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# *Review and Analysis of Pumped Storage Combined Hybrid Energy Storage Systems*

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***Abstract.*** As carbon - neutrality targets progressed and social electricity consumption witnessed a significant rise, traditional thermal power could no longer satisfy the development requirements of the energy field; wind and photovoltaic power, two typical kinds of clean renewable energy sources, experienced remarkable output fluctuations because of natural constraints like meteorological situations and seasonal changes; although standalone pumped - storage technology was firmly established in actual application, it had inherent defects such as inescapable energy loss and the incapacity to keep high - efficiency power generation for an extended period, becoming a crucial obstacle to constructing a stable clean - energy power supply system; the combined wind - solar - hydro - storage system could effectively stabilize the output instability of wind and photovoltaic power and compensate for the efficiency shortcomings of standalone pumped - storage, emerging as a central pattern suitable for the multi - energy complementary development of clean energy; this article selected four main integrated wind - solar - hydro - storage systems as research subjects, analyzed their operating mechanisms, advantages and disadvantages, essential elements for site selection, as well as cost and economic characteristics, and sorted out specific optimization and cost - reduction strategies for each system, consequently providing practical technical references for the optimal design of these systems and the engineering practice of clean - energy multi - energy complementarity.

***Keywords:*** Wind-Solar-Hydropower-Energy Storage Integration, Multi-Energy Complementation, Hybrid Energy System, Clean Energy

## 1. Introduction

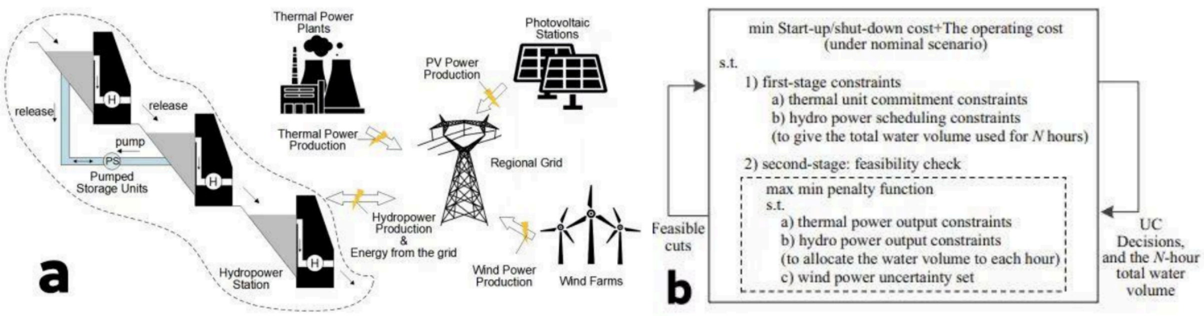
Over the past few years, people have increasingly come to realize the significance of ecological and environmental protection [1], but here's a rather contradictory situation: thermal power continues to occupy a substantial proportion in the present power mix, nonetheless such traditional ways of generating electricity are not at all conducive to attaining carbon - neutrality targets [2], and as human civilization advanced and technology progressed, the social demand for electricity had risen continuously [3], also wind and solar energy technologies are extremely vulnerable to weather and temperature and moreover their power output is greatly restricted by daily and seasonal changes which lead to considerable intermittency and volatility [4] so even though wind and solar power could satisfy the anticipated demand, they were still unable to completely match the power supply efficiency of thermal power, then pumped - hydro storage is a long - established and safe technology that allows for effective electrical energy storage, however energy losses due to factors such as reduced water - turbine efficiency make its mitigating effect less than what was hoped for and it couldn't maintain high - efficiency power generation for a long time, and in most real - world situations, about 10% of energy gets lost during a single one - way hydroelectric - to - electrical energy conversion [5].

The hydro - wind - solar hybrid complementary system has shown obvious progress in this aspect; based on Zhao, G. et al.'s research, the calculation formulas for wind and photovoltaic (PV) power generation output were worked out and this system had great development potential.

