Integrating a pumped-storage hydropower plant with photovoltaics: impacts on energy production and on the water resource system

D. Micocci[1*], C. Bragalli[1], E. Toth[1], M. Zappa[2]
[1] Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna, Italy
[2] Swiss Federal Institute WSL, Birmensdorf, Switzerland
* e-mail: domenico.micocci@unibo.it

Introduction

Variable renewable energy resources (VRES), including solar photovoltaics (PV), are posing new challenges to the management of the electricity grid (Lund et al. 2015), since their availability is driven by climate-related variables and it is therefore independent from the consumers' demand. Reservoir-based hydropower (HP) is particularly valuable to resolve the mismatch between demand and supply, since it is one of the few renewables whose power output can be set almost on demand. Even higher flexibility is provided by pumped-storage HP, which also allows to absorb energy exceeding the consumers' demand and to store it by pumping water from a lower to an upper reservoir (Guittet et al. 2016).

Integrating PV and HP in a single hybrid power station is seen as a promising solution to get more regular power generation profiles compared to stand alone PV, thus facilitating the introduction of high shares of VRES in the energy mix (Jurasz et al. 2020). On the other hand, complementing an existing reservoir-based HP plant with PV may affect the way the reservoir is operated (François et al. 2014), possibly offering potential for improving the conditions of the downstream water resource system.

For a real Swiss pumped-storage HP plant, we set up a numerical experiment to analyse the impacts of expanding the existing plant through a floating photovoltaic (FPV) plant, installed directly on the reservoir surface. The possibility of increasing downstream environmental releases, using water which is not used for HP purpose thanks to PV production, is also explicitly taken into account.

Materials and methods

Lake Sihl is an important artificial reservoir, located in the Swiss pre-Alpine region (catchment area: 155.5 km^2; average elevation: 1243 m a.s.l.; discharge regime: nivo-pluvial-prealpine). Water collected in the lake is mostly used by the Swiss Federal Railways in the Etzelwerk HP plant, which exploits a difference in elevation of about 480 m between Lake Sihl (upper reservoir) and Lake Zurich (lower reservoir); being a pumped-storage plant, water can also be pumped from Lake Zurich, either to store energy or to refill Lake Sihl when its level is too low. Finally, an environmental release from Lake Sihl is prescribed, depending on downstream flow conditions.

Historical meteorological data (including temperature, precipitation and solar radiation) were available for the study area over the period 1981-2018. A calibrated hydrological model, developed using the semi-distributed modelling system PREVAH (Viviroli et al. 2009), was forced with these data in order to obtain all the necessary hydrological input data (including lake inflow and evaporation losses, and natural runoff downstream of the dam, which triggers the environmental release).

A fictional FPV plant was introduced on Lake Sihl, covering 10 % of the minimum reservoir surface (3.15 km^2 at the minimum pool level) and having almost half of the HP generating capacity (120 MW). The hybrid HP-FPV plant was simulated at an hourly resolution through a modelling chain involving: i) a PV production model, converting input temperature and irradiance timeseries into a timeseries of PV power available; ii) a power demand profile, obtained through a multiple linear regression model calibrated on historical plant production data, taking into account only time-related explanatory variables (month, day, hour); iii) a reservoir operation model, setting the amount of water to be turbined or pumped according to the requirements and the available storage. Specifically, reservoir operations were guided by rule curves deduced from a statistical analysis of historical storage timeseries (1981-2023), which unveiled a target storage management strategy, particularly from June to October, when the level of the lake is prescribed not to fall below a given threshold to comply with a legal constraint.

Simulations were repeated according to three scenarios: i) NoPV is a reference scenario, with no PV to support HP; ii) in PV1 solar energy, if available, contributes to fulfil the demand and excess PV power is possibly stored through pumping; iii) PV2 is similar to PV1, but including the possibility to release 50 % of the water saved from HP production thanks to PV, so as to increase the legally prescribed environmental flow from May to October.

Results and concluding remarks

The introduction of PV allows to increase by almost 20 % the overall energy production, compared to the base scenario NoPV (Table 1). Interestingly, a similar energy increase has been obtained both for scenario PV1 and PV2, despite additional water releases, which are allowed in the latter. To this regard, between May and October the mean monthly release from Lake Sihl is increased from 14 % (May) up to about 50 % (June to August) in scenario PV2 compared to PV1 (Table 1), possibly contributing also to lower the downstream water temperature, which is a fundamental ecological variable (Rojas-Aguirre et al. 2025).

Table 1. Energy annually produced in each scenario (GWh/year) and mean monthly downstream release (m^3/s). Average values computed over the entire simulation period (1981-2018).

	Energy total	Energy from HP	Energy from PV	Release May	Release Jun	Release Jul	Release Aug	Release Sep	Release Oct
NoPV	256.6	256.6	–	0.47	0.55	0.60	0.63	0.59	0.71
PV1	319.1	257.7	61.4	0.47	0.55	0.60	0.63	0.59	0.71
PV2	315.2	254.1	61.1	0.54	0.85	0.91	0.93	0.81	0.91

The hybrid plant (PV1 and PV2) meets the power demand more often than the conventional HP plant, as portrayed by the reliability index (here defined as the ratio between energy supplied and energy required in the simulation period), which increases from about 90 % in scenario NoPV to about 97 % in PV1 and PV2. This leads to a significant increase of energy annually produced for self-consumption.

In conclusion, according to the results of the numerical experiment, it seems that introducing PV in the selected case study could improve downstream flow conditions (at least to some extent), while also providing benefits in terms of energy production and reliability of supply.

Acknowledgments: This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

References

François B, Borga M, Anquetin S, Creutin JD, Engeland K, Favre AC, Hingray B, Ramos MH, Raynaud D, Renard B, Sauquet E, Sauterleute JF, Vidal JP, Warland G (2014) Integrating hydropower and intermittent climate-related renewable energies: a call for hydrology. Hydrological Processes 28: 5465–5468. https://doi.org/10.1002/hyp.10274

Guittet M, Capezzali M, Gaudard L, Romerio F, Vuille F, Avellan F (2016) Study of the drivers and asset management of pumped-storage power plants historical and geographical perspective. Energy 111: 560–579. https://doi.org/10.1016/j.energy.2016.04.052

Jurasz J, Canales FA, Kies A, Guezgouz M, Beluco A (2020) A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions. Solar Energy 195: 703–724. https://doi.org/10.1016/j.solener.2019.11.087

Lund PD, Lindgren J, Mikkola J, Salpakari J (2015) Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renewable and Sustainable Energy Reviews 45: 785–807. https://doi.org/10.1016/j.rser.2015.01.057

Rojas-Aguirre AF, Bray EN, Dozier J (2025) Evaluating the effects of climate change on managed lowland rivers in the California Bay Delta Watershed. Journal of Hydrology 647: 132293. https://doi.org/10.1016/j.jhydrol.2024.132293

Viviroli D, Zappa M, Gurtz J, Weingartner R (2009) An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools. Environmental Modelling & Software 24: 1209–1222. https://doi.org/10.1016/j.envsoft.2009.04.001