energies

Article

Improving Pumped Hydro Storage Flexibility in China: Scenarios for Advanced Solutions Adoption and Policy Recommendations †

Leonardo Nibbi [1,*], Paolo Sospiro [1], Maurizio De Lucia [1] and Cheng-Cheng Wu [2]

1 Department of Industrial Engineering, University of Florence, Via S. Marta, 3, I-50139 Florence, Italy
2 International Hydropower Association, One Canada Square, London E14 5AA, UK
* Correspondence: leonardo.nibbi@unifi.it

† This paper is an extended version of the paper published in the Proceedings of the International Conference on Applied Energy 2021, Thailand/Virtual, 29 November–5 December 2021.

Abstract: The decarbonisation targets of the People's Republic of China are ambitious. Their achievement relies on the 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, which can be compensated by increasing the shifting flexibility capacity of the system by integration with energy storage, e.g., by 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 already has the highest PHS capacity installed worldwide and plans to increase it strongly before 2030. The present study, based on the data from the "Pumped Storage Tracking Tool" of the International Hydropower Association, investigates the potential for technological improvement of the existing and future PHS fleet in China. The aims of adopting advanced PHS solutions allow China to better cope with the task of balancing the VRES production. The potential for adopting advanced PHS solutions is evaluated through five different intervention possibilities (here referred to as scenarios). These scenarios consider revamping part of the operational Pumped Storage Plant (PSP) fleet and redesigning future installations that are already planned. As a result, considering all the major technical and authorisation process constraints, 4.0% (5.2 GW) of the 132 GW fleet expected to be commissioned before 2035 could additionally adopt advanced PHS in a high-potential scenario. Meanwhile in the medium and low potential scenarios, the quota can reach 11.1% (14.6 GW) and 26.2% (34.5 GW), respectively. Furthermore, policy recommendations are elaborated to promote, facilitate, and support the adoption of these advanced PHS solutions.

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

check for updates

Citation: Nibbi, L.; Sospiro, P.; De Lucia, M.; Wu, C.-C. Improving Pumped Hydro Storage Flexibility in China: Scenarios for Advanced Solutions Adoption and Policy Recommendations. *Energies* **2022**, *15*, 7918. https://doi.org/10.3390/en15217918

Academic Editor: Helena M. Ramos

Received: 19 September 2022
Accepted: 17 October 2022
Published: 25 October 2022

1. Introduction

The long-term strategy adopted by the People's Republic of China includes pathways toward 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 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 shifting flexibility, meaning shifting surplus feed-in of renewable energy to periods with positive residual load and vice-versa [1–3].

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

2021, China has reached a record wind capacity of 329 GW (303 GW on-shore, 26 GW off-shore) and a solar PV capacity of 306 GW [4,5]. 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 3000 GW by 2060 [6]. Furthermore, the "Medium and Long Term Development Plan for Pumped Storage" issued by the Chinese Government [7] states that by 2030 the total installed capacity of wind and solar power generation in China is expected to reach over 1.2 TW of installed capacity. All these ambitious targets will strongly increase the VRES share in the Chinese electricity mix. Additional shifting flexibility will then be necessary.

Energy storage, a tool to shift the 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 short, mid, and long-term electricity storage. It is presently the most diffused technology at the global level. In fact, according to the 2022 Global Hydropower Report released by the International Hydropower Association (IHA), by the end of 2021, the global installed capacity of pumped storage has reached 165 GW (3.6% increase on 2021), accounting for more than 90% of the global stationary electricity storage capacity [8–10].

The present study investigates the potential of technological improvement of the existing and future PHS fleet in China, aiming to adopt advanced PHS solutions that can better cope with balancing the VRES production task. The potential for adopting advanced PHS solutions is evaluated through five different intervention scenarios, considering both the revamping of part of the Pumped Storage Plant (PSP) fleet presently in operation and redesigning, when possible, future installations that are already planned.

Similar assessments have already been performed during the implementation of the European-funded projects eStorage ([11], concluded) and XFLEX HYDRO ([12], presently ongoing). These projects specifically target selected existing power plants, first evaluating the technical feasibility of the revamping operation and then carrying out the intervention on the plants under study. The project eStorage additionally assessed the potential for revamping old Plants to advanced PHS solutions in 17 European countries. This is carried out after a detailed study of the configuration of each investigated plant operating in the chosen European countries, including the hydraulic circuit, mechanical and electrical components, and the control system.

The present work is part 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) [13]. The project aims to stimulate business and technology exchange, policy dialogue, joint research, and innovation opportunities about the role of hydropower in shared power systems as an enabler for the deployment of intermittent power generation technologies such as wind and solar power. In line with the project's objectives, the present work considers the European experiences in the field, such as the previously cited EU-funded projects, to transfer the major results to the People's Republic of China scenario.

In comparison with what was performed in the EU studies, in particular in the eStorage project, the proposed methodology developed a simplified approach relying on a limited number of parameters such as Age, Net Head, and implementation status, which allows a pre-screening of the most interesting opportunities using information from databases such as the "Pumped Storage Tracking Tool" developed by the International Hydropower Association" [14]. The data necessary to replicate the study in any area at the global level is here available for retrieving. In addition, the present study also considers the possibility of intervening in planned future installations to shift to Advanced PHS solutions.

Given the nature of the SHUI-ChE project and the current plans for PHS capacity expansion in China, the present work applies the methodology to the Chinese scenario, including the possibility of redesigning the future installations that are presently planned. Furthermore, policy recommendations are elaborated to promote, facilitate, and support the adoption of these advanced PHS solutions.

2. Flexible Operation of Pumped Hydro Storage

Pumped Hydro Storage (PHS) plants are electric energy storage systems based on hydropower. They operate by connecting two or more reservoirs with a hydraulic head. The lower and upper reservoirs are connected through tunnels or penstocks. They are also usually referred to as Pumped Hydro Energy Storage (PHES) plants, Pumped Storage Hydropower (PSH) plants, or Pumped Storage Plants (PSP) and, in their most simple and basic configuration, are based on the connection of two different reservoirs, an upper and a lower one. For the concept explanation, we will refer to this basic configuration, represented in Figure 1.

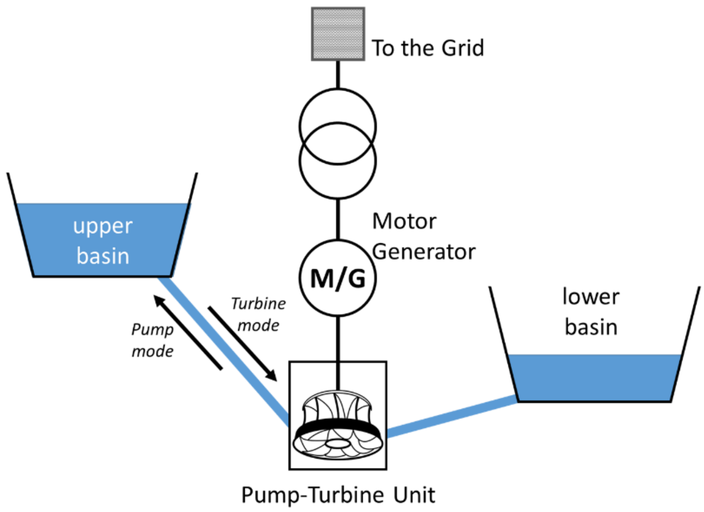

Figure 1. Basic concept of Pumped Hydro Storage.

A PHS plant operates thanks to the exchange of water between the two reservoirs. In production mode, also known as turbine mode, the plant operates like a conventional hydroelectric plant: water is released from the upper reservoir. It passes through the turbines to generate electricity. In pumping mode, electrical power from the grid is used to pump the water from the lower reservoir to the upper one, thus storing electric energy as potential energy in the form of elevated water for on-demand generation. PHS storage efficiency is the highest available for large-scale energy storage systems, ranging between 75% and 80% in most cases, depending on the plant design and configuration [15,16]. Only older design PHS plants can have an overall efficiency as low as 60% while the most recent configurations with variable-speed pumps can reach efficiencies up to 85% [17,18].

A general classification of the configuration of the power plant set adopted for pumping systems can be made based on the number and arrangement of the different machines (pump-turbines) composed of the system. Three main configurations are usually identified: binary sets, ternary sets, and quaternary sets (Figure 2). Binary sets are presently the most implemented solution. A unique pump-turbine device changes the operation mode through the inversion of the sense of rotation. The standard configuration is based on a reversible Francis pump-turbine, but solutions also exist based on Kaplan or Dériaz turbines designed to operate as pumps. Ternary sets are designed as separate pump and turbine devices sharing the same shaft, usually connected through a clutch. The sense of rotation remains the same in both pump and turbine mode, thus allowing, in general, faster changes from the turbine to pump mode and conversely. Quaternary sets design is characterised by fully decoupling pump and turbine units. In this configuration, each device, either pump or turbine, can be better optimised to fit the requested operation necessities and can operate fully independently from the other.

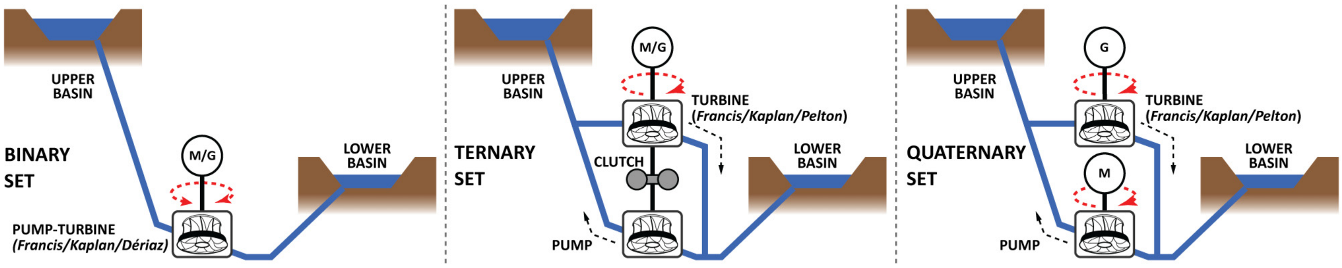

Figure 2. Classification of the configuration of the PHS Plant based on the number and arrangement of the different machines (pumps/turbines) of which the system is composed: Binary, Ternary, and Quaternary Set.

The flexibility that a Pumped Storage Plant (PSP) fleet can provide to the Electricity system depends not only on the amount of installed capacity and energy storage, it also relies on the capability of the single plant to follow the variable combination of system load and excess Variable Renewable Energy Source (VRES) 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 [19–24]), 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 for 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, has an increasing and challenging balancing and flexible role. Following these new operation challenges, Pumped Hydro Storage (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) for binary sets and Ternary Systems (TS) with hydraulic short-circuit, described in [25]—have been designed and implemented, allowing for power regulation in both pumping and turbine mode, the latter being capable of even finer frequency control [26–29].