Against this background, the hydro - wind - solar integrated system was able to reduce the fluctuation of wind and photovoltaic power generation to some degree and make up for the efficiency shortcomings of pumped - hydro storage, showing remarkable development potential; this paper took this system as the research subject, examined its advantages and disadvantages, the factors that influenced it, the considerations for site selection and the cost analysis of different models, and offered a reference for system optimization and the development of clean energy multi - energy complementarity.

## 2. Production principle

The hybrid system mainly consists of cascade hydropower stations and altered pumped - hydro storage units [6] and makes use of the pumped - hydro storage system to indirectly back up the power grid combined with wind and PV energy (Figure 1 a), which includes wind, PV and thermal power generation, with the research scope specified as the particular situation of cascade hydropower stations adapted for pumped - hydro storage [6], and through the collaborative operation of cascade hydropower and pumped - hydro storage units, the best capacity distribution was achieved by pumping water for energy storage when the load was low and generating electricity when the load was high [6,7], and there was energy transformation between hydraulic potential energy and electrical energy: excess electrical energy was utilized for pumped - hydro storage and then changed back to electrical energy for power supply during peak times [6], which to some degree fulfilled the constraint criteria [6].




*a Indirect interactions of hybrid and other energy systems[6] b HTUC model in two stages of wind power generation[8]*

Figure 1. Schematic diagram of two hybrid energy storage systems

The strong hydro - wind - thermal unit commitment (HTUC) model is mainly set up with wind power, run - of - river hydropower, and thermal power [8-10] and some researches incorporated pumped hydro storage systems [11], the research range was expanded to a multi - regional interconnected power grid system [12] and the modeling regarding wind power uncertainty was

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further improved (Figure 1 b) which reduced wind power volatility by a two - stage method, based on robust optimization, the system's emphasis changed from just operational safety to the coordinated development of safety and economy [10], wind power and run - of - river hydropower were directly connected to the grid, thermal power provided stable operational support, and pumped hydro storage made it possible to convert energy between electrical and potential forms [11,13], operational limitations were further detailed and practical engineering constraints like hydropower head were added [13,14].

## 3. Analysis of merits and demerits

This paper went on to carry out a comprehensive and in - depth analysis of the strong points and weak aspects of diverse mainstream hybrid energy systems and made clear their crucial features regarding energy utilization and other vital indicators, thus offering firm support for the wide - spread application of different hybrid systems.

### 3.1. Hybrid energy system (HES)

The hybrid energy storage system composed of cascade hydropower and pumped - storage hydropower was constructed through the retrofitting of existing cascade plants and functioned as an integrated system having both the capability of regulating peaks in a cascade manner and the ability for bidirectional energy storage [6,7] had a powerful capacity for reducing peak loads on the grid and excellent adaptability to alterations in load, but the connection of multiple power sources made daily operation more complicated and the system was significantly influenced by the inflow from rivers resulting in evident seasonal variations in its energy storage performance [7], so ideal locations were those with substantial differences in water levels (river head) and well - established cascade plants which made the process of retrofitting easier [6], could enhance the utilization of the plant and boost peak - shaving revenue to a certain degree, however, the expenses for modifying the equipment initially and coordinating the dispatch later would rise.

### 3.2. PV-wind-diesel-PSH-battery hybrid system

The system combines photovoltaic (PV) energy, wind power, battery storage, hydrogen energy, and pumped - hydro storage to create a multi - energy complementary power supply system [15,16], provides a stable power supply with enhanced utilization of new energy but requires rather intricate daily maintenance because of the diverse energy storage forms; the influence of seasons on PV and wind power is quite evident resulting in significant seasonal disparities in power generation [16]; it has great flexibility in terms of site selection and can be utilized in grid - connected regions as well as remote areas [15]; it assists in cutting down fuel consumption and enhancing power supply dependability but demands a large initial investment in equipment and also incurs relatively high subsequent maintenance expenses [15,16].

