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From Green Energy to Green Ecology: A Review of Ecological Impacts and Regulatory Strategies of Pumped Storage Hydropower (PSH)

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Abstract:

In the context of the "dual-carbon" goal and the global energy transition, pumped storage power plants have been widely deployed as an important support for green energy systems due to their peak-regulating and energy-storage advantages. However, while bringing resilience to the energy system, pumped storage power plants also have multi-dimensional impacts on the ecological environment. In this paper, we systematically sort out the potential disturbances to water ecosystems, biodiversity, landscape patterns and socio-ecological systems during the planning, construction and operation of pumped storage power plants, and analyze the typical ecological risks such as water quality changes, habitat fragmentation, and land-use transformation. The current mainstream ecological regulation and management strategies are further summarized, including eco-friendly engineering design, water level regulation, environmental impact assessment systems, and ecological compensation mechanisms. Case studies demonstrate that the ecological impacts of pumped storage vary across regions and plant types, requiring adaptive and site-specific solutions. This paper highlights the importance of integrating ecological science and engineering technologies. It provides theoretical insights and practical guidance for promoting the sustainable and ecologically compatible development of pumped storage systems.

Keywords: Pumped Storage Hydropower; Ecological Impacts; Environmental Regulation; Sustainable Energy; Ecosystem Management.

1. Introduction

It is known that the Paris Agreement aims to limit the global average temperature increase to 1.5 °C above pre-industrial levels [1]. Achieving net-zero carbon emissions and global carbon neutrality requires a profound transition in the energy sector, which is one of the key contributors. Developing renewable energy sources (RES) such as wind and solar power has become an inevitable trend in meeting the "dual carbon" goals. According to the International Renewable Energy Agency (IRENA), by the end of 2021, global renewable energy capacity had reached 3.064 billion kilowatts, representing 38.3% of total installed power generation capacity [2]. Although renewable energy is providing a larger proportion of electricity in power system, it poses inevitable challenges that need to be faced with. RES like solar and wind are intermittent in nature; their output fluctuates based on weather conditions and time of day; it is difficult to accurately forecast the quantity and timing of production, which poses difficulties for grid stability and power supply reliability [3]. As one of the general methods for intermittency management, electricity storage technology has been a hot issue in research and application fields.

Among RES, wind power is particularly variable, changing on hourly, daily, weekly, monthly, and annual timescales [4]. Therefore, to effectively integrate wind energy into the grid and ensure a stable power supply, large-scale energy storage systems are essential. As pumped storage hydropower (PSH) is the only proven large scale (4100 MW) energy storage scheme for power system operation [5], PSH is the most widely adopted utility-scale electricity storage technology. PHES comprises about 96% of global storage power capacity and 99% of global storage energy volume [5]. In addition, PSH is a technology that is mature enough to be applied to load balancing [6]. Multiple researches have proven that PSH is an energy storage technology that is critical and mature enough to play a role in power system. For example, Researchers conducted a survey and found that providing renewable support and peak power adequacy are two key functions of PSH [7].

Although PSH is a technology that can well support renewables penetration and is considered as a clean energy, it poses other ecological risks. Conventional PSH construction sometimes involves damming a river to create a reservoir. This causes several environmental problems like blocking natural water flows that disrupts the aquatic ecosystem, flooding of land that destroy terrestrial wildlife habitats, increasing water temperature that deteriorate water quality, etc [8]. Other environmental impacts might be brought up during the constructions of PSH including project constructions and daily operations [6]. In addition, large requirements of water may also cause problems in water resource management. As a result, it is important to raise concerns of the potential ecological risks in PSH and take actions to protect terrestrial and aquatic environment in the process of PSH plants installation.

2. Overview of Pumped Storage Hydropower

PSH works by storing energy as the potential energy of water pumped from a lower to an upper reservoir. When energy is needed, water is released to flow back down through turbines, converting potential energy into electricity. Also, it can store power when water is pumped to the upper reservoir, which makes the generator spin in the reverse direction [6]. For reliable operations, it requires basic facilities including two reservoirs with adequate capacity and waterhead, penstocks that can withstand large pressure and turbines that can accomplish the transformation of forms of energy. Generally, PSH is an energy storage technology that can store power and release it when needed.

