ISSN 2004-2965 Energy Proceedings, Vol. 24, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 864

Improving Pumped Hydro Storage (PHS) Flexibility in China

Leonardo Nibbi[1] (Corresponding Author), Paolo Sospiro[1], Maurizio De Lucia[1]

1 Department of Industrial Engineering, University of Florence, Italy

ABSTRACT

The decarbonisation targets of the People's Republic of China are ambitious, and their achievement relies on large-scale deployment of variable renewable energy sources (VRES), such as wind and solar. High penetration of VRES may lead to balancing problems on the grid, that can be compensated by increasing the shifting flexibility capacity of the system, i.e. installing additional electricity storage. Pumped Hydro Storage (PHS) is the most diffused electricity storage technology at the global level, and the only fully mature solution for long-term electricity storage. China has already the highest PHS capacity installed worldwide, and it is planning to strongly increase it before 2030. The present study, based on the data available from the "Pumped Storage Tracking Tool" of the International Hydropower Association, investigates the potential of technology improvement of the existing and future PHS fleet in China, aiming to the adoption of advanced PHS solutions able to better cope with the task of balancing the VRES production. Furthermore, policy recommendations are elaborated to promote, facilitate and support the adoption of these advanced PHS solutions.

Keywords: pumped hydro storage, grid balancing, flexibility, variable renewable energy sources, China, curtailment

NOMENCLATURE

Abbreviations	
PHS	Pumped Hydro Storage
PSP	Pumped Storage Plant
VRES	Variable Renewable Energy Sources
VSPS	Variable Speed Pumped Storage

1. INTRODUCTION

The long-term strategy adopted by the People's Republic of China includes pathways towards a fully decarbonised economy by 2060, as pledged by China's President Xi Jinping speaking at the UN General Assembly in September 2020.

One of the key elements to achieve carbon-neutrality is a large-scale deployment of renewable or zero-GHG-emissions electricity sources. The major expected increase is from the so-called Variable Renewable Energy Sources (VRES, mostly PV and wind) for direct and indirect electrification (e.g. via the use of synthetic gases, hydrogen, and liquids produced with electrolysers). On the other hand, the variability of PV and wind electricity production will substantially increase the need for flexibility.

In China, the rapid growth of wind and PV installations, mostly in the remote and poorly served northwest areas of China, is the main reason for VRES curtailment. As of 2020, China has reached the record wind capacity of 288GW (278GW on-shore, 10GW off-shore), and a solar PV capacity of 254GW [1], [2]. Following the Net-Zero pledge at 2060, more than 400 companies in the Chinese wind industry adopted the Beijing Declaration, in October 2020, aiming for 50 GW of annual wind installations from 2021 to 2025 and 60 GW from 2026 onwards, bringing, therefore, China's cumulative wind capacity to 800 GW by 2030 and 3,000 GW by 2060 [3]. This ambitious target will strongly increase the VRES share in the Chinese electricity mix. Additional shifting flexibility will then be necessary.

Energy Storage, as a tool to shift overproduction of non-programmable Variable Renewable Energy Sources (VRES), increases the Shifting Flexibility capacity of the system and will play a fundamental role in balancing the grid in the next decades.

Within all the available energy storage technologies, Pumped Hydro Storage represents a reliable resource for

Selection and peer-review under responsibility of the scientific committee of the 13_{th} Int. Conf. on Applied Energy (ICAE2021).

short, mid, and long-term electricity storage. It is presently the most diffused technology at the global level [4].