As a matter of example of the different behaviour of fixed- and variable-speed operation, Figure 3 compares the load following capacity of a power station equipped with two conventional units and one equipped with two variable-speed units (power regulation range in pump mode per single unit: 70~100%), during the pump mode operation following a surplus power to be stored in the PSP [30]. On the left side, the powerhouse equipped with a fixed-speed configuration cannot properly follow the surplus power curve, leaving a non-negligible amount of energy not possible to be stored (probably left to curtailment). The same surplus power curve is a better fit adopting a two-unit power station with variable-speed capability (centre). On the right, the overlap of the two curves shows (light blue) the energy that the two-unit fixed-speed is not able to store in the PSP due to the lack of flexibility.

The solutions presently adopted to provide variable speed to pump-turbine binary sets are based on two different main technologies for the motor-generator: Doubly Fed Induction Machines (DFIM) and Full Converter Synchronous Machines (FCSM) [31]. In the DFIM electric machine, the stator is directly connected to the grid. In contrast, the rotor windings are connected via a power electronic converter using slip rings, providing a variable frequency. Therefore, changing the rotor current frequency makes it possible to have the variable-speed operation of the mechanical part while maintaining the grid frequency at the stator output/input. In the Full Converter Synchronous Machine (FCSM) configuration, the motor-generator frequency and the grid frequency are decoupled, connecting the machine to the grid via a Full-Rated Converter (FRC). The fixed frequency Alternate Current (AC) provided by the grid is converted into Direct Current (DC) and then into variable frequency AC again for the synchronous motor-generator. Therefore, the rotor is now able to rotate with variable and controllable speed. A comparison of the power regulation ranges in turbine and pump modes for different technical solutions at the design head is presented in Figure 4, elaborated from [32,33].

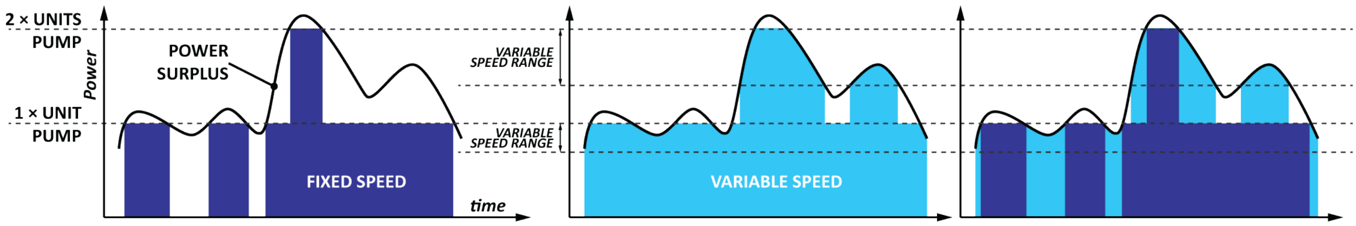

Figure 3. Power surplus utilisation with multiple units in pump mode (example with two units): Fixed-Speed units (**left**), Variable-Speed units (**center**), comparison (**right**).

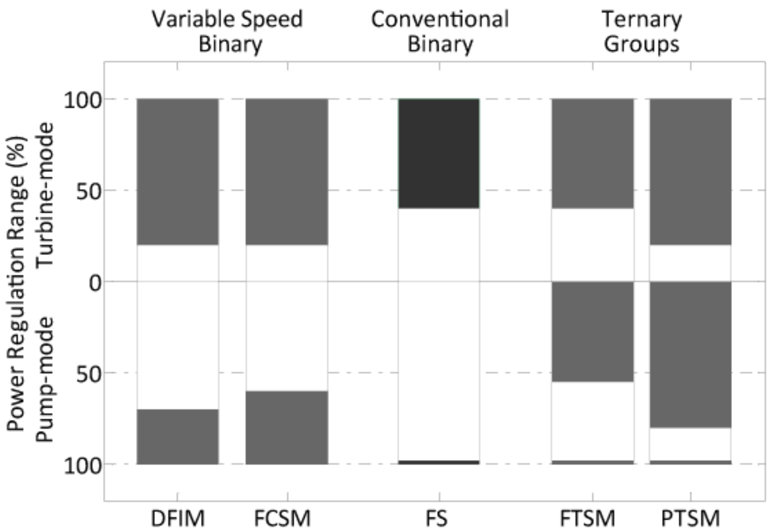

Figure 4. Comparison of power regulation ranges in turbine and pump modes for different technical solutions at the design head. FS: Conventional Fixed-Speed Synchronous Machine; DFIM: Double Fed Induction Machine; FCSM: Full Converter Synchronous Machine; FTSM: Francis Ternary Synchronous Machines with Hydraulic Short Circuit; PTSM: Pelton Ternary Synchronous Machines with Hydraulic Short Circuit.

The choice of the best solution from a technical point of view is generally a trade-off between the costs of the intervention and the operation needs. Despite the additional costs incurred, a recent publication by [34] discusses the results of case studies on the Pan-European system. This example demonstrates that variable-speed Pumped Hydro Storage could further enhance the positive effects of PHS on the total system cost in a scenario with a high share of renewables. The gain on the system's long-term benefits has been evaluated in an additional 10~20% range. Further studies and technology reviews are available comparing the different available solutions, showing the general advantages of the variable-speed technology, either binary or ternary groups with hydraulic short circuits, compared to the standard fixed-speed.

An important parameter related to the PSP operation is the time needed to transition from one operation mode (e.g., turbine mode) to another (e.g., pump mode). The mode change times for the solutions presented here are summarised in Table 1, which is intended for general comparison purposes only since these values differ depending on the plant's specific configuration and the installed machinery [28,33].

Table 1. Comparison of mode change times (in seconds) for various operating concepts. Synchronous Condenser Mode: the runner is rotating in air and the motor-generator supplies reactive power to the grid.

Mode Change in Seconds			Conventional Fixed-Speed	Fast Response Conventional Fixed-Speed	Variable-Speed DFIM	Francis Ternary Set with Short Circuit	Pelton Ternary Set with Short Circuit
Standstill	to	Turbine	90	75	90	90	65
Standstill	to	Pump	340	160	230	85	80
Synchronous Condenser	to	Turbine	70	20	60	40	20
Synchronous Condenser	to	Pump	70	50	70	30	25
Turbine	to	Pump	420	240	470	45	25
Pump	to	Turbine	190	90	280	60	25

The longest transition times are for the change from the pump to turbine mode (and vice-versa) for binary units. This is due to the necessary change in the verse of rotation of the machine: the unit must stop, and the motor-generator disconnected before changing the operation mode. Additionally, changing from standstill to pump mode requires more time since the unit must be discharged from the water before starting to rotate in the air until it further reaches the operating rotational speed. Fixed-speed binary units exist and adopt special features allowing shorter mode change times (fast response conventional fixed-speed in the figure). This is the case, for example, of the two synchronous units of Goldisthal PSP (Germany) coupled with two variable-speed units in the same power station. Considering Ternary sets with Hydraulic Short circuits, their major advantages are evident in the mode change between turbine and pump mode, in both senses, since it is not necessary to invert the rotational verse of the machine. This leads to a strong decrease in the change times, which is extremely evident compared to conventional fixed and variable-speed binary sets.

Based on the literature review targeting reversible binary units, a general overview of the benefits of variable-speed operation for both power systems and hydropower facilities is available in [31,35]. At the same time, Ref. [36] compares the pros and cons of fixed-speed and variable-speed technologies, stating that no solution is one-size-fits-all. By means of studying the feasibility of introducing an Adjustable Speed Pumped Storage generation system to the Asian region, Refs. [37,38] gives a comprehensive overview of the main characteristics of advanced PHS solutions. By improving the modelling representation of advanced PHS and conventional plants in power system and electricity market models, the report [39] quantifies the technical capabilities of advanced PHS. It analyses various grid services, the value of these services under different market conditions, and levels of variable renewable generation in the system. It also provides information on the full range of benefits and value of PSPs. While comparing different solutions based on the situation in Europe and the U.S., Ref. [33] states that the energy generation and supply business is dynamic, influenced by politics, incentives, supply and demand, weather experiences, and the overall state of the economy. This means that the factors that influence costs and economic returns of pumped storage equipment, thus the specifically adopted solutions, may change with the change of the previously cited political and economic factors. Through simulations, Ref. [32] demonstrates that, for the variable-speed PHS, operation costs are effectively lower than for fixed-speed, also benefiting from the higher flexibilities of their units. A quantitative modelled comparison between variable-speed and fixed-speed units conducted through four indicators based on ancillary service compensation is presented in [40], showing that variable units outperform the fixed-speed by one order of magnitude in the aspect of regulation performance. Paper [41] shows how ternary and variable-speed units offer various advantages compared to classical fixed-speed reversible pump-turbines. Meanwhile, Ref. [42] is more peremptory in stating that for hydropower units to provide a fast responding service, variable-speed solutions must be used; their increased complexity is thus compensated with the additional new features gained. Regarding system inertia, Refs. [41,42] also point out the positive flywheel effect of the generator, allowing to operate the unit to have an extended range of output, compensating for the loss of system inertia of variable-speed binary sets that are discussed in [36]. Papers [43–45] show technical data presenting the advantages of the Converter Fed Synchronous Machine for variable-speed PHS, such as installing the frequency conversion unit without impacting the plant's operation and with limited use of the space.

Recent Research, Networking, and Technology Transfer Activities

In the last decade, following the new balancing needs due to the VRES penetration, several studies were performed in Europe, supported mainly by the EU Commission funding programs, aiming to study the technical and economic value of flexible pumped storage operation and to challenge the technical issues of variable speed and flexible operation of pump-turbine systems.

The project "eStorage" (2012–2017), supported by the European Commission (Directorate-General for Research) in the frame of the "7th Framework Programme Cooperation: Energy", aimed to improve energy management by developing a solution for cost-effective integration of intermittent renewable energy generation into the electrical grid [11,34]. The project aimed to demonstrate the feasibility and benefits of converting EDF's Le Cheylas (France) fixed-speed pumped hydro storage into a variable-speed pumped hydro storage, together with an analysis of the market and regulatory frameworks in Europe, in order to propose changes supporting appropriate business models for flexible energy storage. In particular, deliverable 4.1 [26] reported the study's results of the potential for classical PSP converted to variable-speed units in EU15, Norway, and Switzerland. These are the most important European countries in terms of installed PHS, with the long-term objective of enabling the conversion of over 75% of European fixed-speed pumped hydro storage.

The project XFLEX HYDRO (2019–2023) is funded through the European Union's Horizon 2020 research and innovation programme [12]. The innovation project aims to demonstrate how countries and regions can be helped in meeting their renewable energy targets through the implementation of additional flexible hydro assets. The aim is to demonstrate new hydropower technologies, including a battery-turbine hybrid, advanced smart controls, and enhanced variable- and fixed-speed pump-turbine systems. The work will deliver a roadmap outlining the market and policy challenges for governments, regulators, and industry. This roadmap is intended for the European hydropower fleet, aiming to increase the adoption of these solutions and prepare their impact assessment. Seven hydropower plants are subject to seven different interventions to study how to increase plant flexibility with advanced technologies. Four of the plants under study are PSPs: Z' Mutt (CH), Frades 2 (PT), Grand Maison (FR), and Alqueva (PT). The project also elaborates an Ancillary Services Matrix based on the demonstration sites, obtained by combining the most recent power balancing/ancillary services products, the emerging market supporting mechanics associated with them, and the hydropower technologies under evaluation [46].

