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Carbon emission reduction and reliable power supply equilibrium based daily scheduling towards hydro-thermal-wind generation system: A perspective from China

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ABSTRACT

The carbon emission reduction being achieved by Chinese coal combusted electricity generation are critical for global sustainable development and environmental protection. In this paper, to achieve carbon emission reduction and reliable electricity generation, an equilibrium strategy based on a hydro-wind-thermal complementary system under an uncertain environment that fully considers the cooperation of hydro power plants, wind power plants, and coal combusted thermal power plants is proposed as an optimization method. By considering the randomness of seasonal wind speeds, the water flow uncertainty and the fuzziness of coal thermal plant carbon emissions, the complementary model is more scientific and practical than current models. A case study from Bijie City is presented to demonstrate the practicality and efficiency of the optimization model. The results from 12 different wind speed and water flow level scenarios showed that the complementary system provides a superior method to solving the conflicts between carbon emission reduction and reliable electricity generation and therefore could be of great assistance to system operators when scheduling generation.

1. Introduction

Many hazardous air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), dust, and greenhouse gases are emitted from coal combustion, all of which pose a threat to the environment and the atmosphere. Desulphurization and denitrification technologies are relatively mature so that more than 90% of SO_2 and NO_x are removed during coal combustion. For instance, from Liu's latest research, the highest simultaneous removal efficiencies of SO_2 and NO from flue gases have reached 100% and 91.3% respectively [1]. However, the technology to reduce carbon emissions during generation is so complex and expensive that significant carbon emissions still being released. The International Energy Agency statistics published in 2017 reported that the world's carbon emissions from fuel combustion reached 32.29 billion tonnes in 2015, 13.54 billion tonnes of which were directly attributable to electricity and heat production [2]. Of all these, emissions from Chinese electricity and heat production were the largest at 4.42 billion tonnes, accounting for 32.64% of the total, followed by the United States (1.98 billion tonnes) and India (1.07 billion tonnes) [2]. The China Electricity Council reported that the coal-combusted power generation was the largest sector in Chinese electricity generation, accounting for about 57.27% of total installed capacity and 65.21% of total power generation [3]. However, as the world's largest carbon emissions producer and faced with ever-increasing economic development pressure, China's demands for clean, reliable electricity is expected to remain high in the near future [4]. Therefore, the carbon emission reduction being achieved by Chinese coal combusted electricity generation are not only of great significance to China, but also critical for global sustainable development and environmental protection.

There has been significant research on emissions mitigation and the environmental impacts of coal combustion power plants from both "hard-path" and "soft-path" perspectives. The "hard-path" perspective focuses on clean coal technology and includes coal transformation technologies, integrated gasification combined cycles, highly efficient combustion, advanced power generation technologies, and carbon capture and storage. For example, Xu reviewed methanol-based coal conversion technologies in China, discussed the commercial and successfully demonstrated units in China in details [5]. Skorek-Osikowska analyzed the environmental effect of systems integrated with carbon capture installations and found that annual emissions in the post combustion system decreased from 735 kg CO_2 per megawatt hour to 100.77 kg per megawatt hour [6]. Cao presented two power generation

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systems composed of the chemical looping air separation technology and the integrated gasification combined cycle with CO_2 capture, carried out a thermodynamic comparison and analysis [7]. Generally, hard-path solutions have been considered the most useful way to remove pollutants because of the efficiencies that can be achieved, however, the capital costs for CO_2 infrastructure and the substantial additional costs can be very high for developing countries like China to deploy on a large scale [8]. The "soft-path" is focused on optimization and energy policy control methods. For example, Lv proposed an equilibrium strategy based coal blending method for combined carbon and PM_{10} reduction [9]. Wang proposed a multi-objective unit commitment approach to hand the problem with conflicting profit and emission objectives [10]. Cao explored better policy for society with investigation of cap-and-trade policy and low carbon subsidy policy [11]. Of these, unit commitment strategies, which are used to determine the operating schedules of generating units at hourly intervals with varying loads and different constraints, has proven to be effective in controlling emissions and has been implemented successfully. Chandrasekaran et al. for example, proposed a thermal unit commitment which minimized fuel costs and individual unit start-up costs, and then successfully used this model on IEEE-118 and IEEE-24 systems [12]. However, with the significant increase in renewable sources, especially in wind and solar power integrated power networks, there have been significant changes to traditional energy mixes; therefore, more appropriate scheduling strategies are needed to align with world energy system changes.

