermal power units and EES systems deliver the flexible services for the renewable energy integration.

4.2.3. To Coordinate the Dispatch of Flexibility Services Based on the Overall Benefits of the Power System

The share of renewable energies increases at the cost of the flexibility service provisions under the operating constraints of the grid, which has an effect on the overall benefits of the power system and these benefit distribution among the power market entities. Renewable energy resources vary in different regions in China, and the variance and intermittency of renewable energy power generation can be offset to a certain extent. Therefore, from the perspective of the power system as a whole, the requirement of flexibility services for the aggregated renewable energy generation will be reduced, finally, the costs of flexibility services and the power system will decrease. In addition, the curtailment of renewable energies can also be regarded as one type of flexible services on the basis of the overall cost of the power system. When the costs of flexibility services are beyond the costs and benefits of the renewable energy integration, their curtailment is a reasonable option for the operation of the power system.

The flexibility services dispatched from the perspective of the power system can guarantee the utilization effectiveness of flexibility resources and reduce the overall dispatch costs of the power system, and the economics of scale from the flexibility resources could be leveraged. Thus, the coordinated dispatch of flexibility services should be improved based on the price signals and compensation mechanisms from the overall benefits of the power system.

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Nomenclature

Symbol	Description
$Cost_{sys}$	Total cost of the power system
$Cost_{inv,conven}$	Total capacity cost of existing conventional thermal power units incluing their flexibility-retrofitted costs
$Cost_{inv,res}$	Total investment cost of renewable energies
$Cost_{inv,sto}$	Total investment cost of an EES system
$Cost_{oper,sys}$	Operation cost of the power system
$c_{inv,coal}$	Unit investment cost of existing coal fired unit i
$c_{inv,gas}$	Unit investment cost of existing gas fired unit j
$c_{retro,coal}$	Unit flexibility-retrofitted cost of existing coal fired unit i
$c_{inv,wind}$	Unit investment cost of wind power unit k
$c_{inv,pv}$	Unit investment cost of solar PV unit l
$c_{inv,stoc}$	Power capacity cost of EES system m
$c_{inv,stoe}$	Energy capacity cost of EES system m
i	Number index of existing coal-fired units

nc	Total number of existing coal-fired units
j	Number index of existing gas-fired units
nj	Total number of existing gas-fired units
k	Number index of wind power units
nw	Total number of wind power units
l	Number index of solar PV units
np	Total number of solar PV units
m	Number index of EES systems
nm	Total number of EES systems
$N_{i,coal}$	Capacity of coal-fired unit i
$N_{j,gas}$	Capacity of gas-fired unit j
$N_{k,wind}$	Capacity of wind power unit k
$N_{l,pv}$	the capacity of PV unit l
$N_{m,sto}$	Power capacity of EES system m
$E_{m,sto}$	Energy capacity of EES system m
T	Sheduling period
$c_{i,op}$	Operating cost of existing coal fired unit i
$c_{j,gas}$	Operating cost of existing gas fired unit j
$c_{m,sto}$	Operating cost of EES system m
$G_{i,t}$	Power output of existing coal fired unit i at time t
$G_{j,t}$	Power output of existing gas fired unit j at time t
$G_{m,stin}$	Power input of EES system m at time t
$G_{m,stout}$	Power output of EES system m at time t
$u_{i,t}$	Status of existing coal fired unit i at time t
$u_{j,t}$	Status of existing gas fired unit j at time t
$us_{i,t}$	Startup status of existing coal fired unit i at time t
$us_{j,t}$	Startup status of existing gas fired unit j at time t
S_i	Startup cost of existing coal fired unit i
S_j	Startup cost of existing gas fired unit j
$G_{k,t}$	Power output of wind power unit k at time t
$G_{l,t}$	Power output of PV unit l at time t
D_t	System power load demand at time t
$cr_{k,wind}$	Wind capacity factor of unit k at time t
$cr_{l,pv}$	PV capacity factor of unit l at time t
$CU_{k,t}$	Curtailed power output of wind power unit k at time t
$CU_{l,t}$	Curtailed power output of PV unit l at time t
$G_{m,stout,rsrv}$	Reserve discharging capacity of EES system m at time t
$G_{m,stint,rsrv}$	Reserve charging capacity of EES system m at time t
Rs_t	System reserve capacity at time t
$Stolev_{m,t}$	Energy level of EES system m at time t
$\eta_{m,stin}$	Charging efficiency of EES system m
$\eta_{m,stout}$	Discharging efficiency of EES system m
$\gamma_{i,coal}$	Minimum load rate of existing coal fired unit i
$\gamma_{j,gas}$	Minimum load rate of existing gas fired unit j
r_{iup}	Ramping-up constraints of existing coal fired unit i
r_{ido}	Ramping-down constraints of existing coal fired unit i
r_{jup}	Ramping-up constraints of existing gas fired unit j
r_{jdo}	Ramping-down constraints of existing gas fired unit j
$u_{i,dur}$	Status of continuous operation time of existing coal fired unit i
$u_{j,dur}$	Status of continuous operation time of existing gas fired unit j
Abbreviations	
GDP	Gross domestic product
EES	Electrical energy storage
IPCC	Intergovernmental panel on climate change
NDCs	Nationally Determined Contributions
GW	Gigawatts
TWh	Terawatt-hours
MINLP	Mixed integer nonlinear programming

MIP	Mixed integer programming
GAMS	General algebraic modeling system
VRE	Variable renewable energy
PV	Photovoltaic
CHP	Combined heat and power
CCGT	Combined-cycle gas turbines
NDRC	National Development and Reform Commission
NEA	National Energy Administration

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