The Project HydroFlex (2018–2022) aims to enable hydropower plants to utilise their full power and storage capability by operating with very high flexibility [47]. This objective is achieved through scientific and technological breakthroughs by performing targeted research and innovation activities on the key bottlenecks of hydropower units. Such bottlenecks restrict the operating range of the units, thus limiting their flexibility capabilities. The Horizon 2020 Programme supports the project that is creating the environmental, social, and technical basis for its targets. Some of the project's results related to the flexibility of the turbine, have already been published [48–52].

At the global level, the International Forum on Pumped Storage Hydropower (IFPSH) was launched in November 2020 by the International Hydropower Association. The Forum, chaired by the U.S. Department of Energy, brought together governments, industry, financial institutions, academia, and NGOs. During the activities, these stakeholders shared their experiences and built best practices, intending to shape and enhance the role of PHS in future power systems [53]. The forum was attended by 13 governments (USA, Austria, Brazil, Colombia, Estonia, Greece, India, Indonesia, Israel, Morocco, Norway, Sri Lanka, and Switzerland), several international financial institutions, and over 70 organisations. Within these organisations, leading energy companies such as EDF, GE Renewable Energy, Voith, and Hydro Tasmania, were included. The activity of the forum was organised in working groups. At the end of the work, the "Capabilities, Costs, and Innovation Working Group" issued the final report titled "Innovative Pumped Storage Hydropower Configurations and Uses". The report shows that thanks to the latest technological advancements it is possible to enhance, with viable costs, the performance and flexibility services provided by existing PHS. The use of variable-speed pump-turbines or hydraulic short circuit is included in the available technological advancements [54].

3. Methodology

The present work aims to investigate the potential of technology improvement of the existing and future PHS fleet in China, aiming to adopt 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.

Given the present status of the implementation of PSPs in China, the adoption of advanced PHS solutions can be achieved in two different ways:

1. by upgrading
    a. the existing fleet that needs revamping at the end of the machinery life, or
    b. the units that, although not at the end of their operational life, may need a strong maintenance intervention due to causes, such as, for example, mechanical damages due to the frequent operation mode changes necessary to the VRES balancing needs, and
2. by redesigning future installations that are already planned.

For plants presently in operation, upgrading, revamping, or fully substituting the whole pump-turbine unit is generally 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 an intervention that needs less creation of additional space in the cavern. For this reason, upgrading with installing a Ternary Set with hydraulic short-circuit is more difficult and expensive to carry out, therefore it is rarely considered.

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

Assuming it is not feasible to redesign the hydraulic machinery for plants already under construction, the possibility of changing the design in the other cases should be investigated on a case-by-case basis. It can certainly be considered easier for plants that were just announced or where approval from the regulating authority was not already obtained. It is also worth saying that, if we talk about new installations, there is 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 advanced alternative solutions away from what already decided.

The present analysis also considers the operating heads of the plants that could be a potential target for revamping or planning upgrades since this can be a limiting parameter for intervention. Worldwide, 13 variable-speed plants are presently in operation, the majority (10) operating at heads below 600 m. It can, in many cases, be precautionarily 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 [21] and presented in Figure 5. However, the Kazunogawa variable-speed power station in Japan operates above this limit, with a maximum head of 714~785 m, as well as Omarugawa (Japan, 672 m), and Limmern (Switzerland, 623 m) [14,55]. Thus, the limit of 600 m head will be considered as a potential additional constraint, and it will be considered while discussing the results. The list of VSPS presently in operation is presented in Table 2.

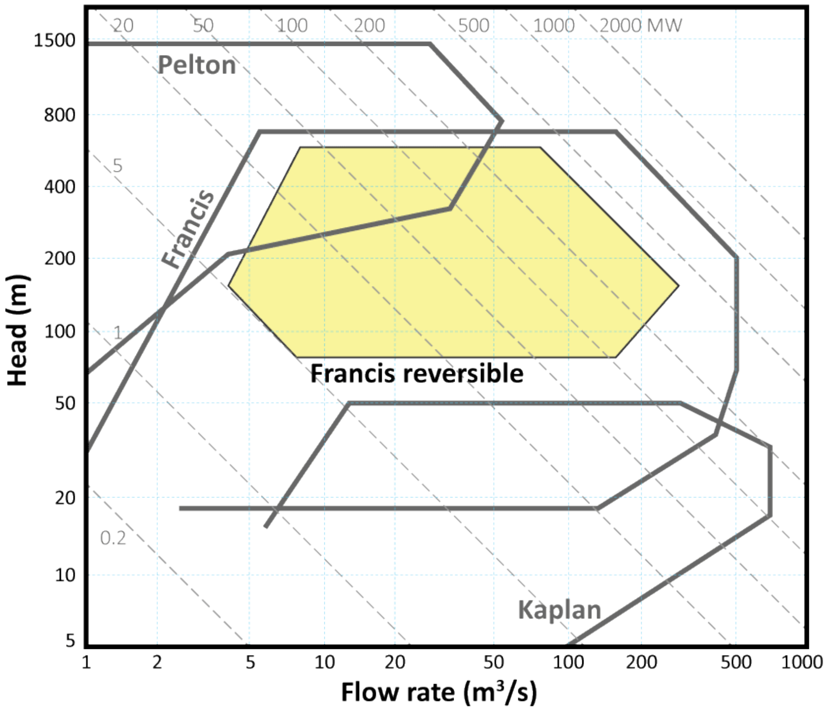

Figure 5. Diagram of flow rate over the head for the most common hydraulic turbines.

Table 2. Variable-Speed Pumped Storage Plants presently in operation at the global level. Japanese names of plants in Japan are presented as a reference within brackets. Gray cell background is for plants whose maximum head is beyond 600 m. (*) Nant de Drance was commissioned in July 2022.

Plant Name/Country	Power in Turbine Mode (MW)	Max Head (m)
Yagisawa–(矢木沢)/Japan	240	94
Takami (Koken)–(高見)/Japan	200	105
Cheylas (Le)/France	500	256
Goldisthal/Germany	1060	302
Okutataragi–(奥多々良木)/Japan	1932	388
Okochi (Okawachi)–(大河内)/Japan	1280	395
Grimsel 2/Switzerland	348	397
Frades II/Portugal	780	420
Nant de Drance/Switzerland(*)	900	425
Avce (Avče)/Slovenia	185	521
Limmern/Switzerland	1000	623
Omarugawa–(小丸川)/Japan	1200	672
Kazunogawa–(葛野川)/Japan	1200	714

Therefore, following the proposed approach, in order to calculate the potential for flexibility increase, the present study identifies five different scenarios for the intervention on the existing and future PSPs. For the plants presently in operation, the criterion is based on the age of the plant from the commissioning year. In contrast, for future installations, the criterion is based on the state of advancement of the path to commissioning. The five scenarios are described in the following.

1. High Potential Scenario; this scenario considers:
    a. PSPs in operation that are older than 30 years, thus the cases where a major revamping is likely to be necessary, and
    b. planned future PSPs whose construction is only announced, making then possible to intervene with major design changes, including the possibility to switch to TS solutions with Hydraulic Short Circuit.
2. Medium Potential Scenario; this scenario considers:
    a. PSPs between 20 and 30 years old, where a revamping may be necessary due to the combination of ageing and the possible damages due to the modern use of VRES balancing, and
    b. future PSPs already planned but still waiting for approval, where major changes could lead to delays in the approval path, thus delaying the whole path to commissioning.
3. Low Potential Scenario; this scenario considers:
    a. PSPs between 10 and 20 years old, where a revamping may be necessary due to wear and tears caused by the modern use of VRES balancing, needing a deep case-by-case evaluation, and
    b. future PSPs already planned that received approval, where major changes in the design could lead to the need to go back again all through the approval process, thus causing major delays that are critical to the path to commissioning.
4. Unknown Potential Scenario; this scenario considers the maximum head as an additional constraint to the previous scenarios. Where the operating head is unknown or above 600m, the potential is marked as unknown. A case-by-case specific evaluation is here necessary.
5. No Potential Scenario; this scenario considers all the other cases where revamping or major redesign is not likely to be implemented, as previously discussed, e.g.,:
    a. PSPs operating for less than 10 years, and
    b. future PSPs that are already under construction.

An evaluation will also be performed not considering the maximum head constraint. An analysis of the available information to perform the evaluation has been conducted in order to select the most appropriate database to be used.

4. Pumped Hydro Storage in China: Needs, Present, and Future

4.1. Variable Renewable Energy Sources Production Curtailment in China

Electricity curtailment is the reduction in the generation below what a system of well-functioning power plants is capable of producing. It is activated when the safe operation of the electricity production and distribution system is threatened or when local transmission lines cannot absorb additional power. Regarding China, wind and solar PV energy curtailment figures in the period 2011–2019 (wind) and 2015–2019 (solar PV) are presented in Figures 6 and 7 [56–60].

Although it represents a significant loss in economic and energy efficiency, curtailment is one of the three basic types of flexibility provision available for an electricity network concerning residual (positive or negative) load smoothening: Downward, Shifting, and Upward Flexibility [2,3]. Curtailment belongs to the latter category (Upward Flexibility), and it is generally associated with Variable Renewable Energy Sources, i.e., solar energy (e.g., Photovoltaics) and wind energy. Curtailment can represent a flexibility option because studies are available showing that, depending on the system configuration, integrating the available feed-in from VRES plants is not always the most efficient solution from a system perspective, both from the economic or environmental point of view [3,61].

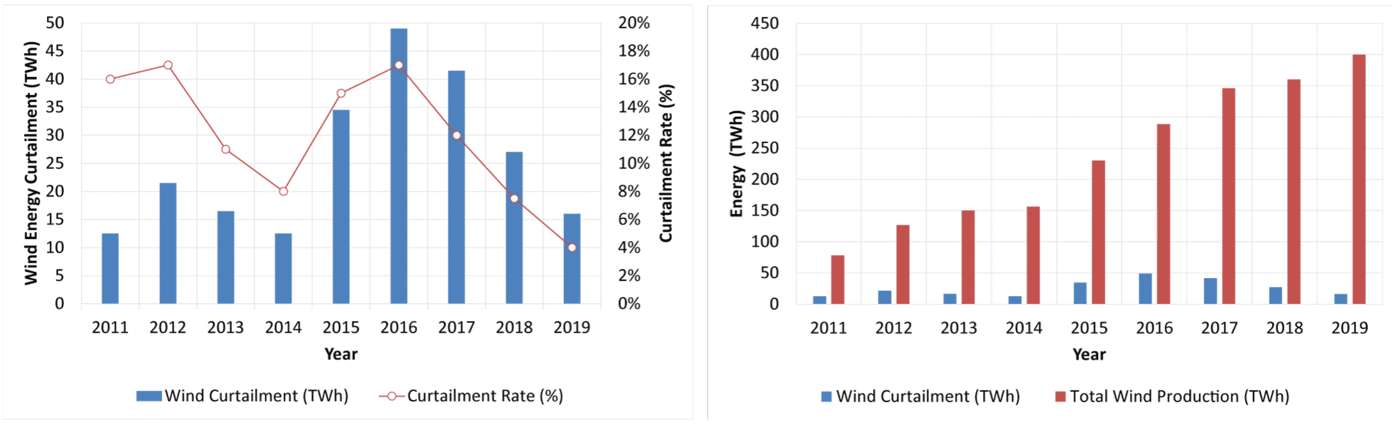

Figure 6. Wind energy curtailment in China 2011–2019: curtailed energy production and curtailment rate (**left**), curtailment compared to total wind energy production (**right**). Source: [56–60].