There has been increased interest in the integration of renewable energy sources into traditional power networks, with many researchers and engineers searching for new methods [13]. Of these sources, wind power, which has relatively low carbon emissions during operations, has achieved the largest market share and become the most feasible integration source [14]. For instance, Sun proposed an optimal day-ahead wind-thermal generation scheduling method that considered the statistical and predicted features of the wind speed to achieve secure power system operations and economic scheduling [15]. Laia proposed a bidding strategy with a profit maximization goal for wind-thermal energy producers taking part in a pool-based electricity market [16]. These studies have made important contributions to the integration of wind energy into power networks to reduce fossil fuel use and the associated carbon emissions. However, due to natural conditions, wind power is not easy to control and has power supply reliability problems. Further, the use of on-grid electricity has been in dispute recently because of government policy and pricing decisions. Nonetheless, as coal combusted power units at low-loads have low efficiency, are not environmentally friendly, and are a safety risk [17]; new integration sources and methods are needed to guarantee energy supply reliability and reduce carbon emissions.

As hydroelectricity can lower fuel combustion and reduce carbon emissions, it is regarded as a promising complementary energy source to mitigate wind power fluctuations and reduce the dependence on thermal power [18]. Therefore, the joint scheduling of hydro, wind, and thermal energy is attracting increasing research attention. To enhance the flexibility and reliability of power system operations, Chen et al. proposed a distributionally robust hydro-thermal-wind economic dispatch method which described the uncertain wind power output and optimized expected operating costs for the worst distribution [19]. Zhou et al. developed a unit commitment model that coordinated hydro and thermal power generation to support secure and economic wind power integration by scheduling reserves which successfully guaranteed a reliable power supply while properly maintaining hydropower station reservoir water levels [20]. Chen et al. presented a risk aware optimization model to reliably evaluate the risk and profits for short term hydro-wind-thermal scheduling, which focused on wind power risk and system economics [21]. Moreover, several different algorithms were proposed to solve the hydro-wind-thermal optimization model in other studies. For example, Zhou et al. proposed an enhanced multi-objective bee colony optimization algorithm to solve the short-term economic/environmental problem of hydro-thermal-wind complementary scheduling system [22]. Banerjee et al. applied PSO technique to solve the optimal hourly schedule problem of power generation in the hydro–wind–thermal power system [23]. Dubey et al. employed the novel ant lion optimization algorithm to solve the combined hydro-thermal-wind scheduling problem of multi reservoir cascaded hydro plants [18]. These researches have been very important in modelling the integration of hydro, wind, and thermal power, but few have considered the cleanliness and reliability of hydro-wind-thermal complementary systems or fully considered the stochastics of the wind and water flows.

In this paper, a multi-objective optimization model for a clean, reliable hydro-wind-thermal complementary system is proposed that fully considers seasonal wind power fluctuations and water inflow uncertainties, for which 12 scheduling scenarios are given. As the technology to remove sulfur dioxide and nitrogen oxides from flue gas is very mature, but carbon emission reduction remain a difficult problem, carbon emission reduction are directly considered in this paper. Further, although government policies, pricing decisions, and natural conditions are all factors affecting wind and hydropower access, these are considered such complex problems that they are beyond our model formulation ability, therefore, only the wind and hydropower uncertainties are considered in this paper. Details of the hydro-wind-thermal complementary system in Section 2 and the associated mathematical model is built in Section 3. In Section 4, a case study is given to demonstrate the significance of the proposed model, while the results under 12 scheduling scenarios are analyzed and some management recommendations are given in Section 5. Section 6 are conclusions.

2. Key problem statement

The objective of the proposed daily hydro-wind-thermal complementary system is to develop a clean, reliable system that can satisfy local loads, improve wind utilization, reduce carbon emissions, and avoid water waste over a daily scheduling horizon. First, some basic background and descriptions are given.

The generation sources scheduled into the complementary system are hydro power plants (HPPs), coal combusted thermal plants (CCPs), and wind power plants (WPPs). These power plants are fully constructed, located in a relatively near geographical location and under the management of the same dispatching center (System operator). Hydropower has good peak shaving abilities, flexible power generation, convenient start operations, and promising reserves, while thermal power plants bear the basic load, and, as wind power is a new power source, assistance is needed to connect it to the main grid; therefore, to satisfy local loads, effective and efficient coordination and cooperation is needed between the various power sources.

Representing wind speed and water flow uncertainties is a key problem in complementary systems. Because of the influences of geographical location and climate, average wind speed fluctuates across the four seasons [24]. Further, the hydropower station water flows are highly uncertain because of rainfall inconsistencies and reservoir limitations [25]. These seasonal properties associated with wind and hydro power significantly increase operation scheduling complexity, making it unreasonable to consider only one determined scenario. Feng proposed a new metrics to evaluate the variability of wind power, and found this robustness metrics more flexible and complete than the conventional metrics [24]. Séguin built a scenario tree to present the uncertain hydropower inflows and proposed an optimization method to solve the short-term hydropower unit commitment problem [26]. However, the seasonal properties of wind speed and hydro water flow have not been concurrently considered. Therefore, 12 different operating schedules are proposed to examine wind speed and water flow interactions. The wind speed set is made up of typical daily (24 h) wind speed data from the four different seasons, while the hydro power water