Evaluation of Ancillary Service Market Mechanism to Facilitate High Penetration Renewable Integration in China

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Abstract. Renewable energy curtailment is increasingly a critical issue in China. Mechanism barriers are becoming a key constraint for renewable energy integration, in which downward regulation mechanism that incentivizes conventional generators to be dispatched down is playing a key role in some regions, such as Northeast China. Pilots of such market mechanism, i.e. downward regulation ancillary service mechanism, have already been initiated in Northeast China. This paper evaluates the impact of downward regulation ancillary service mechanism in power systems with high penetrations of renewable energy. Firstly, the current situation of renewable energy development in China is analyzed. Secondly, the current practice of downward regulation ancillary service market mechanism in China are summarized and analyzed. Thirdly, the evaluation methodology as well as the case study system are described. Fourthly, simulation results are presented and analyzed. Finally, implications and suggestions are proposed.

1. Introduction

By the end of 2016, the cumulative installed capacity of wind and solar generation in China reached 226.06 GW, which accounts for 14% of the total generation capacity. The total amount of energy generated from wind and solar in 2016 was 307.2 TWh, which accounts for 5% of the total energy being generated [1]. Wind and solar generation has turned to the second largest source of electricity generation in 16 provinces[2]. The proportions of the wind and solar generation capacity in Gansu, Ningxia, Xinjiang and Qinghai are over 30%. However, renewable energy integration has been a critical issue in recent years . In 2016, the amount of wind curtailment in China hit a record height, reaching 49.7 TWh [3]. The wind curtailment rate in Gansu, Xinjiang, Jilin and Inner Mongolia are over 20%. Solar curtailment amounted to 7.04 TWh. Almost all the solar curtailment are concentrated in Northwest China, i.e. Gansu, Xinjiang, Qinghai, and Ningxia.

Mechanism barriers such as a lack of compensation mechanism for conventional generators that provide downward regulation services to wind and solar, inflexible prices, etc. are increasingly becoming key bottlenecks for renewable energy integration in China. Among them, downward regulation services are playing a key role. In this paper, the downward regulation services mean the services provided by the generators when they are dispatched down to make room for renewable energy. Due to a lack of compensation mechanism for conventional generators that provide downward

regulation services to wind and solar, conventional generators do not have any incentives to be dispatched down to help integrate more renewables, and thus partially resulted in the serious renewable energy curtailment issue.

On March 2015，CPC Central Committee and the State Council released *Opinions Regarding the Deepening of the Power Sector's Reform* (Paper #9), marking the official launch of the new-round power sector reform. One of the basic principles of the new electricity reform is to promote the increase of renewable generation and distributed energy systems in electricity supply. Proper market mechanism design is critical for alleviating renewable energy curtailment problem. In some parts of China, pilots of downward regulation ancillary service market have already been initiated [4]. Evaluation of the effectiveness of the market is of significance for its improvement and future establishment of a mature electricity market that facilitate renewable energy integration.

This paper is organized as follows. Part II analyzes the current practice of downward regulation ancillary service market in China. Part III describes the evaluation methodology as well as the case study system. Part IV presents the evaluation results. Part V concludes the paper with implications and suggestions.

2. Current Status of Downward Regulation Ancillary Service Market in China

It is worth to note that downward regulation service is a unique concept of power system dispatching in China. In power systems in an electricity market context, these services are provided by the spot markets, and are not in the arena of ancillary services. Since there is no mature electricity market, especially there is not a spot market in China, the downward regulation services are classified as one type of ancillary services and incentives for these services commonly seen in the documents of "grid-connected power plant ancillary services management "in different provinces and regions [5][6]. In these documents, downward regulation services, named compensated deep downward regulation, are classified as one type of ancillary services. More specifically, in these documents, there is a benchmark downward regulation service, which differs region by region and generally is 50% of the maximum generation capacity of a generator. If the generation is called upon to provide downward regulation services with the output of the generator being above the benchmark, these services are free. If the output of the generator is below the benchmark while providing these services, the amount of energy below the benchmark will be compensated.