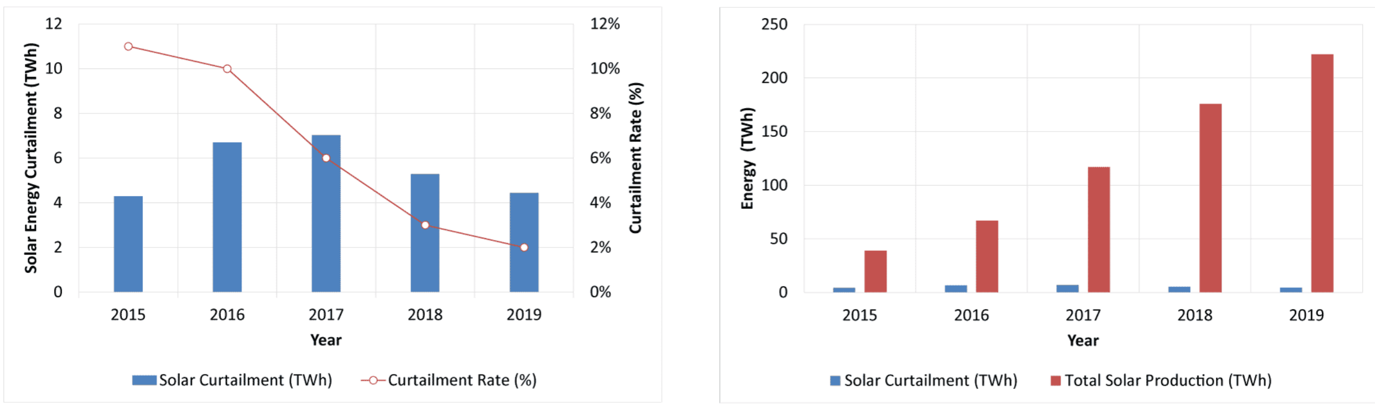

Figure 7. Solar PV energy curtailment in China 2015–2019: curtailed energy production and curtailment rate (**left**), curtailment compared to total solar energy production (**right**). Source: [57–59].

Variable renewable energy curtailment represented a serious problem for China in the 2010s. Wind energy curtailment reached a global average of 17% in 2016 (Figure 6) while around 11% of solar energy was curtailed in 2015 (Figure 7). Considering the economic impact, during the period 2011–2017, the costs of curtailment have been evaluated at around 1 B$ [62,63].

The main reason for the presented curtailment rates in the mid-2010s is mostly due to the rapid growth of wind and PV installations in the remote northwest areas of China, poorly served by grid links. Meanwhile, most electricity demand is located in the southeast coast's populated and industrialised urban areas.

Apart from the political decisions supporting renewable expansion, the strong increase in VRES penetration has also been boosted by economic factors. In the period 2012–2017, solar construction costs in China fell 45%, and wind project costs dropped 20%. This is stated in a report from China's National Reform and Development Commission (NRDC) issued in January 2019. As a consequence, the subsidy system has been updated, and some wind and PV projects were able to go ahead subsidy-free.

Therefore, the rush to the deployment of wind and PV overwhelmed the Chinese grid system, thus causing the loss of not negligible amounts of renewable energy production. The first response to this was a slowdown in the planned installations, thus allowing grid operators to have the necessary time to raise the transmission capacity to reduce the lost energy [64,65]. Apart from the lack of transmission capacity compared to the high renewable energy installed capacity, large-scale thermal power plants with very low flexibility are another important reason for the problem [58].

The decrease in the curtailment rate experienced after 2016 cannot just be expected to be also maintained during the 2020s if no strong action is put in place. In fact, a strong increase in the VRES penetration is expected in the incoming years, due to both policy and market reasons, such as, for example, the expected actions following the Chinese long-term strategy toward a fully decarbonised economy by 2060 pledged by China's President Xi Jinping in September 2020.

4.2. PHS Implementation Status in China

Although a latecomer in worldwide PHS deployment, China overtook the former leader, Japan, in terms of installed capacity in a couple of decades. The development followed several changes in the regulatory regime. Until 2004, PHS facilities were built by local governments and grid companies. However, after the 2002 reform of the Chinese Power Sector that created two state-owned grid companies and five power generation corporations, the National Development and Reform Commission promulgated a regulation specifying that PHS plants are transmission facilities. Therefore, since 2004 their construction, commissioning, operation, and management, were due to the grid companies [18,66–68].

In recent years, the National Development and Reform Commission (NDRC) of the People's Republic of China has gradually established and improved the mechanism of the formation of pumped storage tariffs. Such an action played an important role in promoting the sound development of PSPs. Still, with the accelerated reform of the electricity market, it has also faced problems such as insufficient convergence with market development and inadequate incentive [69,70].

The five stages of PHS development in China are represented in Figure 8.

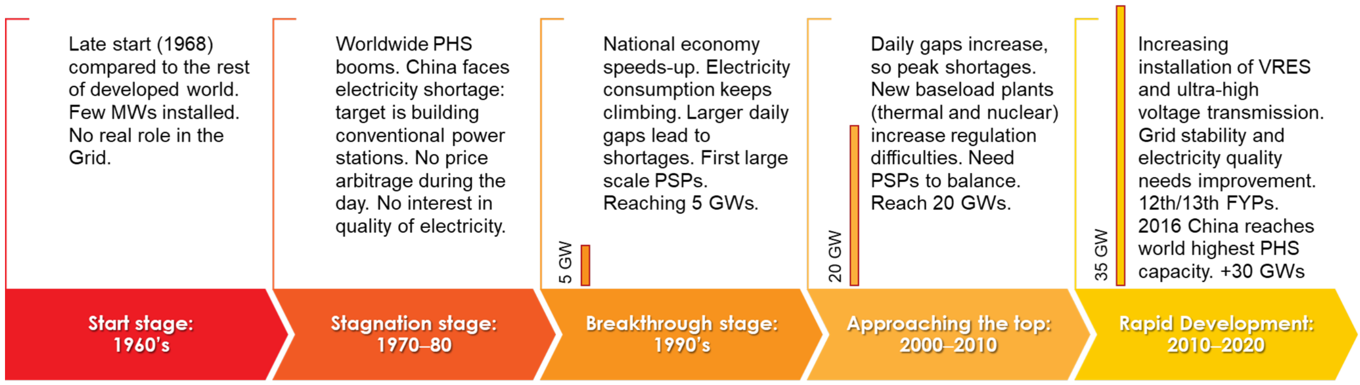

Figure 8. The five stages of PHS development in China.

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 [14], the "DOE OE Global Energy Storage Database"—GESDB [71], and the information available within official documents from the Chinese Government.

If we consider the status in 2019, the latest data publicly available, the IHA database reports a total of 34 PSPs in operation in June 2019 for a total of 31.76 GW (turbine operation mode). The IHA database is presently under update, and the data presented in this study represent the status of China from this database updated until the beginning of 2022 (Q1 2022). The latest update accounts for an additional 7.06 GW (turbine mode) commissioned starting in 2019, bringing the total PHS capacity in China to 38.82 GW. The list of these PSPs is presented in Table 3.

Table 3. New commissioned PHS capacity (in terms of turbine operation mode). From 2019 (namely 2020) to the first quarter of 2022. Plants are also presented by their Chinese name within brackets for reference.

Commissioning Year	Station Name	Commissioned Capacity in Turbine Mode (MW)
2020	Dunhua (敦化)	1400
	Fomo (佛磨)	160
	Jixi (绩溪)	1800
	Yongtai Baiyun (永泰白云)	1200
	Total added in 2020	**4560**
2021	Fengning (丰宁) 1st Phase	600
	Fujian zhou ning (福建周宁)	600
	Huanggou (荒沟)	600
	Yangjiang (阳江) 1st Phase	400
	Total added in 2021	**2200**
Q1 2022	Meizhou Wuhua (梅州五华) 1st Phase	300
	Total added in Q1 2022	**300**

The IHA database also contains information about the PHS capacity that is under implementation in the incoming years.

The GESDB database is presently not updated, accounting for 33 PSPs for a total installed capacity of 31.4 GW. In fact, the publicly available database (status June 2022) is missing information about most of the plants commissioned after 2019. It only contains information about plants already in operation. No information about the capacity under implementation is available. It is important to point out that the GESDB database is not specifically devoted to PHS technology. Still, it takes into consideration all the energy storage technologies, both electro and thermal energy storage.

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] by the NEA (National Energy Administration) reports 34 PSPs with a total installed capacity of 32.49 GW (turbine mode). The number is in line with the status data publicly available from the IHA information. The IHA reports are also explicitly mentioned in the first chapter (I. Basis of planning. In Chinese: 一、规划基础) of the NEA-Plan. Furthermore, the "China Renewable Energy Development Report" 2021 [72] is in line with the data, stating that in 2021 the total scale of PHS plants in operation is 36.4 GW.

The present study is based on the data available from the updated IHA database, since they are the most complete in terms of detailed information on the technical characteristics of each plant, including their power station.

4.3. PHS Development Plans for China

The IHA Database is the only available source, including detailed technical and commission status information for the PSPs 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 53.2 GW of capacity is under construction, 33.3 GW is planned, and 6.6 GW has been announced. Following this information, if all the reported planned new installations are commissioned, an additional 93 GW will be added to the fleet, theoretically bringing the Chinese PSPs capacity to around 130 GW within 2030~2035 (Figure 9).

