Pumped Storage Hydropower: A Grid Intermittency Solution

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Abstract

As public pressure and state emissions targets increasingly promote grid decarbonization, society must find solutions to the intermittency problem of renewable energy. While several emerging battery technologies provide a solution to this problem, pumped storage hydropower (PSH) is the most promising given its long lifecycle and widespread deployment. This paper will analyze and compare PSH with other battery technologies, review existing funding opportunities, and provide recommendations on how the United States government can effectively promote grid sustainability. By repurposing abandoned mountaintop removal coal mining sites, the government can increase PSH capacity.

Keywords Grid Decarbonization · Pumped Storage Hydropower · Sustainability · Energy Storage · Coal Mining

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1 Introduction

Since the industrial revolution, technological innovation has increased, and so have greenhouse gas emissions (GHG). If left unchecked, this rise will create disastrous global economic challenges (Portner et al., 2022). This is because of the greenhouse effect, a physics property where GHGs like carbon dioxide and methane trap heat and keep the Earth warm. However, with an increase in GHGs, this effect will increase temperatures and significantly alter weather patterns (Denchak, 2019). The United States, and the world as a whole, must transition away from GHGs to protect future generations.

In 2020, the United States produced 6000 million metric tons of carbon emissions, 25 percent of which came from an electric grid that relies primarily upon coal, oil, and natural gas. Environmental experts and policymakers have come to a consensus that this significant source of emissions must be reduced (US EPA, 2022).

Intermittency issues of renewable energy pose a key challenge to grid decarbonization. Solar and wind energy are inconsistent because they are generated from natural events, an issue typically combatted with nonrenewable natural gas. Without progress in energy storage, this reliance on natural gas will hinder grid decarbonization (Gürsan and Gooyert, 2021). As renewable energy costs decrease, deployment of solar and wind increases, so it is clear that increased energy storage is also needed (Jansen et al., 2022; Feldman et al., 2021).

2 Lithium-Ion vs. Pumped Storage Hydropower

The two most popular forms of grid-scale energy storage in the United States are lithium-ion battery (LIB) storage and pumped storage hydropower (PSH). In March of 2022, PSH accounted for 23 GW of active storage, while all battery storage, the vast majority of which is lithium-ion (Kamiya, Hassid, and Gonzalez, 2021), accounted for 4 GW of storage (EIA, 2022a). Lithium-ion is an appropriate comparison for PSH because both are time-tested and widely deployed forms of energy storage (Bowen et al., 2021).

2.1 Costs and Impacts of Lithium-Ion Batteries

LIBs discharge by moving lithium ions from the anode of the battery to the cathode through a separator. Electrons move to the cathode through an external wire to bring the charges to equilibrium. When charging the battery, the opposite happens (Chapman, 2019).

LIBs have a highly competitive price. An analysis by the National Renewable Energy Laboratory (NREL) has found that they have one of the lowest costs of grid-scale energy storage with a range of $1408 to $1947 per kilowatt (Bowen et al., 2021). Analysts predict battery costs will fall further over the coming years, even with the disruption by the coronavirus pandemic (Frith, 2021).

Another key advantage of LIB storage is its high energy density. Compared to other chemically-based energy storage, lithium-ion battery systems have the highest energy density at 210-325 wH/kg (Bowen et al., 2021). The electric car company Tesla, for example, designs a 3 MW system with a footprint of 7.14 x 1.60 m (Lambert, 2018). With a smaller footprint, there is reduced installation-related environmental damage.

However, the creation of lithium-ion batteries results in a catastrophic environmental and social impact. Their short lifespan leads to a high amount of electronic waste. Due to battery degradation, LIBs only have a lifespan of 10 years (Bowen et al., 2021).

Lithium-ion batteries are also difficult to recycle. A 2022 paper found that the current recyclability of LIBs is less than 1 percent due to their human-risk potential from flammability (Yanamandra, 2022; O'Connor and Wise, 2021). While continued research and development in the field will increase this percentage, existing low recyclability makes it difficult to argue that LIB systems are truly sustainable.

