Capacity Market Model Considering Flexible Resource Requirements

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***Abstract*—With increasing installations of renewable generation, such as wind and solar, electric power systems need significant amounts of flexible resources to provide fast responses to mitigate the additional variability and uncertainty in generation. Current market designs have been shown to be insufficient in their mechanisms to compensate flexible resources for their services. Ancillary service markets can cover some of these costs, but they are likely not enough to attract additional flexible resources into the system. Although some independent system operators have started to design markets for flexible resources, their focus is on the short-term operating time horizon. This time horizon has significant real-time price uncertainties for flexible resources and might provide insufficient motivation for them to participate in the market. The capacity market has traditionally been the incentive to invest in new generation resources. Therefore, if a system needs new flexible resources, it is necessary to introduce flexible resource requirements into the capacity market to directly attract more flexible resource investment. This paper proposes a simplified capacity market model including flexible resource requirements. Case studies are examined to validate the proposed method.**

***Index Terms*—Flexible resources, capacity market, wind uncertainty.**

I. Introduction

The development of renewable energy sources has brought new challenges to power system operations to maintain system reliability in the face of additional generation uncertainty. Power systems require an optimal combination of energy, capacity, and flexible resources to maintain reliability at the minimum cost [1]; however, the fast development of renewables is rapidly changing the generation portfolio in many power systems in the United States and in other countries [2], [3], making an optimized mix a moving target. This change leads to several operational issues, such as the net load changes seen in the “duck curve” of the California Independent System Operator (CAISO) [4] and ramping capacity shortages in both CAISO and the Midcontinent System Operator (MISO) during periods when renewables increase and decrease their output in a short time span [5].

To alleviate this flexible resource shortage, several independent system operators (ISOs) have proposed flexible products to compensate the flexible resources that provide ramping capability, such as the flexible ramping products in CAISO or the ramp product in MISO [5], [6]. These proposals focus on how to compensate flexible resources in short-term market operations; however, short-term payments alone may not necessarily solve the flexible resource shortage problem because investments in new flexible resources is a long-term issue. The short-term price signal might delay long-term investment, and the price volatility in the short-term market reduces the motivation for flexible resource investment. In [7], PJM proposed a seasonal offer framework for renewable generation in the capacity market to employ the generation flexibility of renewable generation during different seasons. This proposal focuses on the peak load capacity without considering the system flexibility requirement at other times which may become more important with increasing wind power penetrations.

The capacity market is a long-term market designed to provide capacity payments for generation resources [8]–[10]. In designing capacity markets, ISO and regional transmission organization (RTO) market authorities follow three general objectives as defined by the Federal Energy Regulatory Commission: markets should provide 1) reasonable returns for producers, 2) just and reasonable costs for energy services, while 3) meeting system reliability targets. The current capacity markets in several ISOs—such as PJM, New York Independent System Operator, and ISO New England [11], were created to satisfy the peak load reliability concerns by implementing administratively determined demand curves for capacity that reflect an estimated demand at associated price levels. Supply curves for capacity are based on generation bids for generation capacity. As shown in Fig. 1, the ISOs give a predetermined variable resource requirement (VRR) curve, as shown by the blue line; the supply curve is the red line [12]. The intersection of the VRR curve and the supply curve gives the market clearing price (MCP) for the capacity to maintain system reliability.

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However, system reliability is not based on only the peak load capacity but also on the adequacy of a system's flexible resources, such as the ability to provide fast ramping. Because the solar generation is often very well correlated with the system's peak load during the daytime while concurrently decreasing rapidly before the evening load's peak, it is increasingly important to consider when the penetration of solar photovoltaic increases in a system. The current capacity market model does not include the flexible resource requirement, and this might lead to fewer incentives for flexible resource investment.

