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# Optimal design of an autonomous solar–wind-pumped storage power supply system ☆

Tao Ma *, Hongxing Yang, Lin Lu, Jinqing Peng

*Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China*

## HIGHLIGHTS

- Optimal design of a pumped storage-based renewable energy power generation system.
- Assessment on the techno-economic performance of the optimized microgrid system.
- Sensitivity analysis on key parameters.

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## ABSTRACT

Renewable energy, particularly solar and wind power integrated with microgrid technology, offers important opportunities for remote communities to provide power supply, improve local energy security and living conditions. The combination of solar, wind power and energy storage make possible the sustainable generation of energy for remote communities, and keep energy costs lower than diesel generation as well. The purpose of this study is to optimize the system design of a proposed hybrid solar–wind-pumped storage system in standalone mode for an isolated microgrid of a scale of a few hundred kW. The initial design process of the system's major components is presented, and then optimized based on a techno-economic evaluation. The optimal system configuration under zero loss of power supply probability (LPSP) is further examined. In addition, the system performance of hybrid solar–wind, solar-alone and wind-alone systems with pumped storage under LPSP from 0% to 5% is investigated and compared. Results demonstrate that addition of wind turbine can result in a lower cost of energy (COE) and help reduce the size of energy storage. Sensitivity analysis on several key parameters is also performed to examine their effects on system COE.



## 1. Introduction

Recent years the rising price of fossil fuels and concerns about the environmental consequences of $CO_2$ emissions have resulted in emerging interest in the development of renewable energy applications [1,2]. In particular, the Fukushima nuclear accident was a turning point in the call for a transition from the risky nuclear and $CO_2$ intensive fossil fuels to the sustainable and environmental-friendly renewable energy for power supply [3]. Therefore, a global expansion of solar and wind energy applications has been witnessed in the past decades, meanwhile the cost of renewables continues to drop.

However, one challenge of renewable energy utilization is its fluctuation in production and time-dependent characteristic. Flexible demand management [4–6] and smart energy management [7,8] may help but they do not fully suffice in maintaining the balance between production and demand of electricity. In this regard, energy storage technology could be an effective solution to overcome the intermittency problem of the production of renewable energy [9]. It stores the generated energy when production exceeds demand and allows for dispatching the stored energy when production is low than demand. Pumped hydro storage, as a leading energy storage technology, has been widely used in the world [10]. In recent years, a considerable amount of work [11–18] has been carried out to study large-scale pumped storage facilities integrated with the grid-connected wind or solar power system. These studies were carried out with respected to feasibility study, system hybridization, modeling, optimization, operation and management, demonstrating that the pumped storage can be

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* Corresponding author. Tel.: +852 2766 5863; fax: +852 2765 7198.
*E-mail address:* tao.ma@connect.polyu.hk (T. Ma).

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a good partner to renewable energy integration, especially for the island power supply system. However, none of these studies explored the potential of using small-scale pumped storage of a scale at a few hundred kW in standalone hybrid renewable energy power generation systems for remote areas.

Inspired by pumped storage for conventional power plants, this paper presents a novel pumped storage-based solar–wind power generation system for a remote island. In our previous study, a technical feasibility of such hybrid system has been examined in [19], demonstrating that technically the pumped storage-based renewable energy system can support a 100% energy autonomy in remote communities, while there was no economic evaluation in that work. A follow-up study on the economic analysis of the two energy storage technologies was performed in [20], showing that the pumped storage has significantly lower life cycle cost compared to battery storage, particularly when some variables are controlled such as increased storage capacity and days of autonomy, whereas this was just a case study and thus it might not be the optimal system in terms of technical and economic performance. Furthermore, the system modeling and techno-economic optimization of the pumped storage based solar PV system has been investigated in [21]. However, the wind energy contribution was not considered in that study.

The present study focuses on optimizing the configuration of a standalone solar–wind-pumped storage power system through evaluating its techno-economic performance. The proposed system schematic is illustrated in Fig. 1. It consists of photovoltaic (PV) array and wind turbine (WT), pumped hydro storage, end-user and control station. The whole system is isolated from the utility grid, hence called standalone/autonomous system, aiming for remote areas where utility extension is very expensive or impossible. The physical model and operating principle of the microgrid solar–wind-pumped storage system has been examined in [19].

