Journal of Physics:
Conference Series

PAPER • **OPEN ACCESS**

Coordinated short-term dispatch for variable-speed pumped storage units, wind, solar and data center hybrid system

To cite this article: Xudong Li *et al* 2025 *J. Phys.: Conf. Ser.* **3001** 012016

View the article online for updates and enhancements.

Coordinated short-term dispatch for variable-speed pumped storage units, wind, solar and data center hybrid system

Xudong Li[1], Yibo Ding[1,2] and Zhao Xu[1,2,3*]

[1] Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China
[2] Research Institute of Smart Energy, The Hong Kong Polytechnic University, Hong Kong SAR, China
[3] Shenzhen Research Institute, The Hong Kong Polytechnic University, Hong Kong SAR, China

*E-mail: eezhaoxu@polyu.edu.hk

Abstract. Seawater and mine pumped storage hydropower (PSH) based on variable-speed PSH units are becoming the mainstay of sustainable PSH development. These unique operational environments of these PSH offer potential complementary scenarios for data center (DC) constrained by energy consumption. For instance, Google is actively integrating seawater PSH can be integrated with offshore wind power to support the offshore DC that Google is actively developing, where seawater cooling utilization can significantly reduce energy consumption for cooling. In response to these potential applications, this work establishes models for variable-speed PSH units and DCs; then we conduct four case studies to preliminarily investigate the feasibility of complementary operations between variable-speed PSH and integrated wind and solar power with DCs. The results indicate that this emerging operational model can enhance the average economic benefits of the hybrid system by 5.74%, which provide valuable insights for the sustainable development of both PSH and DCs.

1. Introduction

Pumped storage hydropower (PSH) is recognized as the most technically mature and reliable technology for large-scale energy storage, playing a crucial role in ensuring the safety, stability, and economic efficiency of power systems[1, 2]. From a flexibility perspective, PSH units can be classified into fixed-speed and variable-speed types, with fixed-speed PSH being widely implemented globally[3]. The primary distinction lies in the ability of variable-speed PSH (VSPSH) units to adjust power output during pump conditions flexibly. In contrast, fixed-speed units operate at a constant power level.

The increasing demand for flexibility in power systems, driven by the growing integration of variable renewable energy sources such as wind and solar[4, 5], underscores the necessity for more adaptable VSPSH units. Concurrently, the sustainable development of PSH is gaining attention[6, 7], particularly with innovations like seawater PSH[8] and mine PSH[9]. These emerging systems are designed to utilize VSPSH technology. However, current dispatch research predominantly focuses on modelling fixed-speed PSH units[10] and the VSPSH units at the power station level[9]. Consequently, existing studies often overlook the unique characteristics of unit-level operations, especially the hydraulic characteristics of VSPSH units.

Additionally, the substantial energy consumption of data centers (DCs) has emerged as a significant barrier to the advancement of AI[11]. To mitigate this issue, two primary strategies have been identified: (1) reducing energy consumption—exemplified by Google's data center in Hamina, Finland, which employs seawater cooling to minimize air conditioning needs; and (2) DCs geographical adjacent energy sources—illustrated by Baidu's Yangquan DC in Shanxi Province, which is a power center for enrichment of abandoned mine. In China, there are a total of 238 potential sites along the coastline for developing seawater PSH, with an estimated installed capacity of 42.08 GW[12]; the potential for repurposing existing mine sites for mine PSH development is approximately 365.5 GW[13] (Fig. 1). Therefore, integrating seawater PSH or mine PSH based on VSPSH technology with nearby wind and solar power sources presents a promising scenario for the sustainable development of PSH, renewable energy, and DCs.

To address these emerging application scenarios, we aim to develop models for both VSPHS units and DC. Then, we propose a short-term economic dispatch method for the complementary operation of the VSPHS-Wind-Solar-DC hybrid system (hereinafter referred to as the hybrid system). Finally, we apply this method to a practical engineering case to evaluate its feasibility. The structure of this paper is outlined as follows: Section 2 details the proposed method, Section 3 discusses the results of a case study, and Section 4 summarizes the key conclusions.

