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Economic-environmental equilibrium based optimal scheduling strategy towards wind-solar-thermal power generation system under limited resources

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HIGHLIGHTS

- Multi-objective model for wind-solar-thermal power generation system is proposed.
- Trade-offs between economic benefit and environmental impact is analyzed.
- 12 scheduling scenarios to handle natural limits of renewable sources are considered.
- Real case in China to demonstrate the model practicality and efficiency is presented.

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ABSTRACT

The integration of renewable sources into traditional power networks through the development of hybrid systems has attracted increasing international attention. However, simultaneously considering the environmental impacts, the economic benefits, and the natural limits of renewable sources in hybrid systems has proven difficult. This paper proposes an optimal scheduling strategy that fully considers the contributions of wind farm, solar parks, and coal thermal power plants to determine economic benefit and environmental impact equilibrium in a hybrid generation system under natural limitations. By factoring in the seasonal fluctuations in wind power, the weather driven characteristics of solar power, and the fuzzy coal thermal plant parameters, the optimal strategy better depicts the system characteristics than current strategies. A case study from Hami, China is presented to demonstrate the practicality and efficiency of the optimization model. The calculation results for twelve scheduling scenarios under different wind speeds and weather conditions found that this multi-objective strategy for hybrid generation systems was a superior method for solving the conflicts between emissions reduction and profits under natural renewable source limitations. Compared with previous studies, the optimal strategy this paper proposed is more applicable for developing countries such as China, and provide system operators with less calculation burdens. Management recommendations including the application of equilibrium scheduling strategy, policy support from the government, and improvements in solar power installed capacity have also been proposed.

1. Introduction

Over the past decades, electricity demand and supply have been dramatically increasing as a consequence of continued population growth, economic development and improved living-standards, leading to an unceasing exploitation of energy resources, especially fossil fuels [1]. The “BP Statistical Review of World Energy (2018)” stated that the world’s total electricity generation was 25551.3 TWh in 2017, 38.1%, 23.2% and 3.5% of which were respectively generated by coal, natural gas and oil. However, if these fossil fuels continue to be mined at the 2017 level, the world’s remaining reserves would only last 134, 52.6 and 50.2 years [2]. Further, the excessive combustion of fossil fuels have caused a significant rise in air pollutant emissions such as sulfur dioxide, nitrogen oxide and particulate matter, which have led to and continue to exacerbate global environmental problems, such as acid rain and photochemical smog pollution, particularly in developing

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Notations

Indices

i	index for coal fired power plants
j	index for wind farms
l	index for solar power plants
k	index for thermal units
t	index for time period

Decision variables

x_{ikt}	coal to be combusted by unit k at thermal power plant i at time t
g_{ikt}	turn-on or turn-off status of unit k at thermal power plant i at time t. $g_{ikt} = 0$ means turn-off, $g_{ikt} = 1$ means turn-on
y_{jt}	wind turbines to be operated at wind farm j at time t
z_{lt}	photovoltaic arrays to be operated at solar power plant l at farm t

Certain parameters

a_{min}^{ik}	minimum power output of unit k at thermal power plant i
a_{max}^{ik}	maximum power output of unit k at thermal power plant i
b_{min}^{j}	minimum power output of wind farm j
b_{max}^{j}	maximum power output of wind farm j
c_{min}^{l}	minimum power output of solar power plant l
c_{max}^{l}	maximum power output of solar power plant l
w	on-grid price of Ha-zheng line
s_1	government subsidies of wind power
s_2	government subsidies of solar power
s_3	coal price
m^-	the lower transmission variation bound of Ha-Zheng Line
m^+	the upper transmission variation bound of Ha-Zheng Line
CE	carbon emissions of last production periods
NE	renewable energy utilization of last production periods
α	system operators' attitude towards carbon emissions
β	system operators' attitude towards renewable energy utilization
o_{it}	power output of thermal plant i at time t
p_{jt}	power output of wind farm j at time t
q_{lt}	power output of solar plant l at time t
P_t	total power generated and transmitted
H_{ik}	the time period thermal unit k must running at the beginning of scheduling period
K_{ik}	the time period thermal unit k must be off at the beginning of scheduling period
G_0	the solar irradiation in the standard environment
R_l	certain irradiation point of solar plant l
v_{in}	the cut in speed of wind turbines
v_r	the rated speed of wind turbines
v_{out}	the cut out speed of wind turbines
p_{r-w}	the rated output of wind turbines
p_{r-s}	the rated output of photovoltaic cell
UT_{ik}	the minimum time thermal unit k in plant i must running
$U_{ik}(0)$	the time thermal unit k has been running at the beginning of scheduling time
$G_{ik}(0)$	the initial status of thermal unit k, "1" represent "on" and "0" represent "off"
KT_{ik}	the minimum off line time of thermal unit k in plant i
$L_{ik}(0)$	the time thermal unit k has been off line at the beginning of scheduling time