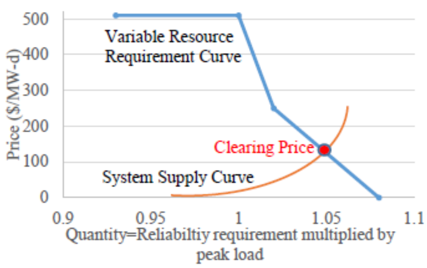

Figure 1. VRR demand curve

This paper explicitly models the flexible resource requirements for load and wind power's uncertain flexible reserve in a capacity market. Through this model, flexible resources can obtain revenue by providing flexible capacity to help a system maintain reliability. In addition, the impact of wind's uncertainty and energy storage on a system's flexibility capacity can also be analyzed.

The rest of this paper is organized as follows. Section II introduces the flexible resource requirement in the actual market operation. Section III proposes the capacity market model considering the flexible resource requirement. Section IV performs case studies to illustrate the impact of flexible resource requirements on capacity market clearing and analyzes the impact of wind power's uncertainty and energy storage systems. The profitability of traditional generation under the current capacity market model and the proposed model is compared. Finally, Section V concludes the paper.

II. Illustration of Flexible Resource Requirements

In actual market operations, such as in a day-ahead market or real-time market, the day-ahead or real-time security-constrained unit commitment (SCUC) considers energy ramping, which represents the load difference from one interval to the next. To mitigate the uncertainty of wind and load forecasts, flexible ramping products have been introduced by several ISOs, such as CAISO and MISO. Therefore, it is necessary to introduce the flexible ramping requirement to help the ISOs compensate for the resources providing the flexible ramping products.

Here, the net load forecast uncertainty is represented by an interval to demonstrate the upper and lower bounds of the load. From time interval t to t+1, if the demand's lower bound at t+1 is larger than the expected demand at t, there is no flexible ramp-down requirement from t to t+1; however, there are flexible ramp-up requirements if the demand's upper bound at t+1 is larger than the expected demand at t. Similarly, if the demand's upper bound at t+1 is lower than the expected demand at t, there is no flexible ramp-up requirement, but there are flexible ramp-down requirements.

Therefore, the flexible ramp-up requirement is:

$$FRU_t = \max(0, \overline{L_t} - L_{t-1}) \tag{1}$$

Similarly, the flexible ramp-down requirement for interval t is given as:

$$FRD_t = \max(0, L_{t-1} - \underline{L_t}) \tag{2}$$

where L is the expected net load, which is the forecasted demand minus the wind power forecast output.

III. Capacity Markets with Flexible Resource Requirements

This section presents the overall formulation of the capacity market model including flexible resource requirements. The objective function of the capacity market problem is to minimize the capacity procurement cost for generation resources minus the cleared load payment. Here, a new term, the flexible resource procurement cost, is added.

$$\min \sum_{i\in sg} c_i G_i + \sum_{m\in sw} c_{w,m} W_m - \sum_{j\in sd} d_j D_j + \sum_{i\in g} c_{rr,i} FC_i \tag{3}$$