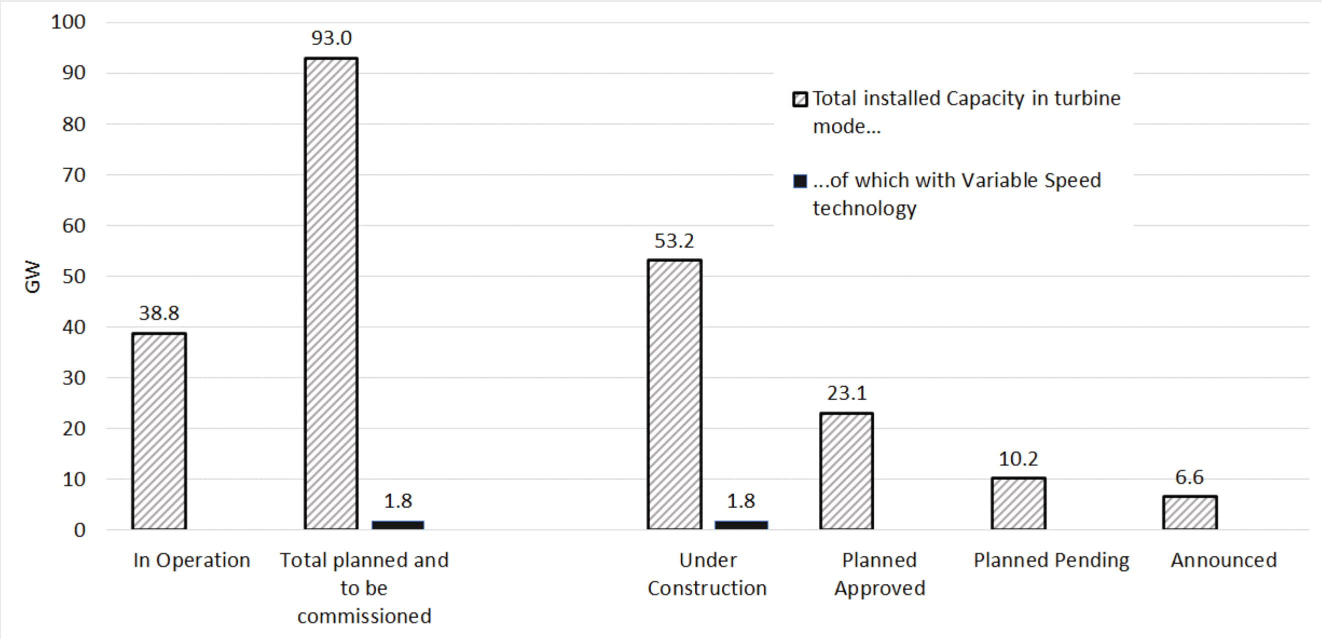

Figure 9. PHS status in China Q1 2022: operational and planned (**left**) and status detail of plants to be commissioned (**right**).

These figures are quite conservative compared to the more recent NEA-Plan, which started from the Chinese long-term strategy to achieve the goal of peaking carbon emissions by 2030 and reaching carbon neutrality by 2060. Accelerating the development of pumped storage in China is an urgent requirement for constructing a new power system based on carbon-neutral energy sources as the main body. PHS represents an important support for the safe and stable operation of the power system and an important guarantee for the large-scale development of renewables. In accordance with the requirements of the Renewable Energy Law, the NEA-Plan was formulated in 2021 to guide the development of pumped storage in the medium and long term following the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Outline of Vision 2035 and the 14th Five-Year Plan for Modern Energy System [7]. The plan spans until 2035, including the future 15th and 16th Five-Year plan periods.

The NEA-Plan aims to reach the relevant PHS installed operational capacity of 305 GW by 2035, developing a modern pumped storage industry with advanced technology, high-quality management, and strong international competitiveness. The planned investment to reach this target is about 1.8 trillion RMB (presently equivalent to nearly 240 G€) spanning over 15 years, of which about 900 billion RMB (~120 G€), 600 billion RMB (~80 G€), and 300 billion RMB (~40 G€) during the 14th, 15th, and 16th Five-Year Plan respectively. This represents an average expenditure of 120 billion RMB per year (equivalent to ~16 G€/y).

The planned schedule is to reach 62 GW cumulative installed capacity by the end of the 14th FYP (2025), 120 GW capacity by the end of the 15th FYP (2030), and finally 305 GW by the end of the 16th FYP (2035).

Furthermore, in June 2022, NEA announced that during the "14th Five-Year Plan" period (2021–2025), the focus would be on the implementation of the "Double Two Hundred Project" (in Chinese: " 双两百工程") with the construction of more than 200 pumped storage projects in 200 cities and counties and a target of 270 GW, with a total investment of 1.6 trillion yuan (237.4 billion USD) [73–75].

Regarding the potential for implementation of new reserves, the NEA performed a study to point out new locations for new PSPs plants. A first shortlist of priority sites has been evaluated for the availability of further installations with a total capacity of 421 GW. In these locations, new installations are feasible and environmentally friendly. Other potential sites exist with basic requirements but may be subject to environmental concerns. If the environmental concerns are solved, these could be moved to the priority sites category, accounting for a total potential expansion capacity of nearly 726 GW [76].

Similar figures result from the planning needs evaluation by the Chinese provinces (regions and municipalities), considering factors such as system demand and project construction conditions. The evaluation is available within the document annexed to the NEA-Plan. It proposes the layout of more than 550 pumped storage reserve projects, with a total installed capacity of about 680 GW.

A comparison (Figure 10) of the NEA-Plan and IHA database time schedules of the expected commissioning in the next years shows that they are almost in line until 2030. The plants that do not yet have a planned year of commissioning in the IHA database (accounting for nearly 18 GW) are precautionarily considered to be commissioned during the 16th Four Year Plan (2030–2035). In the same figure, the expected installations data at the end of 2022 (45 GW) from the CREEI Report [72] and the expected added installations amount following the announcement of NEA in the June 2022 [75] are also presented as a reference.

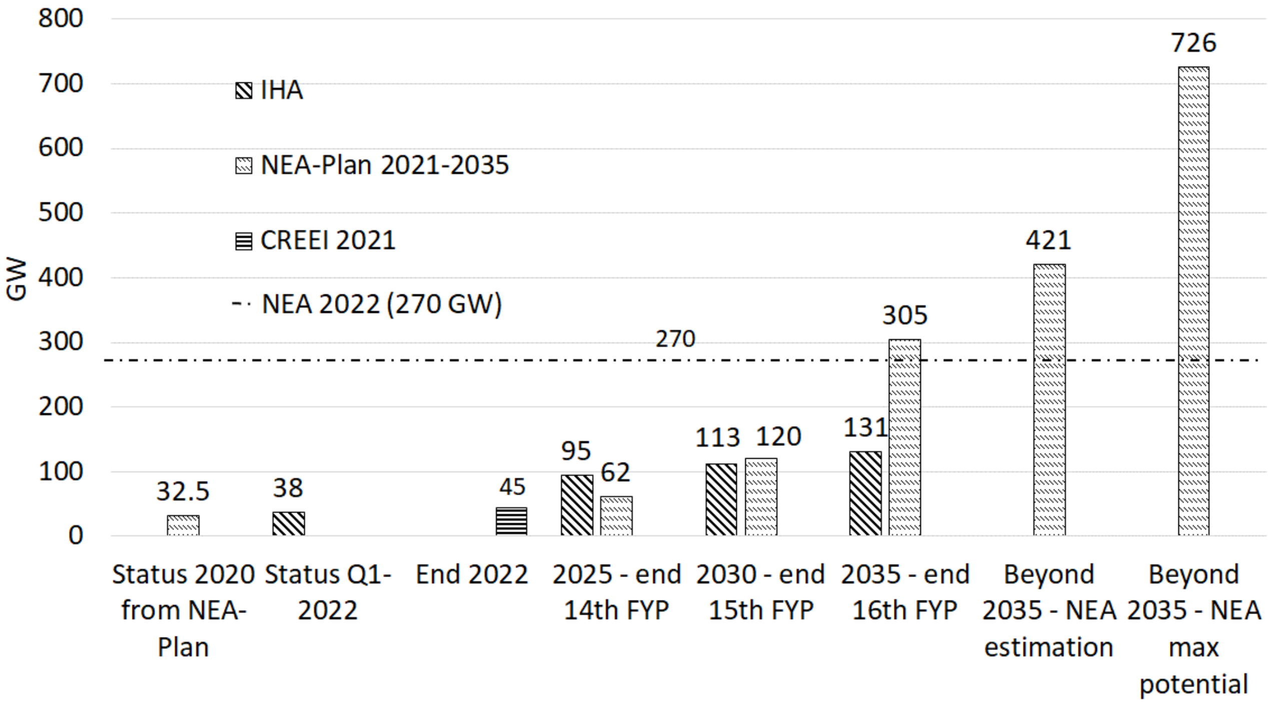

Figure 10. NEA-Plan and IHA Database cumulative PHS installations (turbine mode): comparing planned time schedules. Data from CREEI Report and NEA June 2022 Announcement are also included for reference.

4.4. Flexibility Status of Chinese PHS

The whole operational capacity of the Chinese PSP fleet is presently characterised by fixed-speed plants. In contrast, 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 76.2 GW already under construction or approved are designed for variable speed (Figure 9). No other planned plant is expected to be of any typology with advanced regulation capability. Therefore, PHS plants are able to better deal with the flexibility issues represent nearly 2.4% of the capacity under commissioning.

The awareness of the importance of increasing PSPs flexibility in the Chinese fleet is grown in very recent years, as also demonstrated by the attention given to the challenge in several published studies by Chinese researchers and scholars [40,67,77–83].

Several PHS plants in China also report flow-induced hydraulic instabilities (operation in the so-called rough zone) due to the partial load operation [84]. Apart from adding flexibility to the system, VSPS units can also help mitigate partial load instability problems, thus reducing stress and tear and increasing plant life. The upgrading to variable-speed technology, combined with Battery Energy Storage Systems (BESS) and PV, is the subject of a preliminary study [77] targeting the 600 MW Langyashan PSP in the Anhui Province, East China. The application of variable-speed pump-turbine units for wind storage operation has also been studied for the Chinese electricity market [78]. Thus, the application of VSPS can effectively improve the security and economy of the power grid subject to the increasing penetration of wind energy. Similarly, a study assessing the power regulation rapidity of VSPSPs in high wind penetration scenarios in China [40], while confirming the VSPS contribution to power system stability, also results in a significantly higher assessment in the ancillary service of the electricity market from an economic perspective. The simulation of a PSP equipped with DFIG (Doubly Fed Induction Generator) units with a Demand Response (DR) control loop also adopting Linear Active Disturbance Rejection Control (LADRC) to deal with frequency change shows that this control strategy has smaller frequency fluctuations and can achieve better control performance [80]. A simulation of a 5 MW Converter-Fed Synchronous Machine unit based on a traditional hydroelectric machine was performed [81], resulting in the capability to play a regulatory role in the hydropower system, also achieving a great tracking control. Variable speed is also one of the suggested potential technologies of new advanced PHS, together with seawater and underground PHS [82].

The interest in more flexible PHS in China is increasing. Additionally, there is an increasing need for flexible operating power offers and demand on the grid to better balance the VRES and provide stable and secure electricity to the system. Thus, it is important to evaluate the potential of the PSP already operating and future PSP fleet to match this new challenge.

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. In fact, as stated in the NEA-Plan:

- ***5.7 Strengthen innovation in science, technology, and equipment****; (. . .) Focus on the independent design and manufacture of ultra-high head large-capacity energy storage units and large-capacity variable-speed units, and further enhance the level of localization of auxiliary equipment such as excitation, governors, and frequency conversion devices*.

5. Results and Discussion

5.1. Potential for Increasing PHS Flexibility in China

Huge potential for increasing the flexibility of PHS plants in China already exists, both for operating plants and planned new ones.

The Chinese PSP fleet in operation nearly older than 30 years is quite limited, accounting for only 1.8 GW of turbine capacity (and 333 MW of pump capacity). Better opportunities open if plants older than 20 years are also considered. In that case, the total cumulative capacity available for upgrading accounts for 7.7 GW of turbines (and 6.1 GW of pumps). A deeper technical investigation of this fleet could help to point out which units, although not at the end of their operational life, may need a strong maintenance intervention due to specific causes. For example, mechanical damages due to the frequent operation mode changes necessary to the VRES balancing needs. If the upgrading could also include the plants older than 10 years, in that case, the set of PSPs accounts for 22 GW turbine mode and 20.4 GW pump mode, more than half of the PHS capacity presently in operation (Figure 11).