With high penetration of renewable energy in the system, more frequent and deeper downward regulation services are needed from conventional generators, as in many wind intensive areas in China, wind blows hard during the mid-night when there is low electricity demand in the system. The downward regulation compensation specified for a non-renewable energy or low renewable energy power system is not enough to incentivize conventional generators. For example, in Northwest China, the amount of energy below the benchmark regulation services are paid 0.30RMB/kWh, while in North China, they are paid only 0.05 RMB/kWh. This greatly limits the system's downward regulation capability.

With the advancement of China's new round of power market reform, some areas are actively carrying out market explorations to unlock power system flexibility, which help renewable energy integration. One of the most notable trial is the ancillary service market in Northeast China, which started in October 2014 and improved in 2016. In Northeast China, a market mechanism is introduced in procuring downward regulation ancillary services from thermal generators. Instead of setting up a fixed compensation rate by the government beforehand, thermal generators can bid for their capabilities to be dispatched down and they will be compensated based on the clearing price. The more they can be dispatched down, the higher compensation rate they will get. The bidding cap for downward regulation and cycling are shown in Table I and Table II.

Table 1. Bidding Cap and Floor for Downward Reguation

Period	Type	Loading rate	Bid Floor (RMB/kWh)	Bid Cap (RMB/kWh)

Non-heating	Non-CHP	40%<R<=50%	0	0.4
	CHP	40%<R<=48%		
	All	R<40%	0.4	1
Heating	Non-CHP	40%<R<=48%	0	0.4
	CHP	40%<R<=50%		
	All	R<40%	0.4	1

Table 2. Bidding Cap for Cycling

Capacity (MW)	Bidding cap per cycling (10^3 RMB)
100	500
200	800
300	1200
500～600	2000
800～1000	3000

Besides Northeast China, other regions in China are also in the process of initiating downward regulation ancillary service market pilots. For example, Shandong Province in May 2017 issued the "Shandong Electricity Ancillary Service Market Operating Rules (draft)" [7]. The main idea is also introducing a market mechanism to incentivize downward regulation services from thermal generators, similar to that of Northeast China. In Shandong, the trans-regional interconnections are considered as a provider of downward regulation services. The details on bidding intervals and cost allocation are different from Northeast China.

3. Evaluation Methodology and Case Study System

3.1. Evaluation Methodology
In this paper, an annual production simulation is used to evaluate the performance of downward regulation ancillary service market to facilitate renewable energy integration. The production simulation model is built upon least cost unit commitment in the paper. The model includes a long-range unit-commitment for the scheduling of the generating units and a economic dispatch model to calculate system performance indices, such as annually system operation cost, wind curtailment rate, generation cost per kWh, etc.

In the long-range unit-commitment, the generators are scheduled for a period of 7 days (the optimization horizon), after which the scheduling period rolls forward by 5 days (the rolling step). There are 2 days of look ahead, that is, there is an overlap of 2 days between each consecutive optimization horizon. This overlap gives the model some extra foresight to account for the reduction in demand that typically occurs at weekends. Also, if there was no overlap, an excessive number of units would be shut down towards the end of each optimization horizon. With respect to system operation in practice, long-range scheduling such as this facilitates fuel purchasing and contracts, as well as generator maintenance scheduling.

(1) Objective function

The objective function is the sum of generation cost $C_{Gen}(t)$ and load curtailment penalty cost $C_{LC}(t)$, for all the time steps in the scheduling horizon.

$$f_{obj} = \sum_{t \in T} C_{Gen}(t) + \sum_{t \in T} C_{LC}(t) \qquad (1)$$

The generation costs $C_{Gen}(t)$, for each time step is given in Eq. (2). It includes three parts, i.e. startup cost, no load cost and incremental cost. For no load cost and incremental cost, both fuel cost and CO_2 emission cost are included. U_I is the group set of all generators, which are grouped according to rated

capacities, and u_I is index for members of U_I. The decision variables $V_{start}(u_I,t)$, $V_{online}(u_I,t)$, and $V_{gen}(u_I,t)$, correspond, respectively, to whether the unit started, whether it was online, and its level of production for that hour.

$$C_{Gen}(t) = \sum_{u_I \in U_I} \begin{pmatrix} c_{start}(u_I) \cdot V_{start}(u_I,t) + \\ c_{noload}(u_I) \cdot V_{online}(u_I,t) \\ + c_{incr}(u_I) \cdot V_{gen}(u_I,t) \end{pmatrix} \tag{2}$$