2. PHS OPERATION STATUS IN CHINA

Although being a latecomer in worldwide PHS deployment, in a couple of decades China overtook the former leader, Japan, in terms of installed capacity. Data regarding the global installed operational capacity in China are available from several different sources, the database "Pumped Storage Tracking Tool" of the IHA – International Hydropower Association [5], the "DOE OE Global Energy Storage Database" – GESDB [6], and the information available within official documents from the Chinese Government. These different sources present several discrepancies between them. The IHA database reports a total of 34 PSPs in operation in June 2019 for a total of 31.76 GW (turbine mode). This information has been updated within the present work, based on a survey performed in China, with three additional PSPs put in operation within the end of 2020 adding a further 3.16 GW to the installed capacity, then reaching a total of 34.92 GW provided by 37 plants. The GESDB database reports 33 Pumped Storage Plants (PSPs) in operation, providing a total capacity of 31.40 GW, while the latest information available from official documents such as the "Medium and Long-term Development Plan for Pumped Storage (2021-2035)" (NEA-Plan) issued in September 2021 [7] reports 34 PSPs with a total installed capacity of 32.49 GW (turbine mode), also discrepant with the other information available.

3. PHS DEVELOPMENT PLANS FOR CHINA

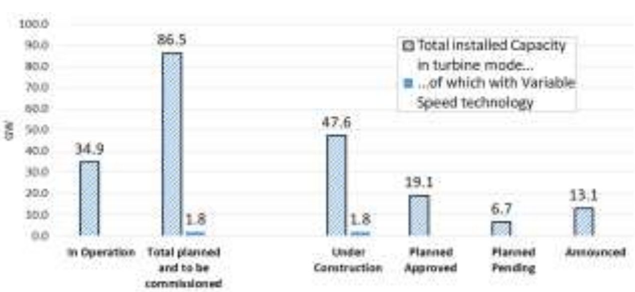

Fig. 1. PHS status in China 2020: operational and planned (left) and status detail of plants to be commissioned (right). Data elaborated and updated from [5]

The IHA Database is the only available source including detailed information both technical and about commission status for the PSPs that are under development. Four different implementation status categories are presently indicated for new plants: "Announced", "Planned - Pending Approval", "Planned - Regulator Approved", and "Under Construction". The IHA Database indicates that 47.6 GW of capacity is under construction, 25.8 GW are planned, and 13.8GW are announced. If all the planned new installations here reported will be commissioned, an additional 86.5 GW will be added to the fleet, theoretically bringing the Chinese PSPs capacity to around 120 GW within 2030 (see Fig. 1). These figures are quite conservative if compared with the more recent NEA-Plan, aiming to reach 200 GW installed PHS capacity within 2030, with the target to reach 300 GW installed capacity in 2035.

4. FLEXIBILITY STATUS OF CHINESE PHS

The flexibility that a PSP fleet can provide to the Electricity system is not only due to the amount of installed power capacity and energy storage but also to the capability of the single plant to follow the variable combination of system load and excess Variable Renewable Energy Source production both in turbine and pump mode. While hydraulic machines operating as turbines, regardless of their typology (e.g. Pelton, Francis, Kaplan etc.), can provide a certain degree of freedom in power regulation, this is not the case for the operation in pump mode. Apart from specific hydraulic machines (e.g. Dériaz pump-turbines), the standard fixed-speed configuration of PSPs pump operation does not allow for any regulation, except for the variation due to the change of head, that cannot be considered as a controllable parameter.

In the last decades, the growing need of the grid for ancillary services and to balance the stochastic and unpredictable short-term supply of electricity from renewables, requested from pumped storage power plants an increasing and challenging balancing and flexible role. Following these new operation challenges, PHS systems started therefore an evolution towards technical solutions specifically designed to provide additional operating flexibility to balance strong fluctuations in the system: Variable Speed Pumped Storage systems (VSPS) and Ternary Systems (TS) with hydraulic short-circuit have been designed and implemented, allowing for power regulation in both pumping and turbine mode, the latter being able of even finer frequency control [8]–[13].

The whole operational capacity of the Chinese PSP fleet is presently characterised by fixed-speed plants, while within the future operational plants only a few GW of installations are planned to be based on the more flexible, in terms of operating regime, solution of variable speed plants: only 1.8 GW to be commissioned in 2025 (Fengning Pumped Storage Power Station in Hebei Province) over the 67 GW already under construction or approved are designed for variable-speed (Fig. 1). No other planned plant is expected to be of any typology with advanced regulation capability. Therefore, PHS plants able to better deal with the flexibility issues represents nearly 2.7% of the capacity under commissioning.