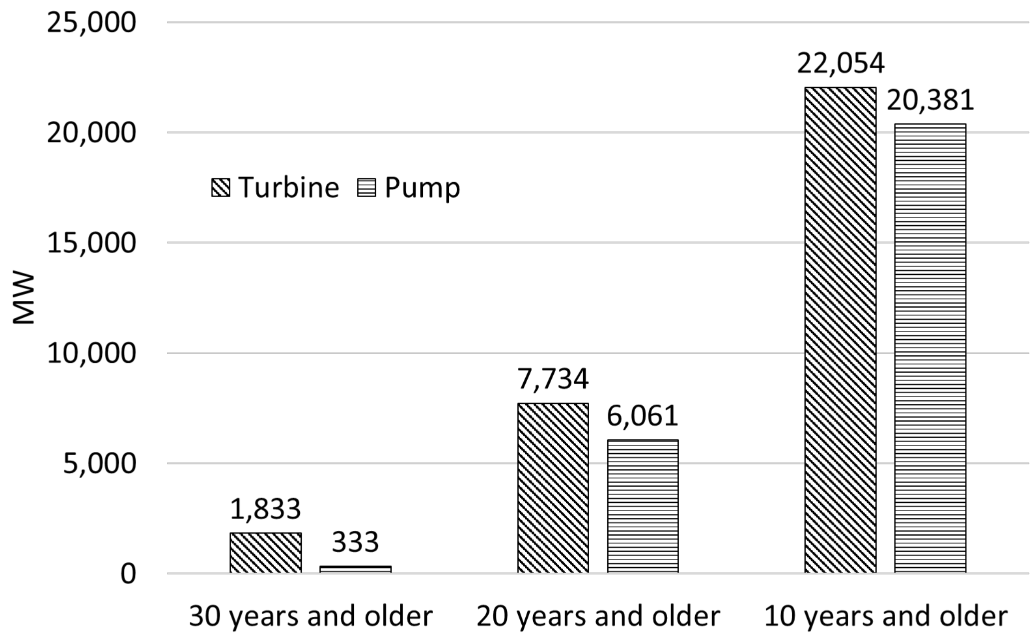

Figure 11. Cumulative capacity of PHS in China by ageing for plants commissioned until 2012.

As already presented in the methodology discussion, the present study identifies five different scenarios for the potential intervention on the existing and future PSPs, aiming to increase their flexibility:

1. **High Potential Scenario**; PSPs older than 30 years and future PSPs whose construction is only announced.
2. **Medium Potential Scenario**; PSPs between 20 and 30 years old and future PSPs already planned but waiting for approval.
3. **Low Potential Scenario**; PSPs between 10 and 20 years old and future PSPs already planned that received approval.
4. **Unknown Potential Scenario**; PSPs 10 years old or more operating with a head above 600m, and future PSPs either announced, planned, or approved where the operating head is unknown or above 600m. It is marked as unknown since in these circumstances it is necessary to have a case-by-case specific evaluation of the possibility of intervention.
5. **No Potential Scenario**; PSPs operating for less than 10 years, and future PSPs that are already under construction.

The analysis results are available in Table 4, where the already under-construction 1.8 GW of the Fengning Pumped Storage Plant is also reported.

These figures are 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 of adopting flexible solutions.

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

If the analysis discards the Maximum Head limit below 600 m ("Unknown Potential" scenario), in that case, the flexibility potentials of each scenario resulting from the analysis increase as from Table 5.

Table 4. Summary of additional flexibility potentials of PHS in China until 2035. Capacity of every single scenario and cumulative capacity with increasing implementation challenges. VSPS under commissioning (Fengning PSP) is included for reference.

Scenarios	Per scenario (GW)	% on Total @ 2035	Cumulative (GW)	Cumulative % on Total @ 2035
VSPSPs under commissioning	1.8	1.4%		
Additional flexibility potential				
High Potential	5.2	4.0%	5.2	4.0%
Medium Potential	9.4	7.1%	14.6	11.1%
Low Potential	19.9	15.1%	34.5	26.2%
Unknown Potential	27.4	20.8%		
No Potential	68.1	51.7%		
Total @2035	131.8			

Table 5. Summary of flexibility potentials of PHS in China until 2035. Here, the Maximum Head limit below 600 m is not considered a constraint. Capacity of every single scenario and cumulative capacity with increasing implementation challenges. VSPS under commissioning.

Scenarios	Per scenario (GW)	% on Total @ 2035	Cumulative (GW)	Cumulative % on Total @ 2035
VSPSPs under commissioning	1.8	1.4%		
Additional flexibility potential				
High Potential	8.4	6.4%	8.4	6.4%
Medium Potential	16.1	12.2%	24.5	18.6%
Low Potential	37.4	28.4%	61.9	47.0%
No Potential	68.1	51.7%		
Total @2035	131.8			

5.2. 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) [34,37,38]. The economic advantage of additional flexibility can result from 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 adopting advanced technology solutions from the economic perspective.

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

The policy regulator should therefore implement targeted market mechanisms 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 accurately measure and calculate. 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 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, combining 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 [69].

The regulation issued by NDRC [70] 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 providing reasonable returns to the plant to achieve a balanced cash flow for the entire operating period (set in 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 achieve fair remuneration of the PSPs all over the services provided to the system, giving an incentive to adopt 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 excavated underground and the installation of new machinery and electrical and hydraulic equipment.

Regarding planned and under-construction plants, further policy measures should support actions to re-design the plant to add flexibility capacity. This is particularly important for all the plants that 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.

The following policy recommendations aiming to support the implementation, in the shortest possible time and with fewer efforts also from the economic point of view, of advanced PHS to provide flexible and reliable energy storage are then elaborated. These are also in line with the "Medium and Long-term Development Plan for Pumped Storage (2021–2035)" [7]. These recommendations refer to the technical issues related to the present state of the art of advanced Pumped Hydro Storage solutions.

- Full and fair remuneration of the Ancillary Services. Apart from the basic storage service, Pumped Hydro Storage can provide most of the ancillary services that are extremely necessary to a decarbonised electricity grid: frequency regulation and control, voltage control and reactive power provision, contingency reserves (spinning and non-spinning), and system inertia provision above all. The higher the flexibility of the Pumped Storage Plant, the higher the technical value of the ancillary services provided to the grid. Not all these services are currently fairly remunerated. Some are under-remunerated or not remunerated at all. In this case, providing advanced flexibility may not result in a direct economic benefit for the plant owner. The Chinese market mechanism presently in force is already on the right track. Still, additional efforts must be made to implement a market that is able to fairly remunerate all the ancillary services provided by a Pumped Storage Plant. In the so-called "two-part tariff" scheme, the capacity fee remunerates only services of power system reserve, regulation, and black start. The market mechanism should be extended to all the other ancillary services the Pumped Storage Plant can provide. Most of these ancillary services' economic value is difficult to measure and calculate accurately. In summary:
    - ➢ *The policymaker, together with the relevant administrative bodies, should as a first step calculate a fair remuneration tariff for all the ancillary services, also considering, when possible, the level of flexibility at which each service can be provided to the grid. These tariffs should be then included in the new market mechanism.*
- Support revamping existing Pumped Storage Plants in the direction of additional and advanced flexibility capacity. Part of the potential to increase the flexibility of Pumped Storage Plants in China can be obtained by upgrading the already operating fleet that needs revamping. The easiest way to achieve additional flexibility is by substituting the old fixed-speed units with new variable-speed units. This kind of intervention in-

creases 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 Variable Renewable Energy Sources. A new variable-speed unit needs additional space compared to the old fixed-speed one. Since upgrading means operating on already existing spaces, the cost of the operation is increased by the need to create additional space in the cavern. Capital Expenditures for upgrading are, therefore, higher when a higher level of flexibility is achieved. Most of the benefits of this new configuration are for the whole system rather than only for the plant owner. In summary:

➢ *The Policymaker should elaborate fair support measures, aligned with the remuneration mechanisms for the additional flexibility, to incentivise the plant owners to upgrade their plants in the direction of higher flexibility*.

- Support re-design of the planned and under-construction plants to add flexibility capacity. The plants commissioned in the future should be designed to provide the highest level of flexibility to the grid to best match the Variable Renewable Energy Sources production. When possible, future plants characterised by low-flexibility technology solutions should be re-designed in order to achieve the highest level of flexibility compatible with the planned hydraulic system. In summary:

➢ *Policymakers should create measures to ease and support actions of re-design of the plant going in this direction, facilitating, streamlining, and simplifying the authorisation and licensing processes, also elaborating fair support measures, aligned with the remuneration mechanisms for the additional flexibility, to incentivise the plant owners to upgrade their design*.

- Elaboration of a plan for Pumped Storage addressing system flexibility and stability needs. The actions proposed in the previous points need to be supported by a clear vision of the whole system and future scenarios. Pumped Hydro Storage development requires a clear plan addressing system flexibility and stability needs as well as policy and market barriers. The "Medium and Long-term Development Plan for Pumped Storage (2021–2035)" already deals with the planning of Pumped Hydro Storage in terms of installed capacity but is still not fully focused on the issue of adopting advanced technology solutions, that are more in line with the needs of a grid with high penetration of Variable Renewable Energy Sources. Therefore, in summary:

➢ *The Policymaker should elaborate a plan for the Pumped Storage flexibility necessary characteristics following an assessment of the system flexibility, adequacy and stability needs to 2030 and beyond, and of potential gaps in national regulatory frameworks*.

All the previously suggested policy measures target improving Pumped Hydro Storage flexibility in the Chinese Electricity system. These could bring China to a better deal, in terms of system flexibility, with the new energy scenarios while supporting the development of a modern pumped storage industry with advanced technology, high-quality management, and strong international competitiveness.

6. Conclusions

The present work evaluated the potential for improving the flexibility of PHS plants in China. The analysis considers upgrading the existing fleet needing revamping and re-designing future installations. The increase in flexibility is achieved by adopting advanced PHS solutions. Three main different scenarios were defined: high, medium, and low potential depending on the age of the operating fleet or the stage of implementation of the future installations. The fourth scenario with an unknown potential was defined, the latter representing plants in operation or future installations whose technical characteristics need further investigation to be properly evaluated. Plants not older than 10 years and plants already under construction have been excluded from the potential.

In a high potential scenario, 4.0% of the 132 GW fleet expected to be commissioned before 2035 could additionally adopt advanced PHS. While extending to medium and low potential scenarios, the quota can reach 11.1% and 26.2%, respectively. Plants with unknown potential account for 20.8% of the expected installation before 2035. The unknown potential refers to the analysis excluding, for technical reasons, the intervention on existing and future plants whose maximum head is above 600 m. If this constraint is removed, figures change from a high potential scenario with 6.4% of the fleet expected to be commissioned before 2035 to medium and low potential scenarios reaching the quota of 18.6% and 47.0%, respectively.

High investments are necessary to implement the proposed interventions, either for revamping plants in operation or redesigning future installations. Although adopting advanced PHS solutions can result in lower operation and maintenance costs (OPEX), these savings can only partially cover the increase in capital costs (CAPEX). Advanced PHS is, therefore, not always fully justified from an economic point of view. Still, it is, in any case, important for the whole system as an asset for stability and safety, especially when the penetration of variable renewable energy sources is high.