### 3.3. Robust wind-hydro-thermal unit commitment (HTUC) model

This system is made up of wind - generated electricity, run - of - river hydropower, and thermal power, and some plans further incorporated pumped hydro storage [8,9,11], its advantage was that coordinating multiple sources could effectively stabilize wind power fluctuations and enhance power supply dependability, however, the drawback was the strong interconnection among energy units which made it more challenging for the modeling and resolution of robust dispatch [10,12,14],

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the system was significantly influenced by seasons as hydropower production was plentiful during the wet seasons but limited in the dry seasons and wind power also exhibited seasonal variability [8,10], these systems were usually located in areas with ample water resources, substantial topographical differences, good wind conditions, and appropriate grid connection conditions [8,9,13] and the operational limitations were more practical, including engineering requirements like hydropower head [13,14].

### 3.4. HPP-BESS hybrid system

The system mainly comprises hydropower and battery energy storage, forming a new-type power generation unit with coordinated operation of the two [17,18].

It has the feature of rapid frequency regulation response, can offer diverse grid services, and functions more nimbly [18-20], but it entails a large initial outlay and a complex coordinated control mechanism [21] and the seasonal variation in the output of hydropower could be effectively evened out by this system [22].Ideally, it should be placed near existing hydropower stations and constructed by retrofitting the grid connections of the original facilities [17,23] and revenue might be increased by enhancing grid service capability and taking part in the auxiliary service market [19,20], however, expenses related to equipment and control technology would go up to a certain extent [21].

## 4. Site selection considerations

The next part delved into the site - selection factors of diverse hybrid systems, furnished perspectives for transforming hydropower stations with different topographies and resource situations into hybrid systems, and supplied decision - making assistance for policymakers.

### 4.1. Hybrid energy system (HES)

For hybrid energy systems that combine pumped hydro storage with cascade hydropower and PV, site selection strategies differ depending on the features and differences of the supporting energy types. When pumped hydro storage units are added to cascade hydropower stations, site selection should be based on the existing cascade stations, fully utilizing basic hydraulic conditions such as reservoir capacity, and maintaining coordination between the site layout and the overall dispatch of cascade hydropower [6], so as to guarantee the energy utilization efficiency of the hybrid system. For hybrid systems combining pumped hydro storage and photovoltaic power generation, site arrangement should be centered on PV plants. The key lies in choosing a location that satisfies the common geographical requirements of both pumped hydro storage and PV stations, matching the fluctuation pattern of PV output and meeting the basic conditions for hydropower development, thus ensuring sufficient regulation capacity when PV generation fluctuates [7].

### 4.2. PV-wind-diesel-PSH-battery hybrid system

Site selection for such hybrid renewable energy systems is determined by fully considering local renewable energy resources, combined with energy storage conditions and facilities [15,16].

For the photovoltaic - wind - diesel - hydrogen - battery hybrid system [16], the complementariness of wind and solar resources was a crucial factor during site selection and the transportation expenses of diesel and hydrogen also had to be taken into account; for hybrid systems incorporating batteries, hydrogen energy and pumped - hydro storage [15], apart from the

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fundamental wind and solar resource conditions talked about earlier, the geographical and water resource demands of pumped - hydro storage needed to be met as well; the power generation and energy storage components required a meticulously optimized arrangement to reduce transmission losses to the greatest extent possible; it was clear that scientific site selection was an important precondition for guaranteeing the technical practicability and economic rationality of both kinds of hybrid systems [15,16].

### 4.3. Robust wind-hydro-thermal unit commitment (HTUC) model

The site selection for the wind - water - thermal hybrid system had to be in line with the characteristics of every energy source as well as the requirements for coordinated operation, which was crucial for the stable operation of the system [8,9].

Run-of-river hydropower requires river sections with stable and seasonally balanced runoff to maintain stable baseload output to a certain extent [8].

Wind farms should be built nearby to reduce transmission losses, so that wind power fluctuations can be smoothed rapidly [9,10].

