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Economical flexibility options for integrating fluctuating wind energy in power systems: The case of China

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HIGHLIGHTS

- The flexible resources for integrating wind power are analyzed from the cost perspective.
- The balancing cost when using coal-fired generation could reach \$4/MWhw.
- The cost of DSM for integrating wind power can be very low.
- The EES will prevail coal-fired generation when its capital cost drops below 400\$/kWh.

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ABSTRACT

The inherent stochastic nature of wind power requires additional flexibility during power system operation. Traditionally, conventional generation is the only option to provide the required flexibility. However, the provision of the flexibility from the conventional generation such as coal-fired generating units comes at the cost of significantly additional fuel consumption and carbon emissions. Fortunately, with the development of the technologies, energy storage and customer demand response would be able to compete with the conventional generation in providing the flexibility. Give that power systems should deploy the most economic resources for provision of the required operational flexibility, this paper presents a detailed analysis of the economic characteristics of these key flexibility options. The concept of "balancing cost" is proposed to represent the cost of utilizing the flexible resources to integrate the variable wind power. The key indicators are proposed respectively for the different flexible resources to measure the balancing cost. Moreover, the optimization models are developed to evaluate the indicators to find out the balancing costs when utilizing different flexible resources. The results illustrate that exploiting the potential of flexibility from demand side management is the preferred option for integrating variable wind power when the penetration level is below 10%, preventing additional fuel consumption and carbon emissions. However, it may require 8% of the customer demand to be flexible and available. Moreover, although energy storage is currently relatively expensive, it is likely to prevail over conventional generation by 2025 to 2030, when the capital cost of energy storage is projected to drop to approximately \$400/kWh or lower.

1. Introduction

The release of carbon dioxide (CO_2) and other greenhouse gases (GHGs) due to human activity results in a host of environmental issues [1]. The enhanced public concern for adverse environmental impacts associated with the use of conventional energy sources requires a transition toward clean energy systems. Moreover, the de-carbonization of electric power systems plays a significant role in reducing anthropogenic carbon emissions, since electric power systems remain the primary source of carbon emissions in the world. As a result, the application of renewable energy in electric power systems generates great interest. Among renewable energy sources, wind energy has experienced rapid development and has made significant inroads into electrical power systems. Over the past decade, the global cumulative installed capacity of wind energy has been growing at a rate of more than 21% annually [2]. In 2015, global wind power capacity increased

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Nomenclature

Abbreviations

CO_2	Carbon dioxide
GHG	Greenhouse gase
ESS	Energy storage system
DSM	Demand side management
UC	Unit commitment
ED	Economic dispatch
SCCR	System coal consumption rate
CER	carbon emission rate
PCR	ESS's power capacity requirement
ECR	ESS's energy capacity requirement
LCR	Load power capacity requirement
LCE	Expected load-curtailment energy
MWhw	Per MWh of wind energy production
MWw	Per MW of installed wind power capacity

Symbols

i, j	Index of conventional generating units (subscript)
w	Index of wind power plants (subscript)
l	Index of electric load (subscript)
t	Index of time periods (subscript)
k	Index of the state
N_C	Number of conventional generating units
N_W	Number of wind power plants
N_L	Number electric loads
N_T	Number electric loads
I_i	Status of the unit i (0 or 1)
c_i^u, c_i^d	Start-up/turn-off cost
R_u	Ramp rate of the generating unit
S_u	Start-up ramp rate of the generating unit
P_i^{gen}	Power out of the generating unit i
P_l^{dem}	Power demand of the electric load l
P_w^{gen}	Power out of the wind plant w
P_w^{rate}	Rated capacity of the wind plant w
$P_{w,t}^{pre}$	Day-ahead wind power forecast
$P_{w,t}^{avi}$	Real-time wind power potential
r_w	Capacity credit of the wind power plant
V_{ci}/V_{co}	Cut-in/cut-out wind speed
V_r	Rated wind speed
P_t^{disc}	Discharging power of the ESS
P_l^{inter}	Interrupted power of electric load l
P_{ESS}^{avi}	PCR of the ESS (MW/MWw)
E_{ESS}^{avi}	ECR of the ESS (MWh/MWhw)
P_{DSM}^{avi}	LCR of the ESS (%)
E_{DSM}^{avi}	LCE of the ESS (MWh/MWhw)
η_c, η_d	Charging, discharging efficiency
Δt	Interval between two time periods
p_E	Unit price of the ESS (\$/MWh)
p_{DSM}	Unit price of the interrupted load (\$/MWh)
E_{CGU}^{day}	Total conventional generation during a day
E_{WIND}^{day}	Total wind power generation during a day
a_i, b_i, c_i	Fuel consumption/carbon emission coefficients
μ, σ	Capacity credit of the wind power plant
σ_{total}	Expected value and standard deviation of wind speed
σ_{wind}, σ_{load}	Standard deviation of the wind/load forecast error