The awareness of the importance of increasing PSPs flexibility in the Chinese fleet is grown in the very recent years, as also demonstrated by the attention given to the challenge in several published studies by Chinese researchers and scholars [14]–[22]. This awareness is also present within the NEA Plan. Although the plan has a strong focus on building PSPs with ultra-high head large-capacity energy storage units, one of the key tasks planned is to insist on the independent design and manufacture of specifically large-size variable-speed units.

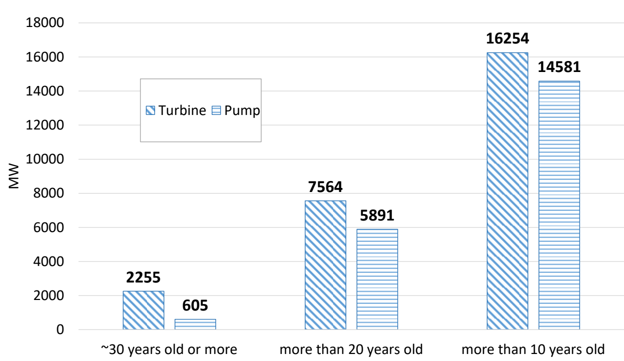

Fig. 1. Cumulative capacity of PHS in China by aging for plants commissioned until 2009. Source [5]

5. INCREASING PHS FLEXIBILITY IN CHINA

A huge potential for increasing the flexibility of PHS plants in China already exists, both for operating plants and planned new ones. This target can be achieved in two different ways: by upgrading the existing fleet that needs revamping at the end of the machinery life, and by redesigning future installations that are already planned.

Upgrading, revamping or full substitution of the whole pump-turbine unit is in general necessary after nearly 30 years of operation. In this case, the intervention can be carried out with the integration of variable speed units substituting the old fixed-speed ones. This increases the flexibility of the plant as well as increasing, in general, the operation head range, the efficiency of the whole cycle, and the resilience to the operation balancing VRES. Since it is necessary to operate on already existing spaces, the replacement of the old unit with a new one is the intervention that needs less creation of additional space in the cavern. For this reason, in general, upgrading with the installation of a Ternary Set with hydraulic short-circuit is more difficult and expensive to be carried out, therefore rarely considered.

The other available option is given by the re-thinking of the present technological strategies that are applied to the future installations. It is then important to verify if and in which case the schedule to commission allows future plants to undergo a redesign.

Assuming as not feasible to redesign the hydraulic machinery for plants already under construction, the possibility to change the design in the other cases should be investigated on a case-by-case basis, where this can be certainly considered easier for plants that were just announced, or where the approval from the regulating authority was not already obtained. It is also worth saying that, if we talk about new installations, there is also the possibility to choose the ternary set solution with a hydraulic short-circuit, since in most of these cases the underground works did not already start, therefore leaving the possibility to study alternative advanced solutions away from what already decided.

The analysis also considered the operating heads of the plants that could be a potential target of revamping or plans upgrade since this can be a limiting parameter for intervention. Worldwide, 12 variable-speed plants are presently in operation, 11 of them operating at heads below 600m, which can be considered the limit for a reversible Francis pump-turbine operation, as also known from the standard flow rate versus head diagrams available in the literature [23]. Only the Kazunogawa variable speed power station in Japan operates above this limit, with a maximum head of 714~785m. Therefore, the limit of 600m head is precautionarily assumed as the limit for the intervention.