The load curtailment penalty cost $C_{LC}(t)$, for each time step is given in Eq. (3). It is calculated with value of lost load c_{voll} and the amount of load curtailment $V_{loadcurt}(t)$, which is a decision variable.

$$C_{LC}(t) = c_{voll} \cdot V_{loadcurt}(t) \tag{3}$$

(2) Main constraints
  Power balance:

$$\sum_{u_I \in U_I} V_{gen}(u_I,t) + P_{wind}(t) - V_{windcurt}(t) + V_{loadcurt}(t) = P_{dem}(t), \forall t \tag{4}$$

The decision variables $V_{gen}(u_I,t)$, $V_{windcurt}(t)$, and $V_{loadcurt}(t)$ correspond respectively to the level of production, wind curtailment and load curtailment at time step *t*. Wind curtailment and load curtailment are used as slack variables in the model for some instances when they are necessary to satisfy the constraint. $P_{wind}(t)$ is wind power forecast at time step *t*, and $P_{dem}(t)$ is load at time step *t*.

  Reserve target:

$$P_{res\_up}(t) \le \sum_{u_I \in U_I} (V_{online}(u_I,t) \cdot P_{max}(u_I)) - \sum_{u_I \in U_I} (V_{gen}(u_I,t)) + V_{windcurt}(t), \forall t \tag{5}$$

$$P_{res\_dn}(t) \le \sum_{u_I \in U_I} (V_{gen}(u_I,t)) - \sum_{u_I \in U_I} (V_{online}(u_I,t) \cdot P_{min}(u_I)) + P_{wind}(t), \forall t \tag{6}$$

Equations (5) and (6) are upward and downward reserve respectively. $P_{res\_up}(t)$ and $P_{res\_dn}(t)$ are respectively upward and downward reserve target. Wind power is allowed to provide reserve in both the reserve constraints ($V_{windcurt}(t)$ and $P_{wind}(t)$ in Equations (5) and (6)). At high wind, for example, wind can be used as downward reserve, or having been curtailed, can be used as positive reserve.
Minimum and maximum output:

$$\sum_{u_I \in U_I} (V_{gen}(u_I,t)) \le P_{max}(u_I) \cdot N(u_I), \forall t \tag{7}$$

$$\sum_{u_I \in U_I} (V_{gen}(u_I,t)) \ge P_{min}(u_I) \cdot N(u_I), \forall t \tag{8}$$

$$V_{gen}(u_I,t) \ge V_{online}(u_I,t) \cdot P_{min}(u_I), \forall t, u_I \tag{9}$$

$$V_{gen}(u_I,t) \le V_{online}(u_I,t) \cdot P_{max}(u_I), \forall t, u_I \tag{10}$$

$P_{\max}(u_I)$ and $P_{\min}(u_I)$ are respectively the maximum and minimum production of generator group u_I. And $N(u_I)$ is the generator number in group u_I.

Unit start identification:

$$V_{start}(u_I,t) \geq V_{online}(u_I,t)\text{-}V_{online}(u_I,t\text{-}1), \forall t,u_I \quad (11)$$

3.2. Case Study System

(1) Case system description

A test system with generators and electric demand from a provincial power system in Northeast China has been used. For load data, measured load data for the provincial power system in Northeast China is used. The total installed capacity of coal-fired generation is 12.9 GW. For the generator data, the case region's generator parameters are shown in Table III. In Northeast China, the large proportion of CHP units is a critical limiting factor for wind power integration. Due to the heat demand, the minimum electrical outputs of the generators are higher. As this paper mainly discuss the performance of downward regulation ancillary service markets, the minimum output of all the generators are assumed to be 60% throughout the year for simplicity. Future studies on unlocking the flexibility of heat generation will be conducted.

Table 3. Information on Coal-Fired Generators in the System

Type	Cap(MW)	Number
Coal-XL	600	5
Coal-M1	300	5
Coal-M2	300	10
Coal-M3	300	4
Coal-S1	200	6
Coal-S2	200	11
Coal-XS	100	8

(2) Simulation scenarios

Three set of scenarios are simulated in the paper. The first set of scenarios (Scenario Set I) assumes no downward regulation ancillary service market in the system, and varies wind capacity in the system, to show the system performances with different wind power penetrations in the system, as shown in Table IV.