by 17.1%, from 369,705 MW to 432,883 MW. In China, wind power has become the third largest power source, following thermal and hydroelectric power, and generates 4% of the country's electricity [3].

However, the power generated from wind is fluctuating and uncertain [4], which presents significant challenges to the efficient utilization of this energy source [5]. As electricity demand and supply must be maintained in balance at all times, power systems need to absorb the electricity fluctuation from wind power. An increasing capacity of fluctuating wind power will increase the need for flexibility during power system operation. Flexibility is the ability of the power system to deploy its resources for re-balancing customer demand and generation when fluctuations exist. For example, downward reserve is required to ensure power system balance when the amount of injected wind power is higher. Conversely, upward reserve is required when the amount of wind power injection is lower. If there is not sufficient operational flexibility, the efficient utilization of wind power cannot be achieved [6]. The seriously wind power curtailment issue in China could well prove that. The coal-dominated generation mix in China works against the high level of wind penetration, since the flexibility of coal-fired generating units is constrained by their ramp-up and ramp-down rates as well as their minimum stable generation output. China's inflexible generation mix, which cannot respond well to changes in wind power output, forces it to curtail a large amount of wind energy every year, despite the country's renewable energy ambitions. Wind energy curtailment in China is becoming increasingly serious. The total energy loss from wind curtailment from 2011 to 2015 was approximately 95.9 billion kWh [7], nearly equals to the gross electricity generated by wind energy in Denmark in 2013 [8].

There is a general consensus that the intermittency and uncertainty of wind power have been the major barriers for large scale wind power integration. To deal with the uncertainty of wind power, many methods have been developed to improve wind power forecasting accuracy [9,10]. Moreover, many studies have been conducted on how to improve the system flexibility so as to deal with the wind power intermittency, which usually combine the wind power with other flexible resources [11–13]. There are three most important flexibility options for integrating the fluctuating wind power, including using the operating reserves from the conventional generation, using the flexibility provided by the energy storage or the demand-side management (DSM) [14]. Traditionally, the flexibility from conventional thermal power generation for providing operating reserves is the most important option for integrating fluctuating wind power. For example, the flexibility for integrating the fluctuating wind power are typically provided by conventional generating units in China, such as coal-fired power generating units [15]. However, utilizing the conventional generating units to integrate the variable wind energy causes additional costs. Examples include the short-term balancing services, provision of firm reserve capacity, and more cycling and ramping of conventional plants for integrating the wind power [16]. Integrating the fluctuating wind power, the conventional generating units should work at part-load and change their output frequently to cope with the variability and uncertainties associated with wind energy. Consequently, the operation of generating units is varying and low load levels results in low energy efficiency, higher fuel consumption and the additional cost. The additional cost arising from the intermittency of wind and the subsequent causation of 'balancing plants' for system security is widely observed [17]. Moreover, the increased fuel consumptions come with the additional carbon emissions. In other word, the effect of developing wind power in decarbonizing the power systems is partially offset by the additional carbon emissions due to providing required flexibility [18]. Fortunately, with the development of smart grid technologies, energy storage and DSM may be able to compete with the flexibility provided by the conventional generation. Actually, energy storage and DSM could be the preferred options since they avoid additional energy consumption and emissions. Recent advances in electric energy storage technologies provide an opportunity for using energy storage to address