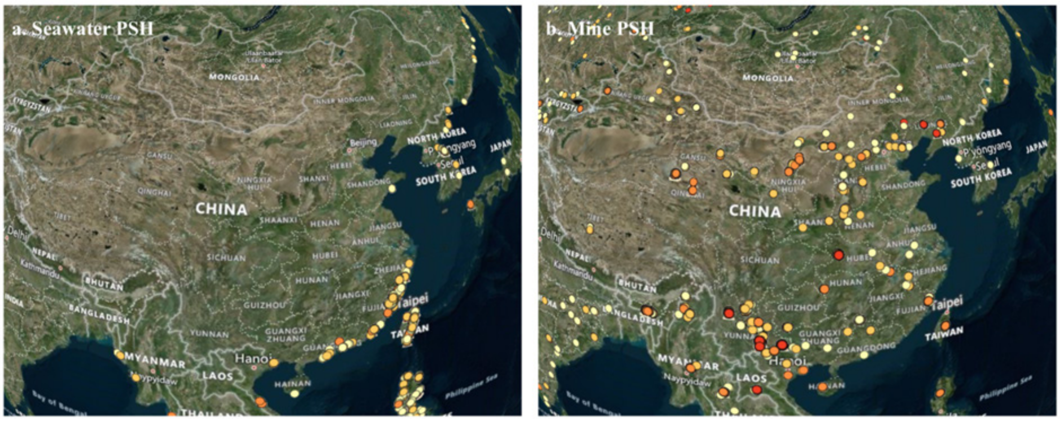

Figure.1. Location of seawater and mine PSH (Data sources: Pumped Hydro Energy Storage Atlases)

2. Method

2.1 Modelling of VSPSH

According to the working conditions, the status of VSPHS units includes turbine condition (generating), pump condition (pumping), and shutdown. The turbine condition is similar to general hydropower unit. The modelling details, such as the constraints, can be seen in the author's recent work [14, 15] and will not be repeated here.

The pump condition is the biggest difference between VPPHS and general fixed-speed PSH units. The modelling of the fixed-speed unit is relatively simple, because the working condition of the pump is fixed power, which is determined that the pumping power is known by the on-off status. For variable-speed units, the approximate relationship between power and speed is shown in Eq. (1). The detailed relationship can be obtained by interpolating the pump-turbine characteristic curve (Fig.2).

$$\frac{P_r}{P_v} = \left(\frac{n_r}{n_v}\right)^3 \tag{1}$$

where n_f and n_v denote rated pump-turbine speed and variable-speed of PSH, respectively; P_f and P_v denote pumping power of rated power and variable power of PSH, respectively.

Thus, we introduce three binary variables to represent turbine, pump, and shutdown conditions, which are constrained by Eq. (2). The pumping power follows the discharge and reservoir constraints presented by Eq. (3-8). Other constraints, including minimum on/off duration of units, are shown in Ref. [6, 14].

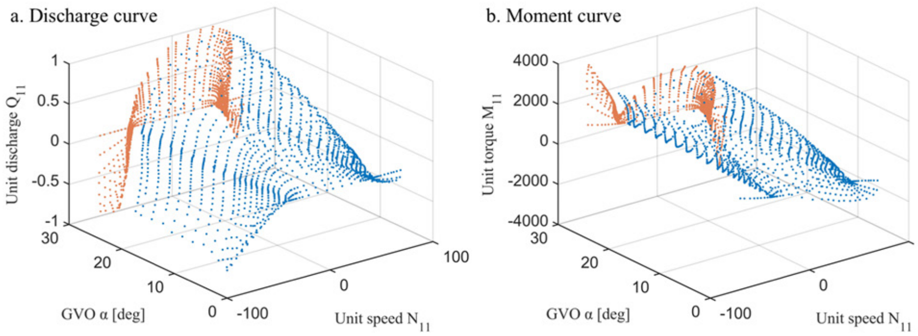

Figure.2. Characteristic curves of VSPSH unit (The orange point is the projection of the blue scatter point on the xz-plane)