Pumped storage power stations demand suitable topographic conditions for upper and lower reservoirs [11].

Constructing such stations in wind-rich areas and near main grid nodes can fully exert the system's advantages in peak-shaving and valley-filling [11].

Wind farms are preferably developed in areas with excellent wind resources [14].

Given the intermittent nature of wind power, a wide - area layout allows for mutual compensation between wind farm clusters which lessens the risk of synchronized wind power fluctuations in a specific region [14].

Matching the regulation capacity of hydropower also supports wind–water coordinated operation to a certain degree [8,10].

The overall system should be located in regions with relatively sufficient wind, water and thermal supporting resources, laying a solid resource foundation for multi-energy complementarity [14].

In the case of head - dependent hydropower, plants need to be located at places where there is a weak connection between reservoir capacity and head fluctuation so as to reduce the influence of head changes on hydropower generation as much as possible [13].

Distributed supplementary systems were arranged in accordance with layered and zoned principles starting from regions having a robust power grid framework so as to comprehensively ensure the coordinated control of sub - systems and the capacity for outward power transmission [12], and the scientific layout of all energy stations demanded the combination of the intermittent nature of wind power, the controllable feature of hydropower, and the supportive function of thermal power to attain complementarity, which thus ensured stable and economical operation [8,12,13].

### 4.4. HPP-BESS hybrid system

The selection of location for the hydropower - Battery Energy Storage System (BESS) hybrid system depends on meeting the criteria for the combined operation of hydraulic turbines and battery energy storage, along with the actual demands for grid services, and the site should be suitable for the overall layout of the entire system and their coordinated control [17,18,23].

For experimental hydropower-BESS facilities, the site should allow scaled model tests and reserve sufficient space for joint control and commissioning [23,24].

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The battery energy storage system was supposed to be set up near hydropower units so as to cut down on the control signal transmission delay and make it easier for them to jointly offer grid services like frequency and voltage regulation [19,20].

Constructing large - scale hydropower - BESS hybrid plants doesn't necessitate the acquisition of new land because they could be constructed depending on the existing hydropower stations and directly utilize the available grid connection conditions [17,21].

Hydropower - Battery Energy Storage System (BESS) units utilized for grid frequency regulation could be situated in regions having a rather high need for grid frequency regulation, at places where the location was appropriate for the integrated setup of variable - speed hydraulic turbines and energy storage systems [18,22].

For grid-forming hydropower-BESS units, site selection should follow the grid structure layout to ensure a certain supporting and regulating effect on the power grid [24].

In general, site selection mainly involves striking a balance between the operational compatibility of hydraulic turbines and energy storage systems, making the greatest efforts to enhance the site's adaptability for their collaborative operation in order to fully utilize the grid - serving capacity of the hybrid system [18,22].

## 5. Cost and economic analysis

The ensuing part conducted an economic analysis founded on the fundamental retrofitting expenses of diverse hybrid systems so as to assist policymakers in estimating the necessary investment and payback duration for transforming hydropower plants into hybrid systems.

### 5.1. Hybrid energy system (HES)

Through research on retrofitting cascade hydropower stations with pumped - hydro storage and employing pumped - hydro storage to even out PV output fluctuations [6,7], the economic performance of the hydro - wind - PV - storage integrated system was partially optimized and the crux was the accurate capacity apportionment of pumped - hydro storage, which attained a rational equilibrium between resource utilization and cost control in actual demand.

The capacity apportionment of pumped - hydro storage ought to a certain degree relinquish the pursuit of an overly large scale [6,7], and when retrofits are carried out for pumped - storage units in cascade hydropower stations, the planning should take into account the pre - existing hydraulic structures and generating apparatus so as to prevent cost overruns resulting from over – retrofitting [6], also the system needs to be compatible with the output traits of cascade hydropower, facilitate grid peak regulation, boost the hybrid utilization of multiple resources, and enhance efficiency as far as possible; moreover, for pumped - hydro storage intended to alleviate photovoltaic (PV) fluctuations, the minimal regulatory capacity should be determined in accordance with the fluctuation pattern of PV output [7] to accurately correspond to the requirements and cut down on issues such as high construction expenses and unit regulation costs brought about by excessive capacity enlargement.

