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Optimizing utility-scale photovoltaic power generation for integration into a hydropower reservoir by incorporating long- and short-term operational decisions

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HIGHLIGHTS

- Cost–benefit analysis used to optimize size of utility-scale PV power generation.
- Employs nested model that considers long- and short-term operating decisions.
- Variation in downstream water level used to restrict the PV integration.
- Case study optimizes size of the PV plant to integrate with Longyangxia hydro plant.

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ABSTRACT

The variability of photovoltaic (PV) power challenges its integration into power grids at the utility-scale. Operating PV power complementarily with hydropower is a promising way for the grid to accommodate more PV energy. This study optimizes the size of a utility-scale PV plant for integration into a hydro plant using cost–benefit analysis and considering variations in downstream water level (VDWL). A nesting model that incorporates both long- and short-term operating decisions is developed to estimate the delivered PV energy. This includes a multi-objective optimization model that provides long-term decisions for the joint operation of the plants. These factors are then incorporated into a short-term simulation model, which produces successive decisions relating to power curtailment and water levels. Finally, the expected net revenue of the PV plant over its lifespan is calculated while constraining the VDWL to protect downstream water users. China's Longyangxia hydro–PV plant was selected for a case study. The results indicate that: (1) the optimal size of the PV plant is 950 MW with a maximum net revenue of 5.2 billion CNY over its lifespan; (2) the optimal PV size is sensitive to financial factors (the feed-in tariff, the initial investment, and the operation & maintenance costs); and (3) a larger reservoir storage capacity tends to be integrated with a larger PV plant. The combination of the cost-benefit analysis and the nesting model appears an effective approach to optimize the size of the PV plant being integrated with hydro plant and could equally apply to integrating other renewable energy sources.

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1. Introduction

Extensive fossil fuel consumption by human activities is responsible for atmospheric and wider environmental pollution. Concerns surrounding the environment along with the depletion of fossil fuels resources and increasing energy scarcity has contributed to the global consensus of the need to develop renewable energy sources, such as solar, wind, geothermal, hydro, wave and tidal power. Among these sources, solar energy has the greatest development potential owing to it being more abundant and more evenly distributed than other renewable energies [1,2]. Solar photovoltaic (PV) and concentrated solar thermal (CSP) are two distinct forms of solar power technologies, which can be deployed at various scales ranging from distributed generation (PV) to utility-scale generation (PV and CSP) [3]. Compared with CSP, PV have experienced huge growth in recent years due to falling prices of the panels and much smaller operating costs [4]. However, PV power is variable and strongly influenced by changeable meteorological factors. The increasing penetration of utility-scale PV power into conventional power grids exacerbates difficulties for system

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security and reliability [5]. As a result, the grid operators are reluctant to accommodate PV power because of worries over grid safety and/or the need to maintain expensive spinning reserves, both of which can lead to large amounts of power being curtailed [6,7]. Complementarily operating PV power with other renewable energy sources (e.g., hydro or wind) offers a promising option to accommodate more PV power without compromising the security and reliability of the power system [8,9].

China is rich in both solar and hydro resources. More than two-thirds of the country's area receives an annual radiation of more than 5000 MJ/m^2 [10]. By the end of 2016, the total installed capacity of PV had reached 67 GW [11]. Alongside this, the total installed hydropower capacity was greater than 300 GW by the end of 2014 [12,13]. Nevertheless, the power from these resources individually is not always available to meet the increased quantity and quality demands on the power grid posed by the booming Chinese economy. Implementation of hydro–PV power generation systems could play an increasingly important role in the development of sustainable power systems. In December 2013, the successful commissioning of the Longyangxia hydro–PV plant, equipped with 320 MW of PV arrays and 1280 MW of hydro turbines, made the idea of complementary hydro–PV operation a reality. Through coordinated operation the plant aims to simultaneously overcome the disadvantages associated with both solar power and hydropower generation. Specifically, changes in PV generation are compensated by the rapidly adjustable hydropower, significantly improving the quality of PV power delivered to the grid. Meanwhile, bundling the plants together to fulfil a power generation plan means that PV power can replace some of the electricity generated from hydro resources when water availability is insufficient during the dry seasons. As well as maintaining the amount of power sent to the grid, this allows water to be reserved to further buffer future energy or water shortages. This novel operating mode will likely also provide a valuable reference for integrating other kinds of renewable energy sources into large or cascade hydropower systems.