$$\sum_{i\in g} G_i + \sum_{m\in sw} W_m \geq \sum_{j\in sd} D_j \tag{4}$$

$$0 \leq G_i \leq G_m^{max} \tag{5}$$

$$0 \leq W_m \leq CC_w * W_m^{max} \tag{6}$$

$$0 \leq D_j \leq D_j^{max} \tag{7}$$

$$\sum_{i\in g} FC_i \geq FRR \tag{8}$$

$$0 \leq FC_i \leq FR_i^{max} \tag{9}$$

$$FRR = k_d \sum_{j\in sd} D_j + (k_w/CC_w) \sum_{m\in sw} W_m \tag{10}$$

where c_i and $c_{w,m}$ are the capacity price for traditional generation and wind power, respectively; G_i and G_m^{max} are the capacity cleared and the maximum capacity of traditional generation; D_j and D_j^{max} are the cleared demand and the maximum demand in the j^{th} segment of the VRR curve; W_m is the wind power's capacity cleared in the market and W_m^{max} is the wind power plants' nameplate installed capacity; sw is the set of wind power producers in the capacity market; sd is the set of demand segment in the model; CC_w is the capacity credit factor of wind power plants; FC_i is the flexible capacity cleared in the market; FRR is the flexible resource requirement; k_d is the coefficient of load for the flexible resource requirement; and k_w is the coefficient of wind power for the flexible resource requirement. The objective function in (3) includes the peak load capacity cost, flexible resource capacity cost, and the load revenue. Eq. (4) represents the generation capacity requirement for peak load reliability. The generation resource limitation is shown in (5). Eq. (6) is the wind power capacity limitation considering its capacity credit [13]. Eq. (7) is the demand constraint. Eq. (8) is the capacity requirement for the system's flexible resources. Eq. (9) is the flexible resource limitation, and (10) represents the system's flexible resource requirement.

Note that the dual variables of constraint (4) and (8) are the clearing price for the traditional peak load capacity and the flexible resources, respectively. Here, only one region for the whole RTO area is modeled to illustrate the concept. If multiple locational deliverability area (LDA) regions are included, the VRR curves and the import and export limitations can be modeled for each LDA.

The parameters k_d and k_w represent the load and wind power uncertainty level for the flexible resource requirement. These flexible resources are needed to mitigate the uncertain fluctuations of load and wind. The methods to decide k_d and k_w are to statistically analyze the fluctuation patterns of load and wind power in historical data for the timescale of the flexible resource requirement [14]. If the flexible resource requirement is for 15 minutes, then k_d and k_w are decided by the load and wind power's 15-minute fluctuations. Alternatively, a probabilistic evaluation model can be used, and the k_d and k_w values for a predetermined confidence level can be obtained. Determining k_d and k_w values is outside the scope of this paper and will be considered in future work. This paper focuses on modeling flexible resource requirements in the capacity market.

IV. Case Studies

This section tests the proposed capacity market model including a flexible resource requirement on the one-area system. A comparison to the traditional capacity market model is performed. The VRR curve in Fig. 2 is used to demonstrate the peak load reliability cost. There are twenty generation resources, and the parameters are listed in Table I. The 20th generation resource is an energy storage system to illustrate the impact of energy storage on providing flexible resources. Assume that the capacity price of wind is \$5/kw-yr [6]. The capacity credit of wind power used in this study is 18% [6].

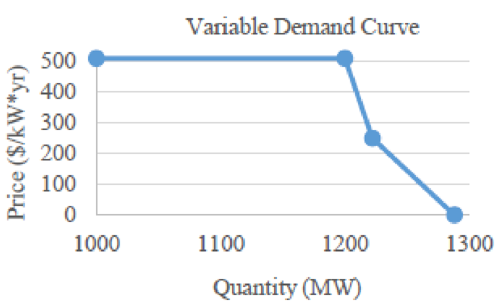

Figure 2. VRR curve used in the testing system

TABLE I. Generation Parameters

U.	*C*	*G*^{max}	*C*$_{rr}$	*FR*^{max}	U.	*C*	*G*^{max}	*C*$_{rr}$	*FR*^{max}
1	5	50	2	5	11	15	100	12	10
2	6	50	3	5	12	20	200	15	10
3	7	50	4	5	13	25	200	17	10
4	8	50	5	5	14	30	15	19	5
5	9	50	6	5	15	35	15	21	5
6	10	60	7	5	16	40	15	23	5
7	11	100	8	10	17	45	15	25	5
8	12	100	9	10	18	50	15	27	5
9	13	100	10	10	19	55	15	29	5
10	14	100	11	10	20	0	0	1	20

A. Impact of Wind Power Capacity

This subsection studies the impact of integrated wind power capacity on the capacity market clearing. In this study, the load and wind uncertainty factors for the flexible resource requirement are both 0.1. The impact of the wind uncertainty factor will be studied in the next subsection. Fig. 3 shows the results from supply curves under various wind capacities without considering the flexible resource requirement. Table II lists the market clearing results with different wind capacities. Figure 3 clearly shows that when the capacity of wind power increases, the supply curve shifts to the right because the capacity offer price of wind power is low (\$5/kw-yr) compared to the traditional generation capacity offer in Table I (). Therefore, as the wind power capacity increases, the intersection of the supply curves and the VRR curve changes, and correspondingly the market clearing price of the capacity decreases, as is also shown in Table II. MCP_PL is the market clearing price for the peak load capacity. The figure also shows that wind power capacity is fully cleared in the capacity market because of its low capacity price.