Retrofitting cascade hydropower stations with pumped hydro storage offers a highly effective means of controlling costs in hybrid systems [6], reactivating existing hydropower resources significantly lessens the initial outlay and decreases capital expenditures, when contrasted to the substantial civil engineering expenses associated with newly - constructed pumped storage facilities, retrofitting could directly make use of the pre - existing reservoirs and water conveyance networks so only specific retrofitting of pumping capabilities and support apparatus was required which

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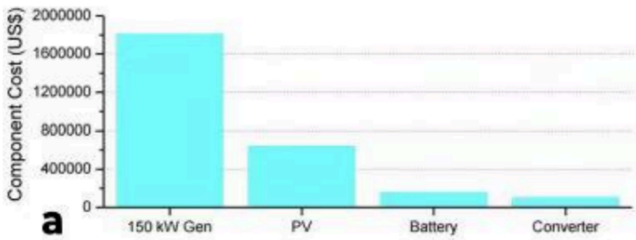
efficiently reduced the retrofitting cost per unit capacity and cut down the investment involved in integrating pumped hydro storage into hybrid systems.

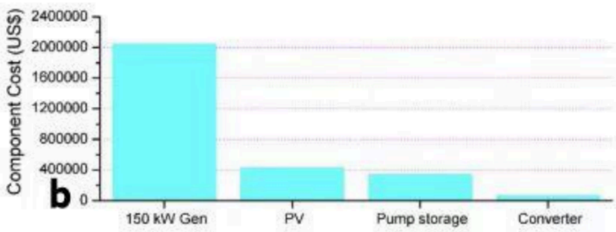
In brief, the economic optimization of the hydro - wind - PV - storage integrated system resides in extensively retrofitting cascade hydropower stations with pumped hydro storage [6], aiming to make full use of the existing installations and inventory assets so as to attain a proper combination of technical viability and economic rationality.

### 5.2. PV-wind-diesel-PSH-battery hybrid system

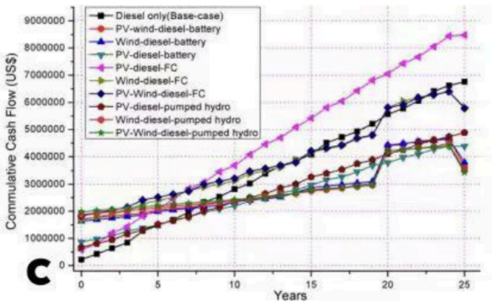
The hybrid system which combines battery energy storage with photovoltaic (PV) and diesel has the most favourable economic performance (Figure 2 a) and represents the best short - term cost solution currently; pumped - hydro storage comes in second in terms of cost (Figure 2 b) and increases the proportion of green power to approximately 89.8%; hydrogen energy storage has the least economic viability because of the high equipment cost and low conversion efficiency [15], which also verifies the common problem that single - type energy storage can scarcely balance cost and reliability, so hydrogen energy needs to be combined with batteries to cut down on redundant configuration and control costs to some extent [16].