Uncertain parameters

$\widetilde{m}_{ik}$	coal to power parameter of unit k at thermal power plant i
$\widetilde{e}_{ik}$	coal to carbon emission parameter of unit k at coal fired power plant i
$\widetilde{v}_{jt}$	actual wind speed of wind farm j at time t
$\widetilde{G}_{lt}$	the solar irradiation forecast solar power plant l at time t
$\widetilde{D}_t$	total power demand

counties like China [3]. The latest research by Yuan et al. (2018) found that the national Chinese electric power industry emissions contributed more than 23%, 45% and 64% of particle material, sulfur dioxide, and nitrogen oxide as well as 44% of the carbon emissions [4]. However, coal thermal power generation continues to be the largest sector in Chinese electricity generation, accounting for 57.27% of installed capacity and 65.21% of total generation in 2016, and it is expected that this energy mix will continue for decades [5]. Faced with ever-increasing economic development pressure and unprecedented environmental protection challenges [6], the construction of environmentally friendly power generation systems is becoming urgent.

Significant efforts have been made by global researchers and engineers to develop generation systems characterized by high efficiency and low emissions. For example, Cai et al. [7] suggested and studied a new power and heat generation system to better exploit the heat content of flue gases with sulfur compounds from combined heating and power systems, the simulation results of which indicated that the novel system made better use of flue gases, with total thermal and energy efficiencies achieved of 82.7% and 28.8%, which was 8.9% and 3.0% higher than the reference system. Liu et al. [8] focused on the simultaneous removal process of sulfur dioxide and nitric oxide from flue gas using vacuum ultraviolet light/heat/peroxymonosulfate in a vacuum ultraviolet light spraying reactor, and received high simultaneous sulfur dioxide and nitric oxide removal efficiencies of 100% and 91.3%, respectively. Ryzhkov et al. [9] studied the basic methods for raising the efficiency of air-blown integrated gasification combined cycles, and proposed a scheme that enabled the approximation of cycle efficiency in a natural gas combined cycle. Li et al. [10] conducted energy and economic analyses on indirect coal-to-liquid coupling carbon capture and storage technologies, which found that energy utilization ratios only ranged from 40.3% to 43.7%, revealing the limited effect of coal type. Generally, these methods have been considered the most effective in dealing with sustainable thermal power generation; however, the capital costs and additional operating fees have remained a barrier to deploying these methods on a large scale for developing countries such as China.

A significant power generation system research focus has been the development of management tools to balance the trade-offs between profit and environmental influence. For example, Felipe et al. [11] developed a two layer mathematical-statistical model to develop Pareto optimal designs for carbon dioxide cap-and-trade policies, from which it was concluded that carbon trade policies were important in achieving reductions in both carbon dioxide emissions and electricity consumption. Ji et al. [12] proposed a systematic Pareto optimal method for emissions allocation problems at China's power plants. Singh et al. [13] introduced a synergic predator-prey optimization algorithm to solve economic load dispatch problem for thermal units. Mason et al. [14] applied a number of particle swarm optimization (PSO) variants to a dynamic economic dispatch problem, and examined the performance of each PSO algorithm when the power demand was modified to form a triangular wave. Roque et al. [15] proposed a metaheuristic approach to a multi-objective unit commitment problem that combined economic and environmental criteria. These explorations have made significant contributions to achieving equilibrium between economic profits and