To cover the highest CAPEX necessary for implementing 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. Furthermore, revamping or redesigning intervention need to undergo an authorisation procedure that must be facilitated. Policies should then be elaborated to address permitting and authorisation barriers to speed up the path from the project phase to commissioning.

The present work elaborated four policy recommendations to support and facilitate the adoption of advanced conventional PHS solutions. These policy recommendations combine actions to be implemented at the economic, authorization, and planning levels.

At the economic level, the adoption of full and fair remuneration of the ancillary services is suggested, given the wide set of ancillary services that an advanced PHS plant can provide to the grid. The Chinese market mechanism already remunerates some of them within the capacity quota of the electricity price thanks to the "two-part tariff" scheme, but this should be extended to the whole set of services provided by the PSP.

At the authorization level, it is recommended that policymakers create measures to ease and support the redesign by facilitating, streamlining, and simplifying the authorisation and licensing processes of those plants aiming to adopt advanced solutions.

At the system planning level, it is recommended that policymakers take into consideration not only the storage capacity of the future PSP fleet, but also their characteristics in terms of flexibility. As a matter of example, the "Medium and Long-term Development Plan for Pumped Storage (2021–2035)" deals with the planning of PHS more in terms of installed capacity rather than adopting advanced technology solutions. A change in the approach to the issue is therefore recommended.

Author Contributions: Conceptualization: L.N.; Data Curation: L.N. and C.-C.W.; Formal analysis: L.N., P.S., and M.D.L.; Funding acquisition: M.D.L.; Investigation: L.N., P.S., and C.-C.W.; Methodology: L.N. and P.S.; Project administration: M.D.L.; Supervision: M.D.L.; Validation: L.N.; Visualization: L.N.; Writing—Original Draft: L.N.; Writing—Review and Editing: L.N., P.S., and M.D.L. All authors have read and agreed to the published version of the manuscript.

Funding: 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 (Contract number PI/2017/382-117) 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.

Data Availability Statement: The main datasets related to this article are available for consultation at www.hydropower.org/hydropower-pumped-storage-tool (accessed on 13 October 2022), hosted on the International Hydropower Association web pages [14]. The database should be integrated with the information additionally provided in Table 3. The DOE Global Energy Storage Database is available at sandia.gov/ess-ssl/gesdb/public/projects.html (accessed on 13 October 2022), hosted by the Sandia National Laboratories web page [71].

Acknowledgments: The authors wish to thank Rebecca Ellis (Energy Policy Manager) and Alex Campbell (Head of Research and Policy) of the International Hydropower Association for the support given to the implementation of the study and for the access to the updated dataset of the "Pumped Storage Tracking Tool".

Conflicts of Interest: The authors declare no conflict of interest. The funding entity had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Nibbi, L.; Sospiro, P.; de Lucia, M. Improving Pumped Hydro Storage (PHS) Flexibility in China. In Proceedings of the International Conference on Applied Energy 2021, Thailand/Virtual, 29 November–5 December 2021; Volume 1, pp. 1–6. [CrossRef]
2. Dotzauer, M.; Pfeiffer, D.; Lauer, M.; Pohl, M.; Mauky, E.; Bär, K.; Sonnleitner, M.; Zörner, W.; Hudde, J.; Schwarz, B.; et al. How to measure flexibility—Performance indicators for demand driven power generation from biogas plants. *Renew. Energy* **2019**, *134*, 135–146. [CrossRef]
3. Müller, T.; Schreiber, S. How to Balance Intermittent Feed-in from Renewable Energies ?—A Techno-Economic Comparison of Flexibility Options. 2017. Available online: https://reflex-project.eu/wp-content/uploads/2017/12/REFLEX_policy_brief_flexibility-options_final_14_12_2017.pdf (accessed on 13 October 2022).
4. Global Wind Energy Council. *GWEC Global Wind Report 2022*; Global Wind Energy Council: Brussels, Belgium, 2022.
5. International Renewable Energy Agency (IRENA). *Renewable Energy Statistics 2022*; IRENA: Abu Dhabi, United Arab Emirates, 2022; Available online: https://www.irena.org/publications/2022/Jul/Renewable-Energy-Statistics-2022 (accessed on 13 October 2022).
6. GWEC; CREIA; CWEA. *Beijing Declaration on Wind Energy*; Global Wind Energy Council (GWEC): Brussels, Belgium, 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): Beijing, China, 2021.
8. International Hydropower Association. Hydropower Status Report 2021. London. 2021. Available online: https://www.hydropower.org/publications/2021-hydropower-status-report (accessed on 13 October 2022).
9. International Hydropower Association. Hydropower Status Report 2022. 2022. Available online: https://www.hydropower.org/publications/2022-hydropower-status-report (accessed on 13 October 2022).
10. REN21. Renewables 2022 Global Status Report. 2022. Available online: https://www.ren21.net/wp-content/uploads/2019/05/GSR2022_Fact_Sheet_Germany.pdf (accessed on 13 October 2022).
11. eStorage. eStorage Project. 2016. Available online: Estorage-project.eu (accessed on 13 October 2022).
12. XFLEX HYDRO. XFLEX HYDRO Project. 2019. Available online: https://xflexhydro.net/ (accessed on 13 October 2022).
13. CEWP. China Europe Water Platform. 2012. Available online: Cewp.eu (accessed on 5 October 2022).
14. Rogner, M.; Law, S. Pumped Storage Tracking Tool. *International Hydropower Association*. 2019. Available online: https://www.hydropower.org/hydropower-pumped-storage-tool (accessed on 13 October 2022).
15. Zipparro, V.J.; Hasen, H.; Davis, C.V. *Davis' Handbook of Applied Hydraulics*; McGraw-Hill, Inc.: New York, NY, USA, 1993.
16. Jülch, V. Comparison of electricity storage options using levelized cost of storage (LCOS) method. *Appl. Energy* **2016**, *183*, 1594–1606. [CrossRef]
17. Corà, E.; Fry, J.J.; Bachhiesl, M.; Schleiss, A. *Hydropower Technologies: The State-of-the-Art*; European Union: Brussels, Belgium, 2019.
18. Letcher, T.M. *Storing Energy: With Special Reference to Renewable Energy Sources*; Elsevier Inc.: Philadelphia, PA, USA, 2016.
19. Deriaz, P.; Warnock, J.G. Reversible Pump-Turbines for Sir Adam Beck-Niagara Pumping-Generating Station. *J. Basic Eng.-Trans. ASME* **1959**, *81*, 521–529. [CrossRef]
20. Dériaz, P. La turbine-pompe réversible axio-centrifuge à pas variable: Le développement d'une nouvelle machine hydraulique. *Bull. Tech. Suisse Rom.* **1955**, *419*, 382–387. [CrossRef]
21. Morabito, A.; de Oliveira e Silva, G.; Hendrick, P. Deriaz pump-turbine for pumped hydro energy storage and micro applications. *J. Energy Storage* **2019**, *24*, 100788. [CrossRef]
22. Quaranta, E. *The Revival of Old Hydraulic Turbines for Innovative Hydropower Generation: Water Wheels, Archimedes Screws, Deriaz and Girard Turbines*; Iris Publishers: San Francisco, CA, USA, 2020; pp. 1–4. [CrossRef]
23. Miyagawa, K.; Fukuda, N.; Tsuji, K.; Suzuki, K.; Saotome, J. Development of a Deriaz type pump-turbine with high head, large capacity and variable speed. *Proc. XIX Iahr. Symp. Hydraul. Mach. Cavitation* **1998**, *1*, 39.
24. Skotak, A.; Stegner, P. Choosing Turbines for Low-Head Pumped-Storage Plants. *HydroWorld.com* **2014**, *22*, 1–5.
25. Illwerke, V.K.V. Kopswerk II Das Grösste Pumpspeicherkraftwerk der Vorarlberger Illwerke AG. 2010. Available online: http://www.aeit-taa.org/Documenti/AEIT-TAA-2010-09-24-25-26-Bludenz-A-Depliant-Kopswerk-2.pdf (accessed on 13 October 2022).
26. eStorage. Potential for Conversion of Classical PSP to Variable Speed Units in EU15, Norway and Switzerland (EXTRACTS). 2016. Available online: http://www.estorage-project.eu/ (accessed on 13 October 2022).