6. RESULTS

The Chinese PSP fleet in operation nearly older than 30 years is quite limited, accounting for only 2.25 GW of turbine capacity (and 605 MW of pump capacity). Better opportunities open if plants older than 20 years are considered. In that case, the total capacity available for upgrading accounts for 7.6GW of turbines (and 5.9GW of pumps). A deeper technical investigation on this fleet could help to point out which are the units that, although not at the end of their operational life, may need a strong maintenance intervention due to particular causes, such as, for example, mechanical damages due to the frequent operation mode changes necessary to the VRES balancing needs. If the upgrading could interest also the plants older than 10 years, in that case, the set of units accounts for 16.2GW turbine mode and 14.6 pump mode, nearly half of the PHS capacity operating in 2020.

The present study identifies five different scenarios for the potential of intervention on the existing and future PSPs, aiming to increase their flexibility:

- High; PSPs older than 30 years, and future PSPs whose construction is only announced.
- Medium; PSPs between 20 and 30 years old, and future PSPs already planned but waiting for approval.
- Low; PSPs between 10 and 20 years old and future PSPs already planned that received approval.
- Unknown Potential; PSPs 10 years old or more operating with a head above 600m, and future PSPs announced or planned where the operating head is not known.
- No Potential; PSPs operating since less than 10 years, and future PSPs already under construction.

The results of the analysis are available in Tab. 1, where also the already under construction 1.8GW of the Fengning Pumped Storage Plant is considered.

	Capacity	% on Total
Existing/planned VSPSPs	1.8	1.5%
High Potential	8.1	6.6%
Medium Potential	8.8	7.2%
Low Potential	12.3	10.1%
Unknown Potential	26.0	21.4%
No Potential	64.4	53.1%
Total @2030	121.4	100.0%

Tab. 1. summary of flexibility potentials of PHS in China in 2030. Source [5] updated 2020

These figures are as a precautionary measure low since there is a lack of necessary information on nearly one-fourth of the planned installation that does not allow a safe evaluation of the possibility to adopt flexible solutions.

Therefore, apart from the potential of revamping plants already in operation, on paper, there is a non-negligible potential to improve the future flexibility of the Chinese grid with the re-thinking of technical solutions for the plants that will be commissioned in the present decade.

7. POLICY RECOMMENDATIONS

Based on the previous results, setting as of primary interest the strategy of increasing the flexibility of the future electrical system, some policy recommendations based on technology considerations can be elaborated.

Adding flexibility capability to a Pumped Hydro Storage plant results in increasing investment costs (CAPEX). The economic advantage of additional flexibility can result from the lower operation and maintenance costs (OPEX), thanks to the more efficient and safe operation while matching the variable load of the VRES scenario. These avoided costs can only partially cover the increase in CAPEX, therefore not fully justifying from the economic point of view the choice of adopting advanced technology solutions.

Although additional flexibility may not result in a direct economic benefit for the plant owner, it represents an asset for the whole system stability and safety. This additional service should be remunerated by the system, to balance the increasing costs, mostly CAPEX, incurred for the plant owner.

The policy regulator should therefore implement targeted market mechanisms aiming to remunerate the plant owner for the whole set of services provided to the system. Frequency regulation and control, voltage control and reactive power provision, contingency reserves (spinning and non-spinning) and system inertia provision should be remunerated, to cover the whole operation functions available from Pumped Hydro Storage.

Most of these ancillary services are difficult to be accurately measured and calculated. These market mechanisms should be integrated into a capacity market where PHS contributes to ensuring sufficient reliable capacity to the system when VRES are not able to provide power to the grid.

In China, the market mechanism presently in force is already partially in line with the suggested objectives, since part of the operating PSPs adopt the so-called "two-part tariff" scheme, which consists of a combination of a capacity-tariff and an energy-tariff. The capacity fee represents the remuneration for the ancillary services power system reserve, regulation, and black start. By the way, the ancillary services that can participate in the market for remuneration are limited and too few and do not represent the real value of the PHS whole operation services for the system [24].