## 2. Background of this study

This study is based on a collaborative research project between the research group and a local power supply company for power supply in a remote island in Hong Kong. Before this study, some potential power supply solutions for this island, such as diesel generator, power grid extension by undersea cable or overhead, and renewable energy, have been examined. In addition, different energy storage technologies, primarily battery and pumped storage, have been investigated [20]. The final decision was to take renewable energy, i.e. solar and wind energy or their combination, since it would be the lowest cost option when compared with remote diesel power generation. In addition, renewable energy technology is now mature enough to provide utility quality power supply at a reasonable cost [22]. In Stage 1 of this project, a 19.8 kWp PV system with battery was installed in 2008 [23]. Given that the power generation and storage capacity in stage 2 will increase to tenfold of stage 1, some problems will arise if energy is stored in battery, such as high cost, environmental problems particularly in ultimate disposal. Therefore, the pumped storage is proposed for this project to be an alternative to battery.

## 3. Methodology

The mathematical models of PV, wind turbine, and pumped storage have been presented in another published paper of the authors [19]. The relationship between output current $I$ and output voltage $V$ of a PV array is modeled using the five-parameter model (Eq. (1)), which has been validated through outdoor tests [24] and in a real PV power plant [25].

$$I = N_p I_{ph} - N_p I_0 \left( e^{\frac{1}{V_t}\left(\frac{V}{N_s} + \frac{IR_s}{N_p}\right)} - 1 \right) - \frac{N_p}{R_p}\left(\frac{V}{N_s} + \frac{IR_s}{N_p}\right) \quad (1)$$

where $I_{ph}$ is the photo current (A); $I_0$ is the diode saturation current (A); $R_s$ is the series resistance (Ω); $R_p$ is the shunt/parallel resistance (Ω); $V_t = nKT/q$ is the diode thermal voltage; $n$ is the diode ideality factor; $k$ is the Boltzmann's constant (J/K); $q$ is absolute value of electron's charge (C) and $T$ is the cell temperature ($K$); $N_s$ represents the number of cells in series and $N_p$ is the number of PV strings in parallel.

The power curve of the specified wind turbine (Fig. 2) is used to model its power output under different wind speeds.

The pumped storage subsystem consists of a separated pump/motor unit and a turbine/generator unit, and they are modeled based on the principle of conservation of mechanical energy,

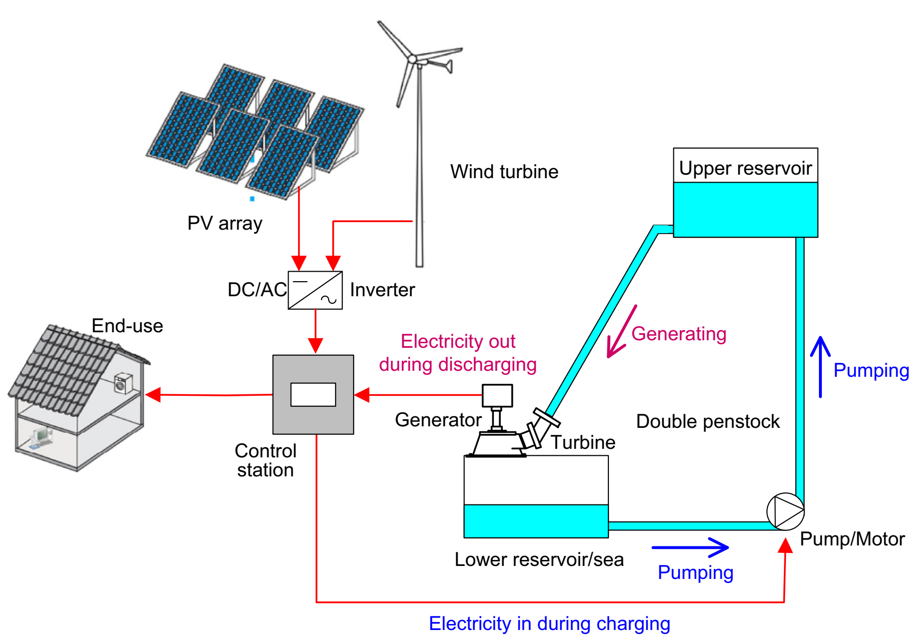


**Fig. 1.** A microgrid solar–wind system with pumped storage system [19].

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