PSH has a wide range of applications but the most major function is the energy shifting, the process of storing electricity during off-peak hours for use during peak hours. Research indicates that 86.3% of total PSH in operation are used for peak shaving, while 4.6% and 3.8% are used for black start and electric supply capacity respectively [9]. Apart from these conventional usages, an application of supporting renewables is developing in the background of the increasing penetration of RES in power system. As it needs low maintenance cost, installs with large capacity and performs environment friendly, PSH are now considered well-suited for balancing large amounts of variable, inverter-based wind and solar [10]. Together, the operation of PSH can completely become an ancillary service of supporting renewable energy.

There are mainly two types of pumped hydro based on water sources, which are closed-loop PSH and open-loop PSH. The closed-loop PSH has two artificial reservoirs and both do not connect to natural flow, while the open loop PSH has reservoirs that is connected to continuous river [11]. Generally, the closed loop pumped hydro stored lower energy than the open loop reservoir. However, it usually has better head, less flood mitigation cost and faster construction time. More importantly, it has better control over environmental impacts as it won't cause extra disturbance to aquatic environment. In addition, PHS can be classified based on various factors, with each type having operational and constructional difference [9]. For

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example, there are fixed speed PSH where the pumping is done at a fixed synchronous speed [11] and variable speed PSH of which the adjustable speed turbines provide flexibility in operating range. Usually, variable speed PSH have better efficiency, less rough zone and can operate at lower power levels as well. Apart from these classification, there are PHS with single/double penstocks, PHS with conventional/non-conventional reservoir configuration. Overall, different types of PHS has their own pros and cons, and our study is also going to figure out different impacts of types of PSH on environment.

3. Ecological Impacts of Pumped Storage Hydropower

Pumped storage hydropower is expected to make great contribution to energy storage in the future as it can support renewables penetration and considered to be a kind of low-carbon energy storage technology. However, many problems can be brought up during the construction and operation of PSH especially the environmental and ecological disruption. Also, those environmental effects vary among different types of PSH (the closed-loop and the open-loop PSH) in different aspects.

3.1 Impacts on Aquatic Ecosystem

3.1.1 Water Quality and Aquatic Biodiversity

The impacts of PSH on water quality are the most immediate. PSH constructions and operations can modify abiotic and biotic properties of the connected water bodies [12]. As conventional PSH often requires damming a natural flow to create a lower reservoir, it directly changes the flow rate downstream and thus have impacts on hydrochemistry of the water body [13]. In addition, water quality could be affected due to the regular pattern of water withdrawal from and discharge to the naturally flowing water bodies. For instance, research of Etzelwerk PSH plant has shown that water exchange can greatly affect the seasonal dynamics of parameters like temperatures and nutrients [13].

Apart from the abiotic impacts, changes in basic parameters of the water body can have further effects on biodiversity. For example, research studied the downstream effects of a PSH plant Čierny Váh and found a significant decrease in benthic species richness downstream, which indicates that the operations of PSH can somehow change the community composition [14]. The PSH constructions and operations can also change other aquatic ecology by directly causing habitat loss and impingement and entrainment. Moreover, open-loop projects might have higher side effects on natural water body than closed-loop projects. Commonly, fish are greatly affected as they might get injured and die due to impingement and entrainment in project facilities especially the water intakes. Also, fish and other aquatic species might lose their sense and directions for migrations because of pumping and generating cycles [13].

3.1.2 Groundwater Quality

With respect to the groundwater quality, the impacts of closed-loop projects are more severe as some of them use groundwater to fill the reservoir. Generally, potential impacts are linked to the effects of underground tunneling or reservoir seepage on groundwater quality or flow. Due to consumptive water use, excessive exploitation of groundwater might induce groundwater connectivity and circulation. In addition, reservoir seepage might cause pollution of groundwater, which indirectly impact aquatic habitat [13]. There are underground pumped storage hydropower using abandoned mines as an alternative system to manage electricity production in flat regions. However, the water hydrochemistry varies during operation. It is reported that those hydro chemical variations may lead to reactions in the reservoirs and in the surrounding porous medium, causing potentially negative consequences for the environment like a decrease in pH and the precipitation of goethite or schwertmannite in the surface reservoir [15].