The regulation issued by NDRC [25] goes in the direction of strengthening the capacity market for PHS: the calculation of the capacity tariff will be based on the principle of covering costs and provide reasonable returns to the plant, to achieve a balanced cash flow for the entire operating period (set in the to 40 years), and the capacity tariff approval mechanism will be improved to remunerate further ancillary services such as frequency regulation, voltage regulation, system backup and black start.

When implemented, these new mechanisms could help to achieve a fair remuneration of the PSPs all over its services provided to the system, giving an incentive to the adoption of advanced technological solutions to increase the flexibility of the plants.

Given the specific scenario of capacity already in operation in China, policies should also be elaborated to address permitting and authorisation barriers. Policy measures should support the revamping of existing plants when the intervention adds flexibility capability, whose implementation usually needs additional costs due to the additional space that must be excavated underground and to the installation of new machinery, and electrical and hydraulic equipment.

Regarding planned and under construction plants, further policy measures should support actions of re-design of the plant going in the direction of adding flexibility capacity. This is particularly important for all the plants who are already authorised, for which repeating even only part of the authorisation procedure with the new configuration could represent a too heavy additional burden and a non-sustainable delay in the schedule driving to commissioning.

8. CONCLUSIONS

The present study shows that a potential for increasing the flexibility of PHS plants in China by the adoption of Advanced PHS solutions already exists, by both upgrading the existing fleet that needs revamping, and by redesigning future installations that are already planned.

In a high potential scenario, 8.1% of the 121 GW fleet installed in 2030 could adopt advanced PHS, while in the low potential scenario the quota can reach 25.5%.

To cover the highest CAPEX necessary to the implementation of advanced solutions, targeted market mechanisms aiming to remunerate the plant owner for the whole set of ancillary services provided to the system must be adopted, while to ease revamping and redesign, policies should also be elaborated to address permitting and authorisation barriers.

ACKNOWLEDGEMENTS

The work is part of the activities of the project “Sustainable Hydropower Use and Integration in China and Europe” (SHUI-ChE). SHUI-ChE is a project supported by the European Commission through the Partnership Instrument (PI) under the “Water and Energy Nexus” focus area of the China Europe Water Platform (CEWP). The European Commission support for the production of this paper does not constitute an endorsement of the contents, which reflects the views only of the authors, and the Commission cannot be held responsible for any use, which may be made of the information contained therein.

REFERENCES

[1] GWEC, “Global Wind Report | Gwec,” Glob. Wind Energy Counc., p. 75, 2021, [Online]. Available: http://www.gwec.net/global-figures/wind-energy-global-status/.

[2] International Renewable Energy Agency (IRENA), Renewable capacity statistics 2021. 2021.

[3] GWEC, CREIA, and CWEA, “Beijing declaration on wind energy.” 2020.

[4] IHA, “Hydropower status report 2021,” London, 2021.

[5] M. Rogner and S. Law, “Pumped Storage Tracking Tool,” International Hydropower Association, 2019. https://www.hydropower.org/hydropower-pumped-storage-tool (accessed Jun. 24, 2019).

[6] U. D. of E. DOE, “Global Energy Storage Database,” 2020. https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/ (accessed Sep. 25, 2020).

[7] NEA, “Medium and Long-term Development Plan for Pumped Storage (2021-2035).” General Department of the National Energy Administration (NEA) of the People’s Republic of China (PRC), 2021.

[8] eStorage, “Potential for conversion of classical PSP to variable speed units in EU15 , Norway and Switzerland (EXTRACTS),” 2016. [Online]. Available: http://www.estorage-project.eu/.

[9] F. Teng, D. Pudjianto, M. Aunedi, and G. Strbac, “Assessment of future whole-system value of large-scale pumped storage plants in Europe,” Energies, vol. 11, no. 1, 2018, doi: 10.3390/en11010246.

[10] XFLEX HYDRO, “The Hydropower Extending Power System Flexibility (XFLEX HYDRO) project D2.1 Flexibility, technologies and scenarios for hydro power,” no. 857832, 2020.