$$I_{t,u}^{h} + I_{t,u}^{p} + I_{t,u}^{off} = 1 \tag{2}$$

$$Q_{u,\min}^{p} \le I_{t,u}^{p} \cdot Q_{t,u}^{p} \le Q_{u,\max}^{p} \tag{3}$$

$$V_{\min} \le V_t \le V_{\max} \tag{4}$$

$$V_t = V_{t-1} + (Q_t^{\mathrm{p}} - Q_t^{\mathrm{g}})\Delta T \tag{5}$$

$$H_t^{\mathrm{up}} = f_V(V_t) \tag{6}$$

$$H_{t,u}^{\mathrm{net}} = H_t^{\mathrm{up}} - H_t^{\mathrm{tail}} - H_{t,u}^{\mathrm{loss}} \tag{7}$$

$$P_{t,u}^{\mathrm{p}} = 9.81 \cdot Q_{t,u}^{\mathrm{p}} \cdot H_{t,u}^{\mathrm{net}} / \eta_{t,u}^{\mathrm{p}} \tag{8}$$

2.2 Modelling of DC

This work simulates a type of centralized DC using concurrent processing instead of simple queuing. When the DC receives a network request, it transmits the data load to the control center for decision-making. If processed, the data load is assigned to a server; if not, it waits. Besides, a large-capacity uninterruptible power supply (UPS) ensures reliability and supports energy storage, affecting total energy consumption:

$$P_t^{\mathrm{UPS}} = \frac{1}{\eta_{\mathrm{rec}}}\left(P_t^{\mathrm{Bat}} + \frac{P_t^{\mathrm{DC}}}{\eta_{\mathrm{inv}}}\right) \tag{9}$$

While for the energy consumption of the DC itself (P_t^{DC}) is mainly composed of three parts: IT equipment, air conditioning refrigeration and network communication equipment:

$$P_t^{\mathrm{IT}} = r_{\mathrm{C}} P_{\max}^{\mathrm{IT}} + r_{\mathrm{s}}(1 - r_{\mathrm{C}}) P_{\max}^{\mathrm{IT}} \tag{10}$$

$$P_t^{\mathrm{Air}} = P_t^{\mathrm{IT}} \beta / \eta_{\mathrm{CoP}} \tag{11}$$

$$P_t^{\mathrm{Net}} = r_{\mathrm{C}} P_{\max}^{\mathrm{Net}} \tag{12}$$

$$r_C = L_{t,i} / L_{\max} \tag{13}$$

Thus, the key is to decide $L_{t,i}$. To simulate whether the data load is delayed and processed, we introduce binary variables U_i and $J_{t,i}$. U_i =0/1 denotes the data load i will/will not be delayed processing and $J_{t,i}$ =1/0 denotes the data load i is/is not in the processing by the server. Further we introduce the following constraints, including servers' content, server resource allocation, data load balance (Eq. (14-16)), and executing state (Eq. (17-18)).

$$\sum_{i}^{I} L_{t,i} \le L_{\max} \tag{14}$$

$$J_{t,i} L_i^{\min} \le L_{t,i} \le J_{t,i} L_t^{\max} \tag{15}$$

$$\sum_{i}^{I}\sum_{t}^{T} L_{t,i} = \sum_{i}^{I} L_i^{Data} \tag{16}$$

$$L_i^{Data} - \sum_{t\in[t_i, t_i+h_i]} L_{t,i} \le M \cdot U_i \tag{17}$$

$$L_i^{Data} - \sum_{t\in[t_i, t_i+h_i]} L_{t,i} \ge m \cdot U_i \tag{18}$$

where P_t^{Bat} is the battery power of the UPS; η_{rec} and η_{inv} denote the efficiency of rectifier and inverter; P_t^{IT}, P_t^{Air} and P_t^{Net} denote the energy consumption of IT equipment, cooling and network communication equipment; $P_{\max}^{\mathrm{IT}}$ denotes the peak power of computer server; r_C and r_s denote the utilization ratio of computer server and the ratio of server under spare condition to the server's peak power value; $L_{t,i}$ is the number of computer server of data load i in time t; $L_{\max}$ is the max number of computer server in DC; $P_{\max}^{\mathrm{Net}}$ is the energy consumption of the network communication during peak power period; η_{CoP} is the cooling efficiency of air conditioning, which is related to the setting temperature[16]; M and m are the setting parameters based on Big-M method.