*a PV-diesel-bess cost diagram [15]*




*b PV-diesel-PSH cost diagram[15]*




*c Cumulative cash flow analysis for representative configurations[15]*

Figure 2. Schematic of cost and payback period for selected hybrid systems

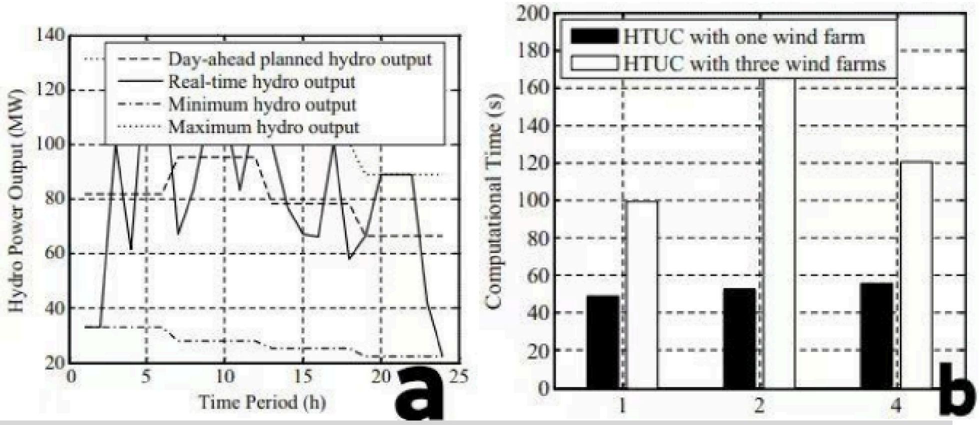
There was no one - size - fits - all solution for cost optimization in the short run and it had to be customized according to actual application situations as both references [15] and [16] demonstrated that diverse scenarios brought about substantial distinctions in low - cost configuration logic; for short - term cost cutting with minimal clean power requirements, the battery - diesel combination presented in [15] could be utilized and for off - grid systems with elevated reliability requirements, the multi - energy complementarity and hydrogen - battery dual - storage system offered a proper guideline, equalizing high initial and operational costs [16]; to attain a high proportion of green power, the pumped hydro storage coupling scheme was a more favorable long - term option [15] and even though its initial outlay was rather high, the PV - diesel - pumped hydro storage hybrid system had the shortest payback duration (approximately 5.53 years, Figure 2 c) and could significantly cut down on fossil fuel dependency.

Although hydrogen is a high-efficiency clean energy source, hydrogen energy storage does not yet have strong economic competitiveness.

Research in both bodies of work indicated that hydrogen energy storage posed a crucial challenge in cost optimization for hybrid systems, and hydrogen had the poorest economic performance across all scenarios [15], could only serve as a supplementary energy storage means and needed to be combined with batteries and diesel to reduce cost risks to some degree [16], and its fundamental issue was the conflict between high equipment costs and low energy conversion efficiency, so for future large - scale utilization, cutting costs through technological progress should have been the primary goal.

### 5.3. Robust wind-hydro-thermal unit commitment (HTUC) model

Various forms of hydropower result in distinct system expenses and diverse requirements for cost reduction; lacking in fuel cost, run - of - river hydropower could be incorporated into the scheduling system to partially substitute for thermal power in peak regulation which directly cut down on the fuel and transportation costs of thermal power [8-10]; when coupled with pumped hydro storage, the hydropower system utilized the high - efficiency peak - shaving capacity of charging and discharging to even out substantial fluctuations brought about by wind power (Figure 3 a) which prevented additional costs arising from the frequent starting and stopping of thermal power units, enhanced the wind power utilization and absorption rate, and decreased revenue losses due to wind curtailment [11]; to a certain degree, unnecessary additional costs resulting from scheduling deviations could be avoided by perfecting the practical constraints within the model; Ref [13]. incorporated the head - dependent output feature of hydropower into the model, averting irrational hydropower scheduling due to over - idealization and further decreasing the cost of supplementary thermal power generation when hydropower output was inadequate; Ref [14]. introduced the spatiotemporal correlation of wind power, depicting the fluctuation pattern of wind power more precisely and mitigating scheduling errors and cost hikes caused by wind power prediction deviations.




