Comparison between newly developed gravity energy storage and pumped hydro storage

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Abstract. The world is currently facing a new energy crisis, which has prompted a focus on energy storage technologies to solve the global energy crisis. Taking advantage of the height difference between two dams and turning them into one is the main difference between gravity energy storage (GES) and pumped hydro storage (PHS) presented in this paper. This paper first introduces the basic principles of each of these two technologies, and then compares the two technologies through economic and parametric perspectives, showing the advantages of GES technology such as higher efficiency, easier construction at less cost, and the promise of GES. Some case studies may not reveal convincing trends in GES development, but they can still be used to compare the technology's present state of development. This research stresses that GES has higher promise as a newly created technology. Both technologies are promising and excellent renewable energy sources, but to truly evaluate which is superior in the long run, economic factors must be analyzed and compared. GES technologies are also being researched to assist the world in alleviating the pressures of the energy crisis and the environmental issues produced by stored energy.

Keywords: GES, PHS, stored energy, economics.

1. Introduction

With the widespread use of electricity and rising demand for electricity, energy storage solutions have been researched for over a century. The importance of energy is demonstrated by the UN's 2030 Agenda for Sustainable Development, which includes affordable and clean energy as the seventh of the 17 Sustainable Development Goals [1]. However, the globe is today experiencing a new energy crisis. With the global COVID situation causing a shortage of natural gas and oil, the costs of these items are fast rising, drawing people's attention to energy storage technology as a solution to the global energy crisis [2]. Energy storage refers to the capturing of energy generated at one moment and storing it for later usage [3]. Dams, for example, are widely utilized as a bulk energy storage strategy to store energy using hydropower, and the connecting of two dams using the difference in elevation to store and create energy is becoming one of the most popular and practical techniques worldwide. The key distinction between GES and PHS is that they both use the same principle of leveraging elevation differences by switching from two dams to one. Because GES does not require two dams with different elevations and similar devices might be utilized in GES, it has a greater potential as a developing approach. This article will compare the two systems and highlight their future possibilities.

There are no research that compare these two technologies. There is some discussion of one of the two technologies, but there is no complete comparison of the two. We intend to compare an existing and widely used technology with a newly developed technology in this article, so that the new technology has less limitations in terms of siting, costs less than the old technology, and performs much more efficiently than the old technology.

The major goal of this article is to evaluate these two energy storage technologies from an economic and parametric standpoint, in order to highlight current GES new advances in comparison to old technologies with comparable operating principles, as well as the future of GES. First, we describe the two core technologies, PHS and GES, as well as their operating principles, and then, in terms of energy storage, we compare the real parameters to emphasize the GES technology's great efficiency. Then, in terms of economic comparison, this research uses a case study from Germany to better demonstrate the GES building cost.

2. Technology

2.1. Gravity energy storage

2.1.1 introduction.

Gravity Power proposes a new notion that is still developing. GES works on the same principles as PHS in that it relies on gravity to store energy [4]. However, PHS's limitations are somewhat addressed by GES; for example, because PHS is required to site near water bodies, GES has more flexibility in location selection. It's crucial to note that there are a variety of techniques to use gravity storage; however, in this post, we'll just look at the mechanism proposed by Gravity Power. The entire system is filled with water, and one side of the container has a piston. The container is also connected to the flow turbine. The entire system is connected to the electricity grid, and a generator connects the system to the grid. The generator rotates the pumping turbine clockwise and lifts the piston when electricity is supplied from the grid. When the system generates power, the piston drops, exerting downward pressure and driving the water to the flow turbine. The water then turns the generator counterclockwise, converting the energy into electricity, which is ultimately fed into the grid.