27. XFLEX HYDRO. *The Hydropower Extending Power System Flexibility (XFLEX HYDRO) Project D2.1 Flexibility, Technologies and Scenarios for Hydro Power*; European Union: Brussels, Belgium, 2020; no. 857832.
28. Koritarov, V.; Feltes, J.; Kazachkov, Y.; Gong, B.; Donalek, P.; Gevorgian, V. *Testing Dynamic Simulation Models for Different Types of Advanced Pumped Storage Hydro Units*; Argonne National Laboratory: Argonne, IL, USA, 2013; pp. 1–152.
29. Koritarov, V.; Guo, T.; Ela, E.; Trouille, B.; Feltes, J.; Reed, M. Modeling and Simulation of Advanced Pumped-Storage Hydropower Technologies and their Contributions to the Power System. *Proc. HydroVision* **2014**, *22–25*, 1–21.
30. Rimpel, A.; Krueger, K.; Wang, Z.; Li, X.; Palazzolo, A.; Kavosi, J.; Naraghi, M.; Creasy, T.; Anvari, B.; Severson, E.; et al. *Mechanical Energy Storage*; Elsevier Inc.: Philadelphia, PA, USA, 2021.
31. Valavi, M.; Nysveen, A. Variable-Speed Operation of Hydropower Plants: A Look at the Past, Present, and Future. *IEEE Ind. Appl. Mag.* **2018**, *24*, 18–27. [CrossRef]
32. Alizadeh-Mousavi, O.; Nick, M. Stochastic Security Constrained Unit Commitment with variable-speed pumped-storage Hydropower Plants. In Proceedings of the 2016 Power Systems Computation Conference (PSCC), Genoa, Italy, 20–24 June 2016. [CrossRef]
33. Fisher, R.K.; Koutnik, J.; Meier, L.; Loose, V.; Engels, K.; Beyer, T. A Comparison of Advanced Pumped Storage Equipment Drivers in the US and Europe. In Proceedings of the HydroVision International, Louisville, KY, USA, 17–20 July 2012; pp. 1–30. [CrossRef]
34. Teng, F.; Pudjianto, D.; Aunedi, M.; Strbac, G. Assessment of future whole-system value of large-scale pumped storage plants in Europe. *Energies* **2018**, *11*, 246. [CrossRef]
35. Valavi, M.; Nysveen, A. Variable-speed operation of hydropower plants: Past, present, and future. In Proceedings of the 2016 XXII International Conference on Electrical Machines (ICEM), Lausanne, Switzerland, 4–7 September 2016; pp. 640–646. [CrossRef]
36. West, N.; Moeini, M. What's the Best Technology for Your Pumped Hydro Project? Conditions, You Need to Understand the Technology Options Available. 2019. Available online: https://www.entura.com.au/whats-best-technology-pumped-hydro-project/ (accessed on 20 March 2020).
37. Japan International Cooperation Agency; Tokyo Electric Power Services; Tokyo Electric Power Company. Final Report on Feasibility Study on Adjustable Speed Pumped Storage Generation Technology. 2012. Available online: Openjicareport.jica.go.jp/pdf/12044822.pdf (accessed on 18 September 2022).
38. Japan International Cooperation Agency. Data Collection Survey on Pumped Storage Hydropower Development in Maharashtra Final Report. 2012. Available online: Openjicareport.jica.go.jp/pdf/12082897_01.pdf (accessed on 13 October 2022).
39. Krad, I.; Ela, E.; Koritarov, V. Quantifying the operational benefits of conventional and advanced pumped storage hydro on reliability and efficiency. In Proceedings of the IEEE Power and Energy Society General Meeting, National Harbor, MD, USA, 27–31 July 2014; pp. 1–5. [CrossRef]
40. Yang, W.; Yang, J. Advantage of variable-speed pumped storage plants for mitigating wind power variations: Integrated modelling and performance assessment. *Appl. Energy* **2019**, *237*, 720–732. [CrossRef]
41. Nicolet, C.; Beguin, A.; Kawkabani, B.; Pannatier, Y.; Schwery, A.; Avellan, F. Variable Speed and Ternary Units to Mitigate Wind and Solar Intermittent Production. *Hydrovision Int.* **2014**, 1–21.
42. Hell, J. High flexible Hydropower Generation concepts for future grids. *J. Phys. Conf. Ser.* **2017**, *813*, 012007. [CrossRef]
43. ABB. *Grimsel 2, Switzerland—The World's Largest Power Converter for Variable Speed Pumped Hydropower*; ABB Ltd.: Shimada Shi, Japan, 2014.
44. ABB. Variable Speed Drive for Converter Fed Synchronous Machine. 2014. Available online: https://new.abb.com/power-converters-inverters/energy-storage-grid-stabilization/converters-for-pumped-storage-plants/pcs-8000-variable-speed-converter/variable-speed-drive-for-converter-fed-synchronous-machine (accessed on 15 October 2020).
45. ABB. *Variable Speed Drive for Converter Fed Synchronous Machine*; ABB Ltd.: Shimada Shi, Japan, 2020.
46. Moreira, H.C.; Moreira, C.L. D2.1 Flexibility, Technologies and Scenarios for Hydro Power. 2020. Available online: https://hdl.handle.net/10216/132977 (accessed on 13 October 2022).
47. Hydroflex. Hydroflex Project. 2018. Available online: https://www.h2020hydroflex.eu/ (accessed on 13 October 2022).
48. Schönefeld, M.; Hüllenkremer, J.; Siemonsmeier, M.; Moser, A.; Anaya-Lara, O.; Campos-Gaona, D. Frequency stability analysis under consideration of virtual inertia emulation of converter-interfaced hydropower plants in the Nordic Transmission Grid. In Proceedings of the 3rd CIGRE South East European Regional Council Conference, CIGRE SEERC, online, 16–19 June 2020.
49. Markov, Z.; Stojkovski, F.; Lazarevikj, M.; Iliev, I. Investigation of the possibilities for development of a variable speed hydraulic turbine. In Proceedings of the International Conference Energetics 2018, online, 25–27 April 2018; pp. 333–341.
50. Saberi, O.; Storli, P.S.; Alfredsen, K. New Technology to Increase Hydropower Plant Operational Flexibility. *Int. J. Hydraul. Eng.* **2021**, *10*, 1–7. [CrossRef]
51. Siemonsmeier, M.; Baumanns, P.; van Bracht, F. *Hydropower Providing Flexibility for a Renewable Energy System: Three European Energy Scenarios*; European Union: Brussels, Belgium, 2018.
52. Trivedi, C.; Iliev, I.; Dahlhaug, O.G. Numerical Study of a Francis Turbine over Wide Operating Range: Some Practical Aspects of Verification. *Sustainability* **2020**, *12*, 4301. [CrossRef]
53. International Hydropower Association. International Forum on Pumped Storage Hydropower (IFPSH). 2020. Available online: https://pumped-storage-forum.hydropower.org/ (accessed on 13 October 2022).

54. IFPSH. Pumped Storage Hydropower Capabilities and Costs. 2021. Available online: https://pumped-storage-forum.hydropower.org/resources/publications (accessed on 13 October 2022).
55. TOSHIBA. Renewable Energy—Hydro Power. 2020. Available online: https://www.global.toshiba/ww/products-solutions/renewable-energy/products-technical-services/hydro-power.html (accessed on 13 October 2022).
56. Xiaojia, Y. *Research on the Method of Combined Control of Heat Storage and Power Storage to Improve Wind Power Consumption Capacity*; Shenyang University of Technology: Shenyang, China, 2019.
57. CNREC. China Renewable Energy Outlook 2018. Volume 2019, No. Creo 2019. 2019. Available online: http://boostre.cnrec.org.cn/wp-content/uploads/2018/11/CREO-2018-Summary-CN.pdf (accessed on 19 December 2019).
58. CNREC. *China Renewable Energy Outlook 2019*; China National Renewable Energy Centre: Beijing, China, 2020.
59. Wang, X.; Tao, Y. 2019 China Wind and Solar PV Overview. 2020. Available online: http://www.fuanguodian.com/news/hangye/470.html (accessed on 18 September 2022).
60. Zhao, Z.; Wu, Z.; Xu, B.; Pan, J.; Variable Renewable Energy curtailment level in China. Project BBChina. 2020. Available online: http://www.bbchina.eu/projects-of-the-course-renewable-energy-technologies-academic-year-2019-20/ (accessed on 13 October 2022).
61. Meissner, F.; Stiewe, C. *Curtailment of Renewable Electricity as a Flexibility Option*; Berlin Economics: Berlin, Germay, 2019.
62. Cook, O.; Leschke, M. Accelerating Corporate Renewable Energy Engagement in China. 2019. Available online: https://resource-solutions.org/wp-content/uploads/2019/11/Accelerating-Corporate-RE-Engagement-in-China.pdf (accessed on 13 October 2022).
63. Zhou, Y.; Lu, S. China's Renewables Curtailment and Coal Assets Risk Map: Research Findings and Map User Guide. *Bnef*. 2017. Available online: https://data.bloomberglp.com/bnef/sites/14/2017/10/Chinas-Renewable-Curtailment-and-Coal-Assets-Risk-Map-FINAL_2.pdf (accessed on 13 October 2022).
64. Elliott, D. Green power curtailment in China. In *Physics World*; IOP Publishing Ltd.: Bristol, UK, 2019; pp. 1–4.
65. Elliott, D. China's Energy Plans. In *Physics World*; IOP Publishing Ltd.: Bristol, UK, 2018.
66. Zeng, M.; Zhang, K.; Liu, D. Overall review of pumped-hydro energy storage in China: Status quo, operation mechanism and policy barriers. *Renew. Sustain. Energy Rev.* **2013**, *17*, 35–43. [CrossRef]
67. Xu, Y.W.; Yang, J. Developments and characteristics of pumped storage power station in China. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *163*, 012089. [CrossRef]
68. Kong, Y.; Kong, Z.; Liu, Z.; Wei, C.; Zhang, J.; An, G. Pumped storage power stations in China: The past, the present, and the future. *Renew. Sustain. Energy Rev.* **2017**, *71*, 720–731. [CrossRef]
69. Zhang, F.; Xu, Z.; Jiao, B.; Feng, J. Study on pricing mechanism of pumped hydro energy storage (PHES) under China's electricity tariff reform. *E3S Web Conf.* **2018**, *38*, 04016. [CrossRef]
70. NDRC. Views on Further Improving the Price Formation Mechanism for Pumped Storage Energy. National Development and Reform Commission, People's Republic of China. 2021. Available online: https://www.ndrc.gov.cn/xxgk/zcfb/tz/202105/t20210507_1279341.html (accessed on 13 October 2022).
71. US Dept. of Energy DOE. Global Energy Storage Database. 2020. Available online: https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/ (accessed on 25 September 2020).
72. China Renewable Energy Engineering Institute (CREEI). China Renewable Energy Development Report 2021. 2022. Available online: https://nmgxny.com/myloads/soft/220629/1-220629104F8.pdf (accessed on 13 October 2022).
73. Chinabidding. A Large Number of Pumped Storage Projects Accelerate the Promotion of Small and Medium-Sized Power Plants to Welcome Development Opportunities. 2022. Available online: Chinabidding.mofcom.gov.cn/article/hyzx/xwzx/hyxw/202207/25571.html%0AA (accessed on 12 September 2022).
74. Xinhua News Agency. NEA Pumps up Hydropower to Stabilize grid. 2022. Available online: Chinadaily.com.cn/a/202208/15/WS62f99b3ca310fd2b29e7220f.html%0AA (accessed on 12 September 2022).
75. Yanzhang, D. Develop Pumped Storage to Promote Green Development. *People's Daily Online*. 2022. Available online: Obor.nea.gov.cn/detail/17621.html%0Afrontobor.nea.gov.cn/detail/17621.html%0Afront (accessed on 12 September 2022).
76. Sheng'an, Z. Speech at 2021 World Hydropower Congress High-level Panel: The International Forum on Pumped Storage Hydropower. 2021. Available online: https://congress.hydropower.org/ (accessed on 13 October 2022).
77. Li, J.; Yi, C.; Gao, S. Prospect of new pumped-storage power station. *Glob. Energy Interconnect.* **2019**, *2*, 235–243. [CrossRef]
78. Zhang, H.; Chen, M.; Peng, Y.; Zhou, J.; He, R. Technology Summary on the Application of Variable-Speed Pump-Turbine Units for Wind Storage Operation. In Proceedings of the 2019 IEEE 3rd International Electrical and Energy Conference (CIEEC), Beijing, China, 7–9 September 2019; pp. 232–235. [CrossRef]
79. Wang, H.; Ma, Z. Dynamic characteristics of pumped storage unit based on the full-size converter. *E3S Web Conf.* **2021**, *233*, 03065. [CrossRef]
80. Yang, Y.; Xiang, L.; Guo, X.; Zheng, Y. Introducing LADRC to Load Frequency Control Model with Pumped Storage Power Station Considering Demand Response. In Proceedings of the 2019 Chinese Automation Congress (CAC), Hangzhou, China, 22–24 November 2019; pp. 610–615. [CrossRef]
81. Li, H.; Li, G.; Yang, B.; Ji, L. Research on variable speed operation of static frequency converter for pumped storage units. *E3S Web Conf.* **2021**, *252*, 02022. [CrossRef]

82. Zhu, B.S.; Ma, Z. Development and Prospect of the Pumped Hydro Energy Stations in China. *J. Phys. Conf. Ser.* **2019**, *1369*, 012018. [CrossRef]
83. Ming, Z.; Junjie, F.; Song, X.; Zhijie, W.; Xiaoli, Z.; Yuejin, W. Development of China's pumped storage plant and related policy analysis. *Energy Policy* **2013**, *61*, 104–113. [CrossRef]
84. Zuo, Z.; Liu, S. Flow-Induced Instabilities in Pump-Turbines in China. *Engineering* **2017**, *3*, 504–511. [CrossRef]