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Value of pumped hydro storage in a hybrid energy generation and allocation system

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HIGHLIGHTS

- We propose a two-stage stochastic mixed-integer programming model for a hybrid energy system.
- We investigate the solar and PHES integration considering the streamflow uncertainty.
- We study the benefit of PHES system over conventional hydropower systems to support solar.
- We examine the role of PHES systems in both isolated and connected systems.

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ABSTRACT

Transition from fossil fuels to renewable sources is inevitable. In this direction, variation and intermittency of renewables can be integrated into the grid by means of hybrid systems that operate as a combination of alternative resources, energy storage and long distance transmission lines. In this study, we propose a two-stage stochastic mixed-integer programming model for sizing an integrated hybrid energy system, in which intermittent solar generation in demand points is supported by pumped hydro storage (PHES) systems and diesel is used as an expensive back-up source. PHES systems work as a combination of pumped storage and conventional hydropower stations since there is also natural streamflow coming to the upper reservoirs that shows significant seasonal and inter-annual variability and uncertainty. With several case studies from India, we examine the role of high hydropower potential in the Himalaya Mountains to support solar energy generation in the form of pumped hydro or conventional hydro system while meeting the demand at various scales. We show that pumped hydro storage can keep the diesel contribution to meet the demand less than 10%, whereas this number can go up to more than 50% for conventional systems where the streamflow potential is limited compared to the demand. We also examine the role of pumped hydro systems in both isolated and connected systems (through inter-regional transmission lines) and show that the benefit of pumped hydro is more significant in isolated systems and resource-sharing in connected systems can substitute for energy storage. In addition, with the help of the proposed model, we show that the upper reservoir size of a pumped hydro system could be lower than the reservoir size of a conventional hydropower system depending on the demand scale and streamflow availability. This means that, most of the current conventional hydropower stations could be converted to pumped hydropower stations without needing to modify the upper reservoir, leading to a significantly reduced diesel contribution and lower system unit cost.

1. Introduction

Current supply for electricity generation mostly relies on fossil fuels. However, fossil fuels are finite and their combustion causes global warming and health hazards. To reduce the role of fossil fuels and ease the concerns on the electricity generation, it is necessary to adopt energy models that employ renewable generation.

Integrating renewable sources into traditional power systems presents two important challenges. First, renewable sources such as solar and wind are intermittent, limiting the controllability of their power output at any given time. Second, their generative properties are heavily dependent on the spatial distribution which can lead to a mismatched between where the renewable energy potential exists and where the energy will be ultimately consumed. Delucchi and Jacobson

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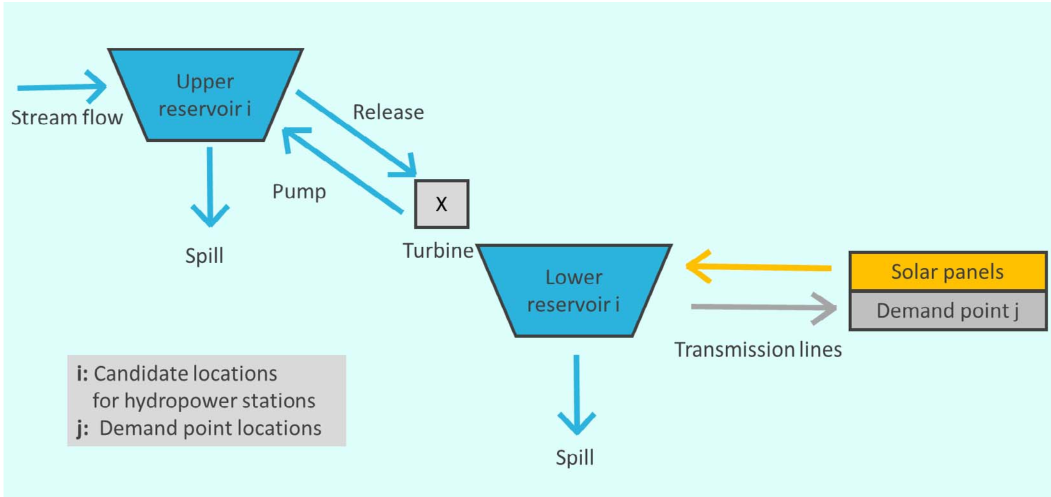

Fig. 1. A schematic illustration for hybrid system with pumped hydro storage. There are two levels of reservoirs and water can be pumped from lower reservoir to upper reservoir using the excess solar energy.

argue in [1,2] that it is possible to overcome the difficulties of working with renewables, and show that it is technologically and economically feasible to meet the 100% of the world's energy demand using wind, water and solar.