Despite their relatively small environmental impact when installed, LIBs have a significant upstream impact. The creation of lithium-ion batteries requires many rare earth minerals. Two of which, lithium and cobalt, have most of their deposits in the Global South. According to the United Nations, in Chile's Salar de Atacama, lithium mining contributes to 65% of water usage, leading to groundwater depletion and soil contamination. According to UNICEF, about 10 percent of the cobalt supply comes from mines where more than 40,000 children work. These two findings exemplify the negative impacts of LIB production (United Nations Conference on Trade and Development, 2020).

Promising technologies suggest viable green methods for extracting these minerals. Significant research has been conducted on the geothermal extraction of lithium, which promises to reduce water use and CO_2 emissions by more than 99 percent (Early, 2020). Much like the recyclability issue, the production of LIBs will continue to get more sustainable over time.

Nevertheless, these batteries still have the key problem of relying on rare earth minerals. Researchers at the University of Augsburg and the Lappeenranta-Lahti University of Technology predict that the world could run out of lithium anywhere between 2040 and 2100. As the lithium supply continues to decrease, basic economics dictates that the price will increase. It becomes difficult for policymakers to support continued investment in a technology that will become cost-ineffective and unusable in the long term (Greim, Solomon, and Breyer, 2020).

2.2 Costs and Impacts of Pumped Storage Hydropower

PSH is significantly different from LIB storage. While LIB uses a chemical method to store energy, PSH uses a mechanical method. It uses two reservoirs, one situated at a higher elevation than the other. During times of excess electricity, water is pumped from the lower reservoir to the upper one. This water is then released and the force of gravity turns a turbine to generate electricity.

The two main types of PSH are open-loop and closed-loop systems. Open-loop systems use at least one natural reservoir, like a lake or river, while closed-loop systems use two artificial bodies of water. According to the NREL, the majority of new PSH capacity is closed-loop because of faster environmental review and location flexibility.

PSH prices remain competitive. At an initial range of $1,504-$2,422 per kilowatt, the upfront cost of installing PSH remains similar to LIB storage (Bowen et al., 2021). Prices will also decrease when adjusted for inflation. An NREL analysis predicts that between 2020 and 2030 the average cost for PSH projects will remain the same, $1,651/kW in 2020 USD, for a 1000 MW 10-hour system. As a result of not requiring rare earth minerals, pricing will remain more stable than LIB in the long term (Mongird et al., 2020).

One of the key advantages of PSH is the lifespan of future sites. Modern PSH applications have lifespans of 50-60 years. Initial investments will be able to provide value for many years after construction (Bowen et al., 2021).

There are, however, a few disadvantages of PSH. One of them is specific location requirements. A large mountain or hill with space to create the reservoirs are absolute necessities for PSHt. To install closed-loop PSH, the land must be cleared and flooded to create reservoirs, leaving a scar on the local environment.

Key differences emerge when comparing open-loop and closed-loop systems. Open-loop systems require less space but damage aquatic and terrestrial life because of pumping from a natural reservoir. Closed-loop systems, on the other hand, have greater impacts on groundwater supply and geology. Overall, the effects of open-loop systems, according to the Pacific Northwest National Laboratory, are more damaging to the environment when compared to closed-loop applications (Water Power Technologies Office, 2021).

Finally, one must consider that the creation of PSH systems leads to the displacement of individuals. PSH development occurs primarily in rural areas because of space requirements, but many of these individuals suffer disproportionately. Because rural poverty is greater than urban poverty, displacement, even with compensation, would damage the livelihoods of the most susceptible demographic (USDA, 2019).

3 Analysis

The key differences between these two types of energy storage can determine which is most promising for addressing the aforementioned intermittency challenges.