2.1.2 GES Principles Analysis.

For equation (1) [5], the underlying premise of GES is as follows. E seems to be the total energy produced in J, mr symbolizes the relative mass to water, g represents gravitational acceleration, z represents the volume of the water in the container, and efficiency of the engine denotes system efficiency.

$$E=m_r g z \mu \tag{1}$$

Some parameters must be defined in order to turn the idea into a practical application of technology. The thickness of containers and turbines [6] is a significant factor for the overall system because the container walls must be able to withstand high pressure from both the external environment and the interior water.

The stress in concrete st as the container walls' material determines the wall thickness, as shown in equation (2) [7]. Where Ht is indeed the maximum hoop tension force acting on the cylindrical wall's vertical segment, m seems to be the modular ratio, and Ast seems to be the area of steel bars used for the structural reinforcement [4]. Equations (3) as well as (4) assist in determining these amounts (5). Where p stands for piston density, w for water specific weight, k0 again for coefficient of earth pressure at rest, y as soil weight, and cbc represents concrete compression stress [7].

$$\sigma_{st}=H_t/(1000t+(m-1)A_{st} \tag{2}$$

$$H_t=[(\rho_p g+w-k_0 y)HD]/2 \tag{3}$$

$$m=280/\sigma_{cbc} \tag{4}$$

$$A_{st}=H_t/\sigma_{st} \tag{5}$$

The water beneath the pump-turbine should have the same exit as the water above it, which is determined by the radius of the container and return pipe. The return pipe should be at the same level as the container in the soil, putting both at the same depth. This idea can be expressed using the equation (6) [5]. The above equation may be used to calculate the radius of the return pipe with the same container height, and Barlow's equation [7] can be used to calculate its thickness.

$$Q=V_1A_1=V_2A_2 \tag{6}$$

2.2. Pumped hydro storage

2.2.1 introduction.

Hydropower was used for utility-scale electricity storage since the 1890s and is a mature and value technology. Hydroelectricity is not only an environmentally friendly and sustainable energy source, but its flexibility and storage capacity also allow for grid stability and the deployment of other intermittent renewable energy sources like wind and solar. As a result, pumped storage has reappeared as a topic of interest around the world. The focus should be on rotor design when it comes to this technology in order to achieve maximum plant performance and reliability.

Pumped storage preserves the potential energy of water pushed from a lower reservoir to a higher reservoir [8]. Pumps in this type of system use low-cost electricity to transport water from lower reservoirs to top concentrations (off-peak power). The stored water is released to power a hydro power turbine when there is a high demand for electricity. The reversible turbine/generator system can be used as a pump or a turbine, depending on the circumstances. Figure 1 and figure 2 depict conventional hypothetical pumped hydro energy (PHES) systems that transport water from either the lower reservoir to the upper reservoir by employing wind and solar photovoltaic electricity [8]. Despite the fact that construction costs and location are important things to consider, this technology is currently the most cost-effective technique of storing significant amounts of electricity. The characteristics of the site have such a significant impact on almost every PHES power plant. If the ecology and geology of the area are appropriate, a site with an adequate water supply is regarded a desirable location to establish a PHES plant [9]. PHES site selection is an important task which requires continuous investigation to develop more reliable, simple, and cost-effective techniques and systems that are actually feasible, commercially successful, and socially acceptable. Furthermore, with the passage of time, the availability of technically and economically viable places is becoming increasingly limited [10]. As a result, new processes and procedures that are much more effective must be developed and implemented. Connolly et al. [11] created computer software that can scan a landscape and determine whether or not there are any potential PHES sites. This intervention is designed in identifying prospective PHES settings [11].