The second (Scenario Set II) and third (Scenario Set III) set of scenarios assumes downward regulation ancillary service market to incentivize deeper downward regulation in the system. In Scenario Set II, different amount of 600MW generators in the system are considered to be flexible, i.e. bid to provide deeper downward regulation. It is assumed that these flexible generators can reduce their minimum output to as low as 30% of their maximum output. In Scenario Set III, different amount of 300MW generators in the system are considered to be flexible, and their minimum outputs are assumed to be 30% as well.

The heat rate curves of the generators are given in the simulation, which shows higher heat rate, thus higher fuel consumption and generation cost per kWh of electricity generated, with the decrease of the output level of the generators.

System performances of these scenarios are calculated with the production simulation model. They are compared and analyzed in Section IV. System performance indices include annual system operation cost, generation cost per MWh, wind curtailment rate, downward regulation cost, etc.

4. Simulation Results

4.1. System Performance with No Downward Regulation Ancillary Service Market

The variation of annually system operation cost, generation cost per kWh, wind curtailment rate, with different penetrations of wind energy are shown respectively in Fig.1 and Fig.2.
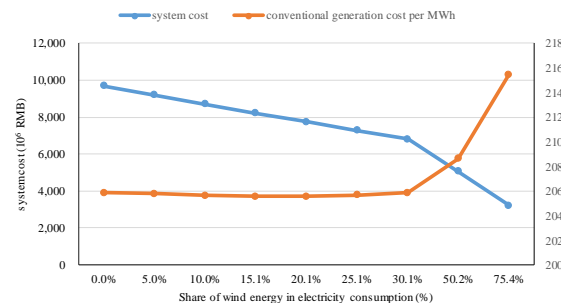

Figure 1. Annually system operation cost and generation cost per MWh with different penetrations of wind energy.
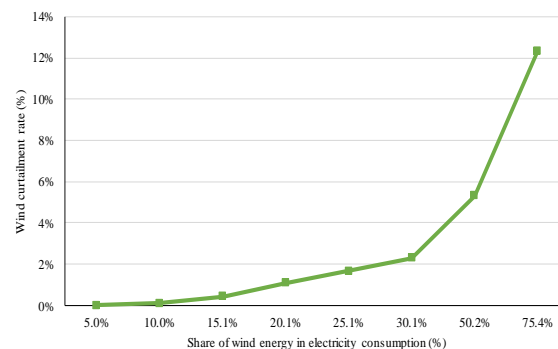

Figure 2. Wind curtailment rate with different penetrations of wind energy.

Results show that with increasingly penetration of wind energy, the annual system operation cost, which consists only the conventional generation cost decreases. However, the conventional generation cost per MWh decreases first, and then increases sharply at high wind penetrations. This is due to the increased fuel consumption rate of coal-fired generators at reduced output level. As the system regulation capability is limited, wind curtailment rate increases with increasing wind energy penetrations.

4.2. System Performance with Downward Regulation Ancillary Service Market
(1) When the 600MW generators in the system are providing downward regulation services (Scenarios Set II))
Fig.3 and Fig.4 shows the system cost and wind curtailment rate with increased number of flexible 600MW generators. System cost includes conventional generation cost and the downward regulation services cost induced in the system. Results show that when there are more flexible 600MW generators in the system, wind curtailment rate decreases, which indicates the effectiveness of downward regulation ancillary service markets in facilitating wind integration. This however, would lead to increased system cost, as the downward regulation services provided by the flexible 600MW generators need to be paid. This can be seen as the price paid by the system to integrate more renewable energy.
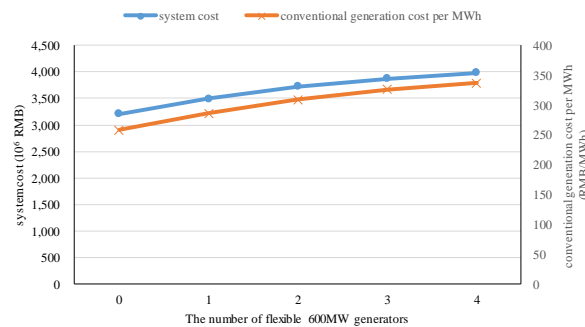
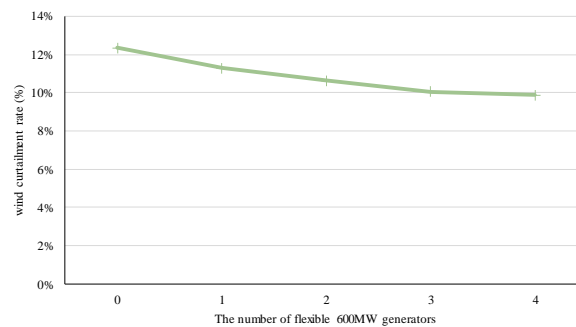Figure 3. System cost with increased number of flexible 600MW generators.