Firstly, it is important to note that the majority of PSH installation happened before the 1990s, while the first commercially viable LIB wasn't sold until 1991 (EIA, 2021 and Li et al., 2018). However, LIB installation is accelerating rapidly. According to the Energy Information Administration, battery capacity is predicted to more than double, with 5 GW projected for installation between March 2022 and March 2023 (EIA, 2022a). However, only 221 MW of PSH capacity is predicted to be installed over the same period.

Another key difference between LIB and PSH systems is their longevity. Lithium-ion batteries only last 10 years because of battery degradation. With every charge and discharge, their capacity decreases. While energy conserved in LIB systems is higher at 88%, PSH's multi-decade lifespan and only slightly lower efficiency (80 percent) create a viable alternative (Bowen et al., 2021).

One final difference between these sources of energy storage is who faces their environmental consequences. With LIBs hundreds of thousands of people, many of which are children, are forced to work in mines to collect the rare earth minerals for the batteries (United Nations Conference on Trade and Development, 2020). These batteries are then installed in compact plots of land. On the other hand, the installation of PSH can displace people where the storage is installed. To address this PSH disadvantage, previously degraded locations, known as brown-field sites, can be used to reduce negative effects and increase construction benefits (Gilfillan and Pittock, 2022).

Overall, PSH and LIB applications differ significantly. However, PSH proves to be a better choice for policymakers because of its more positive social impacts and longer lifespan. National and state policies can be utilized to promote future development.

3.1 Mountaintop Removal Coal Mining Sites for PSH: a Novel Solution

An unexplored solution to increase deployment is the use of former mountaintop removal (MTR) coal mining sites as locations to install closed-loop PSH. Since the 1990s, coal companies have used MTR to access surface coal in Tennessee, West Virginia, Virginia, and Kentucky. More than 500 mountains, or 1.2 million acres, have been destroyed to mine coal, and more than 400 sites have been abandoned (Appalachian Voices, 2021).

The key disadvantages of closed-loop PSH are damage to land and groundwater (Water Power Technologies Office, 2021). Redevelopment of MTR brown-field sites for PSH is an ideal solution to these challenges.

The MTR brown-field sites are previously damaged, so there would not be an additional negative effect on the land through PSH construction. These mountains have prior road access for mining operations, eliminating the need for new roads to enable PSH construction and service. This will reduce project costs and environmental harm. In some cases, companies used explosives on these mountains to access coal buried 600 feet underground. These previous explosions created poor geology and soil at the site, so PSH deployment is expected to have minimal further impact on the surrounding area. During mining, forests are fragmented and a cleared scar is left by the coal company. An impact report by the EPA found that it could take hundreds of years for the forest to reestablish itself on the former mine site. So, without a short-term forested future, precleared MTR sites can be repurposed for energy storage (Appalachian Voices, 2021).

Environmental justice have been an important critique for PSH systems. People are often displaced to open up land required to construct both reservoirs. Installation at previous MTR sites avoids this displacement because peoples were already displaced by coal companies at the onset of MTR mining. MTR PSH will have a *significantly less* negative impact than conventional PSH because it relies on existing brownfield locations. (Appalchian Voices, 2021).

Closed-loop PSH systems negatively impact groundwater levels due to initial filling requirements and subsequent evaporation. MTR already causes significant destruction to groundwater. For MTR, waste rock is dumped into the valleys around the mountains, forming “valley fills” that heavily pollute the water and lead to higher instances of kidney disease, pulmonary disease, and hypertension (Boxer, 2009). After MTR operations are completed, valley fills are left behind, continuing the adverse health effects for local communities long after the mountains are depleted of coal. PSH could harvest and store this polluted water in its closed-loop reservoirs, reducing the negative health impacts of MTR.

The proposed MTR site solution addresses yet another PSH limitation. All PSH installations need a high voltage connection to the power grid. A large energy storage application needs to be able to use high amounts of energy at once to quickly move the water to the upper reservoir and release energy back into the grid when needed. Transmission lines already exist throughout the Appalachians and current and retired coal operations are located near lines, allowing for easy access to the power grid (EIA, 2022b).