2.3 Short-term economic dispatch model of the hybrid system

(1) Objective function: Max. benefit of the hybrid system considering the cost of purchasing and the benefit of selling power, as well as the loss caused by the delay of the data load of DC. This work mainly focuses on the day-ahead dispatch process of the hybrid system, thereby ignoring the charging and discharging conditions of the UPS (i.e., the battery) because the UPS is used for the emergency/burst needs of the DC at the more short-time level.

$$\text{Max. } F = \sum_{t=1}^{T} (\text{Price}_{\text{sell}} \cdot \left| P_t^{\text{Trans,-}} \right| - \text{Price}_{\text{buy}} \cdot P_t^{\text{Trans,+}}) - \text{Price}_{\text{pun}} \cdot \sum_{i}^{I} U_i \tag{19}$$

(2) Constraints. In addition to the constraints described in Section 2.1, the power balance of the hybrid system and the transmission boundary should also be considered in the optimization model presented by Eq. (20-21). Other general battery constraints, such as charging power and SOC, will not be repeated here because of the limited space.

$$\sum_{u=1}^{U} I_{t,u}^{\mathrm{g}} P_{t,u}^{\mathrm{g}} + P_t^{\mathrm{w}} + P_t^{s} = \sum_{u=1}^{U} I_{t,u}^{\mathrm{p}} P_{t,u}^{\mathrm{p}} + P_t^{\mathrm{Trans}} + P_t^{\mathrm{UPS}} + Load_t^{\mathrm{Benchmark}} \tag{20}$$

$$\left| P_t^{\mathrm{Trans}} \right| \le P_{\max}^{\mathrm{Trans}} \tag{21}$$

where $P_{t,u}^{\mathrm{g}}$ and $P_{t,u}^{p}$ denote the generating and pumping power of VSPSH; P_t^{Trans} is the transmission line power; P_t^{w} and P_t^{s} denote the wind and solar power; $Load_t^{\mathrm{Benchmark}}$ is the benchmark load.

3. Case study

The proposed method is applied to a planning case in Guangdong, China (Fig. 3). The data of VSPSH units and DC come from Ref.[17] and Ref.[18], respectively. Other key parameters are shown in Table 1. To evaluate the feasibility and effectiveness of the proposed method, four scenarios are analyzed (Table 2). All simulations are implemented on Matlab 2023a and corresponding optimization problems are solved by Gurobi.

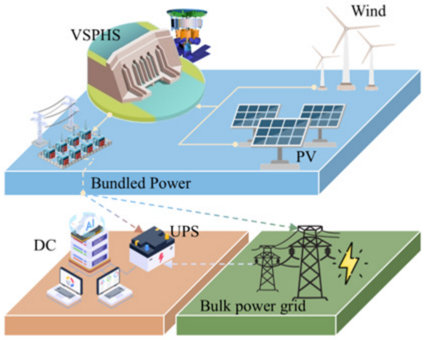

Figure. 3. Simplified schematic of the hybrid system

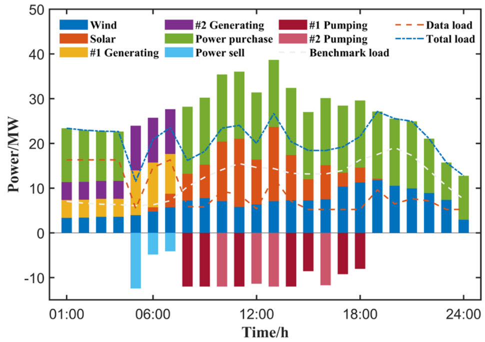

Figure. 4. Results of Case 3

Table 1. Parameters of the VSPSH.