[11] O. Alizadeh-Mousavi and M. Nick, “Stochastic Security Constrained Unit Commitment with variable-speed pumped-storage Hydropower Plants,” 19th Power Syst. Comput. Conf. PSCC 2016, 2016, doi: 10.1109/PSCC.2016.7540845.

[12] V. Koritarov et al., “Modeling Ternary Pumped Storage Units,” pp. 1–30, 2013.

[13] V. Koritarov, T. Guo, E. Ela, B. Trouille, J. Feltes, and M. Reed, “Modeling and Simulation of Advanced Pumped-Storage Hydropower Technologies and their Contributions to the Power System,” Proc. HydroVision, pp. 1–21, 2014.

[14] Y. W. Xu and J. Yang, “Developments and characteristics of pumped storage power station in China,” IOP Conf. Ser. Earth Environ. Sci., vol. 163, no. 1, 2018, doi: 10.1088/1755-1315/163/1/012089.

[15] J. Li, C. Yi, and S. Gao, “Prospect of new pumped-storage power station,” Glob. Energy Interconnect., vol. 2, no. 3, pp. 235–243, 2019, doi: 10.1016/j.gloei.2019.07.016.

[16] H. Zhang, M. Chen, Y. Peng, J. Zhou, and R. He, “Technology Summary on the Application of Variable-Speed Pump-Turbine Units for Wind Storage Operation,” in 2019 IEEE 3rd International Electrical and Energy Conference (CIEEC), Sep. 2019, pp. 232–235, doi: 10.1109/CIEEC47146.2019.CIEEC-2019123.

[17] W. Yang and J. Yang, “Advantage of variable-speed pumped storage plants for mitigating wind power variations: Integrated modelling and performance assessment,” Appl. Energy, vol. 237, no. December 2018, pp. 720–732, 2019, doi: 10.1016/j.apenergy.2018.12.090.

[18] H. Wang and Z. Ma, “Dynamic characteristics of pumped storage unit based on the full-size converter,” E3S Web Conf., vol. 233, p. 03065, Jan. 2021, doi: 10.1051/e3sconf/202123303065.

[19] Y. Yang, L. Xiang, X. Guo, and Y. Zheng, “Introducing LADRC to Load Frequency Control Model with Pumped Storage Power Station Considering Demand Response,” Proc. - 2019 Chinese Autom. Congr. CAC 2019, pp. 610–615, 2019, doi: 10.1109/CAC48633.2019.8997377.

[20] H. Li, G. Li, B. Yang, and L. Ji, “Research on variable speed operation of static frequency converter for pumped storage units,” 2021, vol. 02022, pp. 0–4.

[21] B. S. Zhu and Z. Ma, “Development and Prospect of the Pumped Hydro Energy Stations in China,” J. Phys. Conf. Ser., vol. 1369, no. 1, 2019, doi: 10.1088/1742-6596/1369/1/012018.

[22] Z. Ming, F. Junjie, X. Song, W. Zhijie, Z. Xiaoli, and W. Yuejin, “Development of China’s pumped storage plant and related policy analysis,” Energy Policy, vol. 61, pp. 104–113, 2013, doi: 10.1016/j.enpol.2013.06.061.

[23] A. Morabito, G. de Oliveira e Silva, and P. Hendrick, “Deriaz pump-turbine for pumped hydro energy storage and micro applications,” J. Energy Storage, vol. 24, no. April, p. 100788, 2019, doi: 10.1016/j.est.2019.100788.

[24] F. Zhang, Z. Xu, B. Jiao, and J. Feng, “Study on pricing mechanism of pumped hydro energy storage (PHES) under China’s electricity tariff reform,” E3S Web Conf., vol. 38, 2018, doi: 10.1051/e3sconf/20183804016.

[25] NDRC, “Views on Further Improving the Price Formation Mechanism for Pumped Storage Energy.” National Development and Reform Commission, People´s Republic of China, 2021.