Table II shows that if the flexible resource requirement is not considered, wind power will have a significant impact on the capacity market. Although the capacity of wind power plants is limited by their capacity credit, wind power's participation in the capacity market still greatly reduces the market clearing price of capacity. This means that traditional generation will earn fewer payments from the capacity market for the capacity provided. The increasing penetration of wind will also increase the system's need for flexible resources, which should be provided by traditional generation, but this is not reflected in this capacity market model. Here the penetration of wind power is based on the wind capacity in the capacity market, which means the amount of wind power capacity participating in the capacity market.

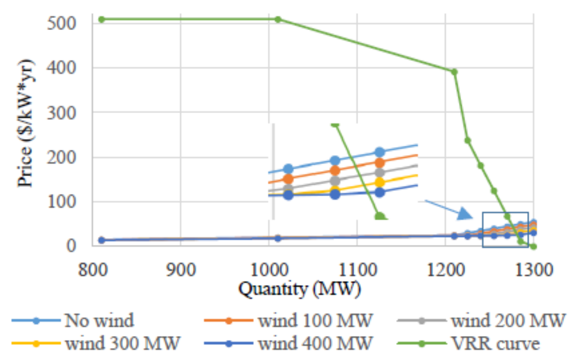

Figure 3. VRR curve and supply curves with different wind capacities

TABLE II. Market Clearing Results without Considering the Flexible Resource Requirement

	MCP_PL (\$/kw*yr)	Cleared Wind (MW)
No wind	45	--
Wind 100 MW	40	18
Wind 200 MW	35	36
Wind 300 MW	30	54
Wind 400 MW	25	72

Next, the proposed capacity market considering flexible resource requirements is tested. Table III shows the market clearing results using the proposed capacity market model. The results in Table II and Table III both show that the MCP_PL decreases with wind capacity. After considering the flexible resource requirement, the MCP_PL remains unchanged after a specific wind penetration level because of the flexible resource limitation. The market clearing price for flexible resources (MCP_FR) increases with wind capacity because the flexible resource requirement increases with wind capacity.

Table III also shows that the system has a maximum wind accommodation capacity that is limited by the system's flexible resource capacity. In cases of 300 MW and 400 MW of wind power integration, the system is short of flexible resources. In these cases, the maximum wind power capacity that can be cleared in the capacity market is 41.9 MW because of the flexible resource limitation. Because the maximum accommodation capacity is 41.9 MW, even if 300 MW or 400 MW of wind power is integrated into the system, the cleared wind capacity in the capacity market is still only 41.9 MW.

TABLE III. MARKET CLEARING RESULTS CONSIDERING FLEXIBLE RESOURCE REQUIREMENT

	MCP_PL (\$/kw-yr)	MCP_FR (\$/kw-yr)	Cleared Wind (MW)
No wind	45	21	--
Wind 100 MW	40	25	18
Wind 200 MW	35	29	36
Wind 300 MW	35	54	41.9
Wind 400 MW	35	54	41.9

Therefore, considering the flexible resource requirement in the capacity market can incentivize the investment in flexible resources under high penetrations of wind, which can improve the whole system's operating flexibility and help maintain system reliability. In the scenario of high penetrations of wind, increasing only the peak load capacity does not improve the system's operating flexibility because the shortage is of the flexible resource, not the peak load generation capacity.