4 Discussion

4.1 Drawbacks

As described above, PSH at MTR sites addresses many concerns that have been historically raised about PSH.

While PSH on former MTR sites addresses many problems associated with pumped storage deployment, several remain. First, transmission line upgrades are required to a greater extent for a renewable grid than for one based on coal and natural gas. One reason is that green energy requires cross-country transmission because of the intermittency requirements. (Gardiner, 2018). PSH is likely to exacerbate the dependence on transmission line upgrades. While the cost for installation is up to several million dollars per mile (MISO, 2022), there are existing and future funding sources for these necessary upgrades. Even without Appalachian PSH development, these upgrades will be required to strengthen renewable opportunities throughout the country.

Fortunately, transmission line upgrades for some PSH sites. For example, one of the largest PSH applications in the world, a 3003 MW system in Bath County, Virginia, commenced operation almost 40 years ago, highlighting how local challenges can be overcome despite antiquated access to transmission lines (Dominion Energy, 2022).

Another challenge with PSH is supplying enough water to create both reservoirs for the system. One GWh of energy requires 1 GL of water, or the equivalent of 400 olympic swimming pools (Blakers, Stocks, and Liu, 2020). In cases such as the Bath County PSH project, local streams supply the water to these areas (Dominion Energy, 2022). Locations can be evaluated on a case-by-case basis for water access because of the hundreds of MTR sites available for PSH installation.

A final challenge with MTR PSH systems is public support. MTR mines are located in politically conservative areas. In these areas, state and public opposition to climate-conscious development often hinder deployment. Renewables at MTR PSH sites would be ideal to reach climate goals, but opposition may prevent renewables alongside energy storage construction in the area. However, standalone energy storage projects in Appalachia, such as the Lewis Ridge PSH project in Bell County, Kentucky, have seen recent permitting success, (Hydro Review Content Directors, 2022). MTR PSH deployment, in particular, will likely see increasing public support because of visible reductions in the negative impacts of mining.

4.2 Funding Opportunities

Due to the global desire for energy storage applications, future PSH projects are anticipated to have greater funding opportunities. In 2019, for example, the BEST (Better Energy Storage Technology) Act was proposed and would have promoted research and development in low-cost energy storage applications. While it ultimately didn’t pass, it had bipartisan cosponsors in the House of Representatives (Foster, 2020). A future passage of this bill could create further investments in energy storage.

Public support for reducing the negative effects of MTR could lead to governmental appropriation for PSH. The Infrastructure Investment and Jobs Act, colloquially known as the Bipartisan Infrastructure Bill, invested hundreds of millions of dollars in storage programs. Interestingly, Section 40334 gives $10 million to PSH projects on tribal land. Given previous niche funding such as Section 40334, it is likely that partial monetary support will be given to PSH projects at former MTR sites (DeFazio, 2021).

A key source of funding for large projects is the Department of Energy’s Loan Program Office. They have given more than $50 billion in investment to renewable energy and electric vehicle programs. In June 2022, they gave $504.4 million to a long-term hydrogen energy storage project in Utah. This created a precedent for energy storage programs to seek out loans from this office (Loan Programs Office, 2022).

A final source is the Department of Energy’s $2.3 billion grant program to fund power grid modernization. To install a PSH application, high voltage transmission lines must be built to bring energy to and from the site. While not the largest cost in the project, governmental funding can alleviate some of the grid improvement challenges required to create a large-scale energy storage project (Department of Energy, 2022).

5 Conclusions

Increased demand for emissions reduction creates industry pressure to decarbonize. However, without effective battery storage methods, zero-emission targets will fail to be realized. Given the comparison between PSH and LIB systems, it is clear that PSH is the best solution to the intermittency challenges of a future grid as lithium mining employs child labor, destroys natural sites throughout the Global South, and depends on a depletable resource. Given the reduced negative effects, the positive economic benefits, and the political and economic feasibility, close-loop PSH should be constructed on former MTR sites.

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Declarations

Conflict of Interest The author declares he does not have any conflict of interest.

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