To mitigate the intermittency of renewable sources, there are several ideas proposed to design and operate cost-efficient and reliable renewable energy systems. Designing hybrid systems that operate as a combination of alternative resources, using energy storage, and building long distance transmission lines can all help ameliorate the effects of intermittent renewable generation and allow for the grid to accommodate more variation in both supply and demand [3,4]. Transmission lines accommodate more geographic aggregation, which smooths the variability of intermittent sources over large distances [5,6]. Large spatial aggregation also allows for the design of more efficient hybrid systems and the use of large-scale energy storage systems such as pumped hydro energy storage (PHES).

Optimal sizing of hybrid systems is not a trivial task, considering the uncertainties of renewable sources. Although there is vast literature on the subject, most studies approach the problem in a deterministic way by either using hourly average values of renewables [7,8] or using time series that only consider variability over time [9–12]. There are a limited number of studies that focus on optimal design and sizing of hybrid systems considering these uncertainties. Stoyan et al. [13] use a scenario-based approach to consider uncertainties and propose a stochastic mixed-integer model that minimizes cost and emission levels associated with energy generation while meeting the energy demand of a given region. Powell et al. [14] model energy resource allocations with long-term investment strategies for new technologies using an approximate dynamic programming approach. Ekren and Ekren size a hybrid system that includes solar, wind and battery storage considering the uncertainty of load and resources with response surface modeling in [15] and simulated annealing method in [16]. Roy et al. [17] and Arun et al. [18] study optimal sizing of wind/battery and solar/battery systems respectively, using chance constraint programming. Kuznia et al. [19] and Kocaman et al. [20] propose scenario based two-stage stochastic programming models for the optimal design of hybrid systems with various components.

Energy storage is one of the most important components to use renewable sources effectively and finding suitable storage technology for renewable systems is an interesting problem [21]. Among the alternative energy storage technologies, PHES systems are the most widely used, especially in large-scale applications [22]. Although PHES systems are very popular and there are a vast number of studies on how vest to operate them [22], the literature on the optimal sizing of PHES systems is very scarce [23] and these studies mostly focus on wind and PHES integration [24–26]. Kapsali et al. [24] and Katsaprakakis et al. [25] take deterministic approaches and study integrated wind and PHES design problems for isolated systems. Brown et al. [26] propose a linear programming model for optimal sizing of generators and reservoirs to store wind energy. On the other hand, in [27] Ma et al. point out the scarcity of the studies on the optimal sizing and techno-economic evaluation of solar and PHES integrated systems and propose a methodology based on a genetic algorithm.

In this study, we propose a two-stage stochastic mixed-integer programming model for sizing an integrated hybrid energy system, in which intermittent solar generation is supported by PHES systems and diesel used as a proxy for an expensive dispatchable source. In this system, solar energy is generated within the demand points and extra solar energy is sent to be stored in PHES systems via bi-directional transmission lines. PHES systems are designed as a two-level hierarchical reservoir system with a combined pump and generator located between reservoirs. When the energy is stored, the water in the lower reservoir is pumped to the upper reservoir to be released again when needed. PHES systems work as a combination of pumped storage and conventional hydropower stations since there is also natural streamflow coming to the upper reservoirs that shows significant seasonal and inter-annual variability and uncertainty. A schematic illustration of our hybrid system with pumped hydro storage is given in Fig. 1.

The aim of the model is to understand the relationship between solar and streamflow patterns and determine the optimal sizing of infrastructure needed for solar and PHES systems to meet demand in a cost effective way and. Our model helps assess how efficiently solar energy could meet the electricity demand with the help of pumped hydro systems utilizing high hydropower potential of rivers.

The contributions of our study can be summarized as follows: we propose the first model that investigates the solar and PHES integration problem while taking into consideration the streamflow uncertainty for large-scale systems. With this model, we also examine the benefit of pumped hydro storage systems by comparing the results with those produced by conventional hydropower stations. We present results from several cases studies in India that help articulate the potential for hydropower sites in the Himalaya Mountains to support solar energy. In [20], conventional hydropower generation capacity along with minimal diesel usage to support 1 GW_{peak} solar power generation is investigated and results are presented for isolated systems and connected systems (through inter-regional transmission) to show the benefits of resource-sharing and to see the effects of geographic diversity on the infrastructure sizing. In this study, we take a similar approach and