Parameters	Values	Units	Parameters	Values	Units
Installed capacity	20	MW	Rated speed of unit	500	r/min
Rated capacity of unit	10	MW	Variable speed range	±8%	/
Maximum pump head	126.5	m	Maximum hydraulic head	124.2	m

Table 2. Scenarios setting.

Scenarios	Type of PSH units	Type of DCs
Benchmark	Traditional fixed-speed PSH units	Unable to delay processing data load
Case 1	VSPSH units	Unable to delay processing data load
Case 2	Traditional fixed-speed PSH units	Considering the delay processing data load
Case 3 (ideal)	VSPSH units	Considering the delay processing data load

The simulation results are presented in Fig.4, Fig.5, and Fig.6. Fig.4 shows the ideal scenario of the hybrid system, where all variable constraints are satisfied. Meanwhile, Fig. 5 presents the benefits of the 4 scenarios, indicating that Case 3 achieves the optimal benefit of RMB 1.67×10^5 compared to the other 3 scenarios. This result suggests that VSPSH units operating in coordination with flexible DCs can enhance benefit by 5.74% averagely.

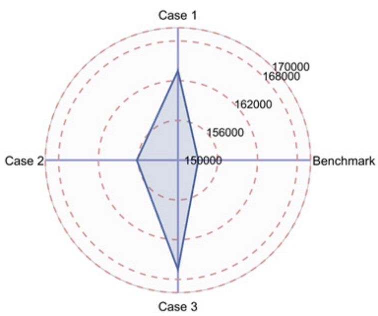

Figure.5. Economic benefit of scenarios.

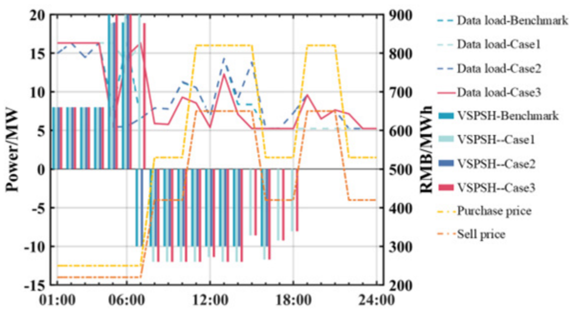

Figure.6. Operation details of VSPSH and DC.

Furthermore, we analyze the impact of the hybrid system between VSPSH units and flexible DCs by examining operational details. From a benefits perspective, compared to Case 1 and Case 3, flexible DCs can improve the hybrid system's benefits by 4.68%. In contrast, the benefits can be

Journal of Physics: Conference Series **3001** (2025) 012016 doi:10.1088/1742-6596/3001/1/012016

increased by 7.05% when comparing Case 2 to Case 3. Thus, the control variable approach allows us to tentatively conclude that VSPSH has a more significant impact on the hybrid system.

Additionally, Fig. 6 reveals that the data loads differ across the 4 scenarios. This variation arises because the Benchmark and Case 1 scenarios do not involve data load delay processing, whereas Cases 2 and 3 do. Notably, Case 2 experiences more delays than Case 3, as it supplements the lack of flexibility in fixed-speed PSH units through regulate data loads. On the other hand, considering the daily regulation function limits of the relatively small VSPSH, both the initial and final reservoir levels should be maintained within a specific range. This requirement explains why pumping conditions are concentrated during midday hours following turbine operations.

4. Conclusions

To address these emerging application scenarios (i.e., VSPSH units coordinates operating with wind, solar, and data center), this work build a short-term economic dispatch method for the hybrid system and evaluate the feasibility of this potential application scenarios. The main conclusions are as follows: (1) Compared with traditional fixed-speed PSH units and other scenarios, the proposed method can enhance the benefit by 5.74% averagely; (2) Flexible PSH (i.e., VSPSH) provides greater hybrid system benefits than flexible DCs.

In total, this work can provide support for the operation and decision-making of these emerging sustainable scenarios. However, this work lacks a comprehensive analysis of the advantages of the proposed methods, which will be strengthened in the future.

Acknowledgement

This work was supported by the National Natural Science Foundation of China under Grant No. 72331008 (Key Program) and No. 72271211 (General Program).