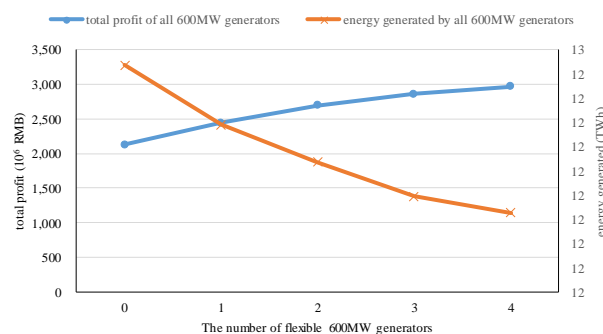Figure 4. Wind curtailment rate with increased number of flexible 600MW generators.

Figure 5. Total profit and energy generated by all 600MW generators.

Fig.5 shows the energy generated by all the 600MW generators and their profit. As shown, when the 600MW generators, which are the least cost generators in the system become more flexible, their income from electricity generation will decrease but they will have extra income from providing the flexible services, which finally leads to increased profit.

(2) When the 300MW generators in the system are providing downward regulation services (Scenarios Set III))

Although system cost and wind curtailment rate present similar patterns when the 300MW generators are providing flexible services, but the impact of such flexibility on 300MW generators are different, as both their profit and energy generation increased. as shown in Fig. 6. The increased generation is due to their flexibility even though their generation cost is high compared to 600MW generators.
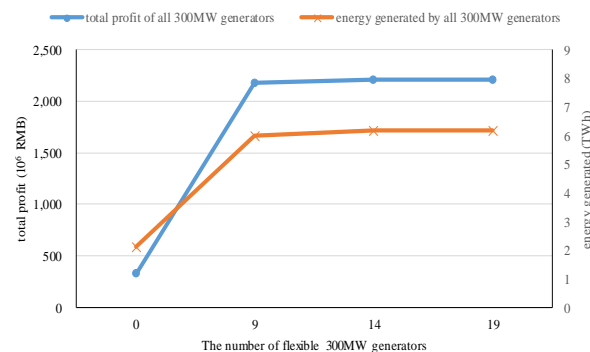
Figure 6. Total profit and energy generated by all 300MW generators

5. Conclusions

Mechanism barriers are increasing becoming a constraint in renewable energy integration. The new round of power sector reform provides opportunities for solving this issue. Pilots of downward regulation ancillary service market have already been initiated in some parts of China. Evaluation of the effectiveness of such a market is of significance for future electricity market development. This paper conducts studies on the performance of the current downward regulation ancillary service market. Results show that downward regulation ancillary service market that incentivizes deeper downward regulation of conventional generators help renewable energy integration. The system cost, however, will increase as the regulation services provided by the conventional generators need to be paid. For conventional generators themselves, increasing the flexibility will make them more profitable. The change of profit differs for different generators. For generators with low fuel rate, which are considered more efficient generators, increasing their flexibility reduces the energy they generate, but their total profit will still increase due to the extra profit brought by the ancillary service market. For generators with high fuel rate, increasing their flexibility will increase their generated energy as well as their profit. This indicates that the value of flexibility are rewarded in the ancillary service market. Judging from the standard that a good market design should reflect system needs as well as reward those providing these services, the downward regulation ancillary service market is playing a positive role in facilitating renewable energy integration.

It is worth to note that the downward regulation ancillary service market is a specific product of the current market transition period in China, i.e. transitioning from a non-market system to an electricity market. In the future, spot markets should be established to facilitate renewable energy integration.

6. Acknowledgment

7. References

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