*a Day-ahead and real-time power output of hydropower plant[8] b Computation Time of Large-Scale Power Systems[8]*

Figure 3. Hydropower scheduling & system computation time

As the quantity of wind farms grows, the complexity of the system also rises (Figure 3b) so ways to get optimized solutions are extremely important for cutting down the costs related to computation and implementation in large - scale systems [12], For large - scale wind - water - thermal systems, a distributed method of solution was put forward which significantly enhanced the efficiency of solving the robust unit commitment model, lessened the costs of scheduling decisions brought about by too much computation time and enabled cost - reduction plans to be practically applied, Researchers simplified the calculation procedure by optimizing the constraint logic of the model which indirectly decreased the actual implementation cost once the scheduling plan was implemented [8-10] and the robust unit commitment framework made the coordinated control of system cost and power supply reliability possible.

All researches confirmed that integrating the strong optimization framework with the regulatory features of hydropower could attain rational energy distribution and effective utilization while dealing with the unpredictability of wind power [8-14].

Substituting hydropower for thermal power was able to cut down on fuel usage and start - stop expenditures to some degree and exact strong constraints could further prevent cost wastage resulting from over - regulation at peak times; on the basis of guaranteeing the dependability of continuous power supply, the ideal minimum cost of the entire scheduling procedure was achieved which also offered a practical notion for further cost reduction within the integrated wind - hydro - solar - storage system.

### 5.4. HPP-BESS hybrid system

A hydropower - battery hybrid system might boost the initial outlay on equipment in the short run but could significantly cut down the expenses related to large - scale retrofitting of the principal hydropower facility thus resulting in a reduced overall cost for system renovation [18,23] and experiments showed that battery energy storage was able to partially substitute for the extensive retrofitting of the hydropower governor and variable - speed systems merely needing a straightforward alteration of the hydropower control interface and commercial technologies further demonstrated that the initial expenditure on batteries was much less than the cost of profound hydropower retrofitting while effectively lowering the unit retrofitting cost of the system [20].

Hydropower - battery integrated systems are able to offer diverse grid services and efficiently broaden revenue avenues, with the extra income sufficient to cover the expenses for battery maintenance; research indicated that the collaborative operation of batteries and hydropower could concurrently provide multiple grid services like frequency and voltage regulation, which broke the revenue constraints of standalone hydropower systems to some degree [19,20], and these hybrid system configurations vigorously promoted grid marketization so the additional income was capable of countering the costs of day - to - day battery maintenance and degeneration, thus the net revenue of the hybrid system was far greater than that of a single hydropower system [17,24].

Optimizing the control and operation strategies of the hybrid system could further enhance equipment utilization efficiency and cut down full - life - cycle operation costs. References [18] and [24] put forward specific grid - forming and frequency regulation control strategies for such systems which made it possible to coordinate more efficiently between hydropower and battery output, lessen the invalid charging and discharging losses of batteries and directly reduce maintenance costs. The frequency regulation plan that combined variable - speed hydraulic turbines with batteries suggested in [22] further decreased ineffective hydropower output, boosted overall energy utilization and reduced the long - term operation costs of the system.

Standardized and large - scale technical solutions are able to further cut down on full - life - cycle costs and enhance the economic feasibility of battery integration within small and medium - sized hydropower stations as both the XFLEX HYDRO standardized plan and the HYBATEC commercial

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plan decreased equipment purchasing and construction expenses via standardized design [17,21] and large - scale utilization further reduced R & D and subsequent maintenance costs which effectively resolved the issue of poor cost - effectiveness regarding battery matching in small and medium - sized hydropower stations brought about by their small size and high individual retrofitting costs.

## 6. Conclusions

Briefly, hybrid energy systems are able to even out the output fluctuations of wind and solar power, compensate for the efficiency drawbacks of pumped - storage hydropower, and substitute for thermal power so as to reduce energy consumption, enhance the absorption of renewable energy and the reliability of power supply, and enlarge diverse grid services which is very much in line with the dual - carbon objectives; the multi - energy complementary pattern reactivates the existing hydropower resources and different hybrid setups fit various situations with their technical and economic feasibility constantly being improved; in the future, we need to push forward with the coordinated dispatching and strong optimization of multi - energy systems, boost the standardization and large - scale development of equipment, and balance cost and reliability to support the high - quality integrated development of clean energy.

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