References

[1] Matthew Stocks, Ryan Stocks, Bin Lu, et al. Global Atlas of Closed-Loop Pumped Hydro Energy Storage. Joule. 2021;5:270-84.

[2] Muhammad Shahzad Javed, TaoMa, Jakub Juraszb, et al. Solar and wind power generation systems with pumped hydro storage: Review and future perspectives. Renewable Energy. 2020;148:176-92.

[3] Ziwen Zhao, Meng Zhang, Mengjiao He, et al. Beyond fixed-speed pumped storage: A comprehensive evaluation of different flexible pumped storage technologies in energy systems. Journal of Cleaner Production. 2024;434:139994.

[4] Jiaqi Ruan, Zhao Xu, Su H. Towards interdisciplinary integration of electrical engineering and earth science. Nature Reviews Electrical Engineering. 2024;1:278-9.

[5] Yibo Ding, Xianzhuo Sun, Jiaqi Ruan, et al. Customized decentralized autonomous organization based optimal energy management for smart buildings. Applied Energy. 2024;37:124223.

[6] Xudong Li, Weijia Yang, Zhigao Zhao, et al. Advantage of priority regulation of pumped storage for carbon-emission-oriented co-scheduling of hybrid energy system. Journal of Energy Storage. 2023;58:106400.

[7] Xudong Li, Weijia Yang, Zhigao Zhao, et al. Risk-averse energy management of hydro/thermal/pumped storage complementarily operating with wind/solar: Balancing risk, cost and carbon emission. Sustainable Energy Technologies and Assessments. 2023;60:103534.

[8] Anish Pradhan, Miroslav Marence, Franca M. J. The adoption of Seawater Pump Storage Hydropower Systems increases the share of renewable energy production in Small Island Developing States. Renewable Energy. 2021;177:448-60.

[9] Yan Ren, Ketao Sun, Kai Zhang, et al. Optimization of the capacity configuration of an abandoned mine pumped storage/wind/photovoltaic integrated system. Applied Energy. 2024;374:124089.

[10] Ran Wang, Weijia Yang, Yifan Huang, et al. Coordinating regulation reliability and quality of pumped storage units for renewables by a novel scheduling-control synergic model. Applied Energy. 2024;376:124162.

Journal of Physics: Conference Series **3001** (2025) 012016 doi:10.1088/1742-6596/3001/1/012016

[11] Hongyu Zhu, Dongdong Zhang, Hui Hwang Goh, et al. Future data center energy-conservation and emission-reduction technologies in the context of smart and low-carbon city construction. Sustainable Cities and Society. 2023;89:104322.
[12] Administration C. N. E. Notice from the National Energy Administration on the Release of Resource Census Results for Seawater Pumped Storage Power Stations. 2017. https://zfxxgk.nea.gov.cn/auto87/201704/t20170405_2763.htm.
[13] Timothy Weber, Ryan Stocks, Andrew Blakers, et al. A global atlas of pumped hydro systems that repurpose existing mining sites. Renewable Energy. 2024;224.
[14] Xudong Li, Weijia Yang, Yiwen Liao, et al. Short-term risk-management for hydro-wind-solar hybrid energy system considering hydropower part-load operating characteristics. Applied Energy. 2024;360:122818.
[15] Xudong Li, Weijia Yang, Jia Wei, et al. Part-load operation risk assessment of hydropower units in hydro–wind–solar hybrid system considering hydraulic characteristics. Energy Reports. 2023;9:332-42.
[16] Saifullah Khalid I. A. Dual Optimization of Revenue and Expense in Geo-Distributed Data Centers Using Smart Grid. IEEE Transactions on Cloud Computing. 2023;11:1622-35.
[17] Harbin National hydropower equipment engineering Technology Research Center Co. L. Model test report of variable-speed pump turbine for seawater pumped storage power station. 2019.
[18] WEN Zhengnan, Jichun L. A Optimal Scheduling Method for Hybrid Wind-solar-hydro Power Generation System With Data Center in Demand Side. Power System Technology. 2019;43:2449-60.