B. Analysis on Wind Power Uncertainty

This subsection analyzes the impact of the wind power uncertainty level on the system's flexibility resource requirement and therefore the capacity market clearing. In this study, the wind power capacity is 200 MW. The load uncertainty factor is 0.1, and the wind uncertainty factor varies from 0 to 0.25 with 0.05 as the increment. Table IV shows the results with different wind uncertainty levels.

TABLE IV. MARKET CLEARING RESULTS UNDER VARIOUS WIND POWER UNCERTAINTY FACTORS

Wind Uncertainty	MCP_PL (\$/kw-yr)	MCP_FR (\$/kw-yr)	Cleared Wind (MW)
0	35	21	36
0.05	35	25	36
0.1	35	29	36
0.15	36.25	37.5	27.9
0.2	40	31.5	21.0
0.25	42.5	27	11

Table IV shows that the clearing price for peak load capacity (MCP_PL) remains unchanged for wind uncertainty factors from 0 to 0.1 but increases with wind power uncertainty when uncertainty factor higher than 0.1. When the wind uncertainty factor varies from 0 to 0.1, the system has enough flexible resources to maintain the wind power uncertainty flexible requirement and the cleared wind capacity does not change. Therefore, the MCP_PL does not change. When the wind uncertainty factor increases to greater than 0.1, the system is short of flexible resources. Then the cleared wind capacity decreases, which leads to an increase in MCP_PL.

The clearing price for the flexible resource capacity (MCP_FR) first increases and then decreases with wind power uncertainty because in the proposed model the peak load capacity and flexible resource capacity are co-optimized. Therefore, because of its uncertainty, the flexible resource requirement of wind power will change the wind power cleared capacity and also change both the MCP_PL and MCP_FC. Consider the uncertainty level 0.25 as an example. In this case, the MCP_PL is \$42.5/kw-yr, and MCP_FC is \$27/kw-yr. In the test system, the price of wind power capacity is \$5/kw-yr. This means that if 1 kW more wind can be cleared for the peak load capacity, the system will save \$37.50 (42.5-5); however, 1 kW more wind power will need 0.25/0.18 kW (wind uncertainty factor/wind capacity credit) flexible resources, which will lead to an additional cost of \$37.50 (27*(0.25/0.18)). In this case, the savings from the peak load capacity equals the cost for the flexible capacity. Therefore, in this scenario, the wind power capacity is limited to 11 MW. These results clearly demonstrate that the proposed model can consider the peak load and flexible capacity simultaneously and maintain both the peak load and flexible resource reliability requirements in the system.

C. Generation Revenue Analysis

This subsection analyzes the profitability of the traditional generators and wind power under both the current and the proposed capacity market models. Consider a load uncertainty factor 0.1 and wind uncertainty factor 0.1 as an example to analyze generation revenue. Table V shows the total profit of the traditional generation under different wind capacity scenarios.

TABLE V. PROFIT OF GENERATION WITH DIFFERENT WIND CAPACITIES

	Current Model (\$)		Proposed Model (\$)	
	Traditional	**Wind**	**Traditional**	**Wind**
No wind	37,050	0	38,205	0
100 MW	30,775	720	32,380	720
200 MW	24,575	1,260	26,670	1,260
300 MW	18450	1,620	29,920	1,466.5
400 MW	12,400	1,800	29920	1,466.5

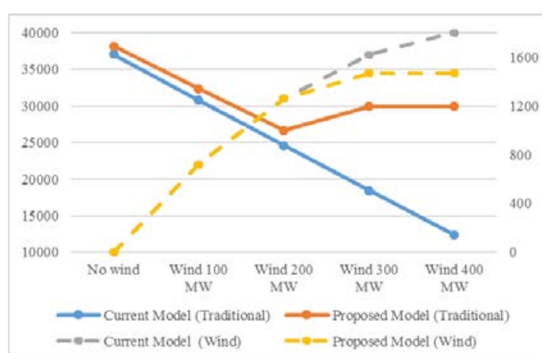

Figure 4. Profit of traditional generation

Both Table V and Fig. 4 show that without considering the flexible resources requirement, the total profit of the traditional generation decreases with increasing wind power penetrations.