Many studies have reported on the evaluation, modelling, and management of various hydro–PV hybrid power systems. For example, Nfah and Ngundam [14] examined the feasibility of hybrid systems consisting of pico-hydro, PV and a biogas generator for remote villages in Cameroon. Meanwhile, Bekele and Tadesse [15] studied the feasibility of a hybrid small-scale hydro–PV–wind system at the district level. Ma et al. [16] conducted a technical feasibility study on a standalone hybrid solar–wind system with pumped-hydro storage for a remote island in Hong Kong, China, while Ogueke et al. [17] evaluated the potential of a small hydro–PV hybrid system in FUTO, Nigeria. Campana et al. [18] developed a dynamic modelling tool for the design of a PV water pumping system by combining the water demands, the solar PV power, and the pumping system. Basir Khan et al. [19] used techno-economic analyses to optimize combinations of solar, wind, micro-hydro and diesel systems for a resort island in the South China Sea. Despite the breadth of such work, most of these studies relate to small-scale or stand-alone power systems with relatively limited detail on wider grid impacts. Compared with small-scale or stand-alone hydro–PV power systems, utility-scale and grid-connected hydro–PV power generation offers a more flexible and impactful option for future energy supply systems. In 2016, the prestigious European Geosciences Union conference included a session on the topic of hydro–solar time complementarity, emphasizing the importance of hydropower in promoting the integration of solar energy [20]. Existing studies on large-scale hydro–PV power systems mainly focus on evaluations of time complementarity [21,22], short-term scheduling [23], long-term optimal operation [9], or sizing PV plant for integration into a hydro plant [6]. However, very few reported studies have tackled some of these issues using a systematic framework. The expansion of hydro–PV power generation in China suggests an urgent need to address a series of challenging issues. In particular, (1) how to determine the optimal size of PV plant integrated into the hydro plant; and (2) how to make effective decisions regarding the joint use of PV and hydro resources to generate power. Addressing these issues simultaneously could have impacts on, and potentially improve, system performance in terms of, for example, the reliability of energy supplied to the grid or the efficiency of its use by the grid [24,25].

Techno-economic analyses follow a generalized method to determine the optimal size of a PV plant for integration [26–28]. The economic performance (the factor deemed most important to investors [29]) is subject to not only the size of the PV plant, but also to the strategies under which the plant is operated. However, the traditional analysis method only conducts a short-term simulation that cannot capture the longer-term seasonality of reservoir inflow and the meteorological factors associated with PV power. These omissions can result in sub-optimal results for the size and economic performance of such plant. Indeed, combining long- and short-term perspectives into operating strategies can improve the operational performance [30–35] and provide a better approximation for the optimal size of the PV plant. For a hydro–PV system, it is important to balance the longer-term issues pertaining to water regulation with the need to restrict the magnitude of downstream changes in the short-term. For example, separate to the longer- (e.g. monthly) scale issues related to water allocation to the plant, frequent and large adjustments in hydropower output to compensate for PV variations may produce drastically unsteady reservoir outflows that could negatively impact river navigation, irrigation, or even the ecological balance downstream of the plant [36,37]. This therefore suggests a constraint on the size of a PV plant that can be integrated into a hydro–PV hybrid plant, a fact that is, to the best of the authors' knowledge, rarely considered when determining the size of a PV plant to integrate into a hydro–PV system.

This study was conducted to: (1) determine the optimal size of a PV plant integrated into a hydro–PV hybrid plant incorporating both long-term and short-term considerations, including, notably, variations in downstream water level (VDWL); and (2) explore the dominant factors (both financial and physical) that influence the optimal size of the PV plant to be integrated. These issues were examined via a detailed case study of the Longyangxia hydro–PV plant in China.

The remainder of the study is structured as follows: Section 2 presents the methods used in the analysis—including a cost–benefit framework, a long-term operation model, and a short-term simulation model; Section 3 introduces a case study; Section 4 presents and discusses the results; and conclusions are then drawn in Section 5.

2. Methods

The PV power is easily influenced by climate conditions, and the changes of power flow in long-distance transmission leads to the difficulty for voltage control in wider power grids [9]. To cope with this issue, the hydro–PV power generation is implemented to promote the PV integration. In a hydro–PV hybrid system (Fig. 1), the amount of power generated by the PV array is communicated to a joint control center that then rapidly adjusts the hydro plant's output to compensate for changes in PV and to guarantee the total delivered output. In this way, the two power sources work in union to cooperatively supply the power grid. Methods used to optimize the power generation of such a system will be introduced in the following subsections.

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