3.1.3 Geology and Terrestrial Biodiversity

Another impact of PSH on environmental issue is mainly focusing on terrestrial resources including geological and ecological problems. About geology issue, it is reported that a surface land subsidence may occur due to underground excavation and tunneling or pumping groundwater from an aquifer. For instance, it is identified that the daily movement of water between the two reservoirs could affect stress conditions during project operations at the Minvielle Project, which might induce earthquakes and collapses. It is also reported that wave actions and fluctuating water levels might induce changes of geological structure of reservoir slope and thus impact stability of the slope [16]. Apart from possible geological disasters, constructions and operations of PSH might also cause soil loss due to large scale of spoils and destruction of vegetation during excavation [17]. In addition, either surface excavation or underground tunneling may disturb terrestrial wildlife and even cause permanent habitat loss. Analysis on Terrestrial Ecological Impact of Wufeng Taiping Pumped Storage Power Station shows that habitats of wildlife animals and plants are largely affected. Also, net productivity and ecological function of soil and water conservation was diminished due to reduced vegetation coverage [18].

3.2 Impacts on Society and Ecosystem

While PSH has side effects on environment, it affects resources and land that humans need for production and residence, and thus induces amounts of social problems. In the final analysis, social problems occur when there's mismatches between the availability of water for irrigation and electricity generation (role of energy storage) and conflicts of plant construction and other land use.

3.2.1 Water resources

During construction and operation of PSH plants, a consumptive water use is inevitable, causing water supply reduction for social uses like irrigation. For instance, It is reported that groundwater withdrawals at The Big Chino Valley project could affect water supply for irrigation, livestock grazing, and domestic and municipal water supplies [13]. In addition, water supply can not only be affected by water shortage, but also pollution. Take the upper reservoir of a pumped storage power station in the eastern part of Shenzhen urban area as an example. During the construction process, a large amount of solid waste is generated. Most of this waste is piled up within the basin. The inflow of waste and the infiltration of surface runoff routes have polluted and damaged a large area of water resources [19]. Apart from water supply, impacts on water quality might also adversely affect recreational fisheries and boating [13], which might eliminate social-economic value in related regions.

3.2.2 Land use and other resources

There's a difference between closed-loop projects and open-loop projects in the impacts on terrestrial ecology, land use and other human activities. It is often difficult to avoid disturbing the sensitive terrestrial resources when they are nearby [13]. Specifically, as with any major dam or infrastructure project, PSH projects can result in loss of land and property, changes in land use and recreation access, and changes in local demographic patterns due to population influx during construction, which, in turn, can strain local infrastructure such as schools and hospitals and create housing shortages, among other issues [20]. Also, PSH project construction and operations can significantly affect tribal and cultural resources and sacred sites in United States. It is reported that Suitable sites for PSH often include ridgelines where project construction and operation can impair viewsheds of areas long used by Tribal members for spiritual rituals [20], while these spiritual rituals is significantly related to local cultural resources.

4. Regulation and Mitigation Strategies

4.1 Ecological engineering

Since open-loop project requires damming a naturally flowing water feature to create the lower reservoir, leakage and evaporation volume increase and thus induce reduction of water flow downstream, which cause numerous ecological issues. To resolve it, the common method is to discharge the ecological flow. For instance, to protect the habitats of birds, amphibians, and fish, the Hubei Dawu Pumped Storage Power Station project has implemented a minimum ecological flow release measure, diverting natural inflow into the downstream river [21]. At the Nanning Pumped Storage Power Station, to maintain downstream ecological balance and meet other water usage demands, the lower reservoir released 1.656 million m^3 of water (over 36 months of impoundment), accounting for 14.8% of the total inflow, which complies with local regulations and requirements [22]. Apart from habitat loss and destruction, losses of fish due to impingement and entrainment should be think highly of. Fortunately, there are now engineering measures to protect fisheries resources. A report suggests that fish interceptions at water intakes by electric barriers can prevent fish from entering water intakes, thereby avoiding harm to them [23]. Wastewater is also a major factor of impacts on water quality and wildlife habitats. There are now methods of purifying wastewater and reuse it in construction. Take the Attaka Pumped Storage Power Station in Egypt as an example: The project site lacked available natural surface water sources, so the treated effluent from the Suez City Wastewater Treatment Plant was utilized. Monitoring showed that the total dissolved solids (TDS) concentration in the treated water was 2,660 mg/L. However, after advanced treatment using Ultrafiltration-Reverse osmosis, the desalination rate exceeded 95%, reducing TDS to 133 mg/L [24].