Additionally, with high penetrations of wind power, the price in the short-term day-ahead and real-time markets will also be reduced because of the low marginal cost of wind power. Low prices in both capacity and energy markets might lead to the traditional generation units considering early retirement because they cannot earn enough payments from the electricity markets, which might impact the system's operational flexibility in the long term. In the proposed model, the profit of traditional generation still decreases at first. Under high penetrations of wind, this profit will increase because the system needs flexible resources and traditional generation can provide some of them. This profit increment might delay the retirement of traditional generation, which can provide flexible resources and maintain the system's operational flexibility in the long term. Therefore, after considering the flexible resource requirement in the capacity market model, the system reliability for both the peak load capacity and the flexible resource can be improved by delaying the traditional generation retirement. It should be noted that the profit increment of traditional generators is due to the flexibility it provides. Most of this profit increment goes to the generation which can provide flexibility. The profit of wind power decreases in the proposed model under high penetration levels because the cleared wind capacity is limited by the flexible resources. Wind power producers can procure flexible resources to improve their profit—for example, by combining with energy storage to form a virtual power plant.

D. Potential of Energy Storage Providing Flexible Resource

In the previous subsection, traditional generation's profitability was analyzed. This subsection studies the role of energy storage in the system when considering the flexible resources requirement. Consider the 300-MW wind power integration case as an example. The uncertainty factor for both load and wind is 0.1. Table VI shows the results with different energy storage capacity.

TABLE VI. PROFIT OF ENERGY STORAGE SYSTEM WITH DIFFERENT CAPACITY LEVELS

ES Capacity	MCP_PL ($/kw*yr)	MCP_FR ($/kw*yr)	Cleared Wind (MW)	ES Profit ($)
0	45	72	6.3	0
10	40	63	24.1	620
20	35	54	41.9	1060
30	30	29	54	840

Table VI demonstrates that the profit of the energy storage system will generally increase with its capacity. In the case of the 30 MW of energy storage, the system has enough flexible resources because of the large capacity of energy storage; and in this case, the wind power capacity is fully cleared in the capacity market. The energy storage profit has a risk of reduction in this specific scenario. Therefore, energy storage investors should optimize the size of the energy storage system according to the potential market clearing price for the flexible resource to maximize the total revenue. Meanwhile, for system operators, it is important to consider how to mitigate the market power of energy storage in the flexible capacity market. The proposed capacity market model provides energy storage systems with the ability to participate in the capacity market, which improves the system's operational flexibility and compensates the energy storage system for its flexible capacity service. This can motivate additional energy storage investment.

V. CONCLUSIONS

This paper proposes a capacity market model considering the system's flexible resource requirement. With this explicit modeling of flexible resources in the market model, the system's reliability regarding both the peak load capacity and the flexible resource requirement can be maintained. The paper analyzes the impact of wind power on the market clearing price of peak load capacity and the flexible resource. Although the cheap wind power capacity price can suppress the clearing price for peak load capacity, increasing wind penetration levels will increase the flexible resource clearing price. Traditional generation resources providing flexibility can still earn substantial payments from the capacity market, which can delay their retirement and improve the system reliability. The proposed model also provides energy storage systems with the ability to participate in the capacity market. This increases not only the energy storage investors' motivation to install energy storage systems but also the total system reliability.

Future work will include determining the k_d and k_w values using advanced data analysis methods and co-simulating the long-term capacity market with flexible resources and the short-term market, including day-ahead and real-time markets, to comprehensively analyze the impact of the proposed model on the revenue of traditional generation, wind power, and energy storage systems. In addition, a case study on an actual ISO's system will be performed to evaluate the impact of the proposed model in a realistic market environment.

VI. ACKNOWLEDGEMENTS

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