In addition to potential surface water contamination during construction, groundwater may also be polluted, particularly in closed-loop projects where groundwater contamination remediation becomes significantly more challenging. Generally, groundwater can be polluted due to seepage or leakage of reservoirs. Solutions of the issue like installation of a liner in project reservoirs, water conveyance tunnels are common. Likewise, sealing mines to prevent infiltration of outside water or loss of water from the project was also frequently proposed to prevent leakage [13]. However, the underground water reservoirs (UWRs) technology is different in China, surpassing the original "blocking method" water retention concept and adopting the "conducting storage" concept to divert mine

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water into the underground goaf for storage and utilization [25].
Fluctuations of water levels can induce soil loss and soil erosion, which might cause terrestrial habitat loss and geological risks. Generally, Erosion control measures to mitigate potential impacts to geologic and soil resources invloves vegetation and adding rip rap to stabilize soils [13]. Increasing vegetation coverage is a common solution but it requires ensuring diversity and preventing invasive species. Apart from simply stabilizing the soil, Wang et al introduce a method which can both eliminate soil loss and tackle the water shortage problems. By constructing sediment basins, turbid water containing silt can be diverted into these depressions. Site-specific anti-sediment measures can then be implemented based on local topography. The water flow is subsequently interrupted by baffle structures, allowing suspended sediments to settle at the bottom. This process effectively reduces turbidity and filters the water, enabling its circulation and reuse [19].

4.2 Environment monitoring and management

To correctly evaluate the impact of PSH on environment, monitoring is necessary. In respect of water quality control, monitoring generally focuses on discharge of sewage during construction and operation. In addition, researchers often use models to simulate different scenarios for further analysis and predictions. For instance, to simulate the transportation of ammonia nitrogen and phosphates in the discharge of sewage into the sea, MIKE21 hydrodynamic model was used in the research for water quality of a seawater PSH in China [26]. Also, research studying the impact of water exchange and deep-water withdrawal on water quality triggered by operation of PSH simulates different scenarios with water quality model CE-QUAL-W2 [27]. Monitoring changes of geological structure and fluctuations of water level is significant for analysis of environmental impacts and collapses risks. It is reported that applying monitoring technologies such as high-precision GNSS and InSAR and establishing a displacement prediction and early warning model can improve stability of reservoir slopes [16]. Moreover, to predict and control occurrence of geological disasters like landslides and collapses during tunneling, monitoring is necessary for analyzing stress and deformation of rocks, and thus ensure the safety of constructors. Apart from modelling, remote sensing (RS) is also a reliable technology of environment monitoring. Research of Tai' an Pumped Storage Power Station analyze land use and landscape based on RS and found that the ecosystem has been improved due to an appropriate preservation for environment. Though monitoring technologies are effective for different kinds of environmental issues, it is useless if regulations and management are too weak to ensure measures implemented in place [28]. For example, During the construction of pumped storage power stations, strict regulations mandate that all construction vehicles must reduce speed when entering work zones to minimize dust emissions and mitigate habitat degradation for wildlife. Additionally, in China, construction personnel are required to comply with the Wildlife Protection Law of the People's Republic of China. Prior to construction, workers receive education on these protocols, with an explicit prohibition against hunting or harming wildlife [21].

5. Conclusion

As a key facility for green energy development, pumped storage hydropower plays an important role in optimizing the energy structure and the consumption of renewable energy. However, their potential impacts on the ecosystem should not be ignored, especially in terms of water allocation, biological habitat and regional landscape. This paper points out that ecological control strategies and governance mechanisms are the key to realizing the transition from "green energy" to "green ecology", and future research needs to integrate ecological science, engineering optimization and policy tools to promote pumped storage energy towards eco-friendly development paths.

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