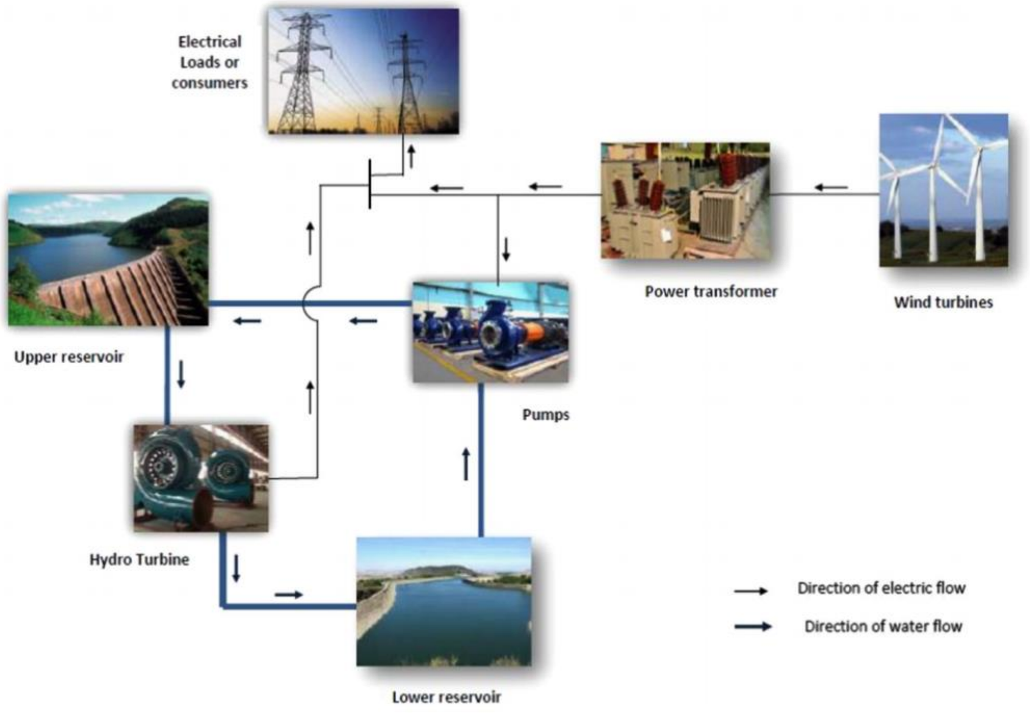

Figure 1. Pumped hydroelectric storage (PHES) system based on wind power [8].

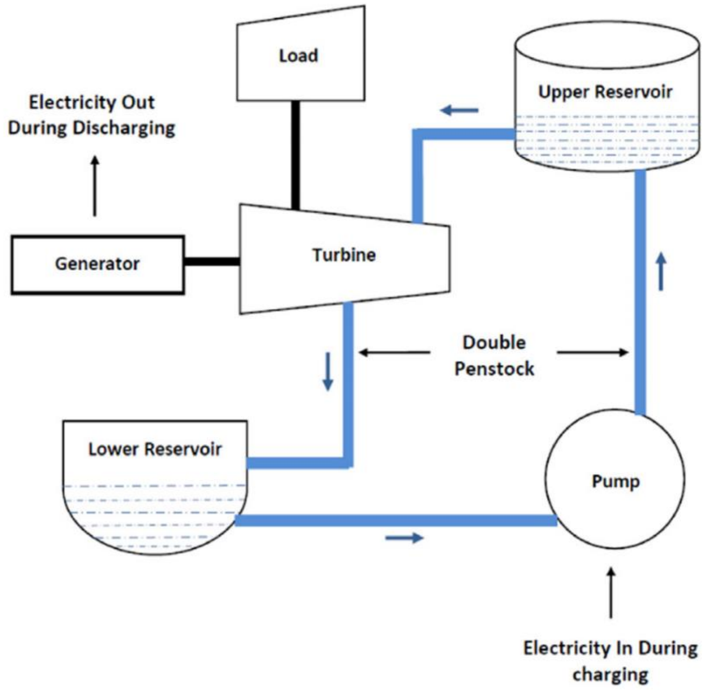

Figure 2. Pumped hydroelectric storage (PHES) technology based on solar PV electricity [8].

2.2.2 PHS Principles Analysis.

Pumped storage stores the potential energy of water moved from a lower reservoir to a higher reservoir. In this system, low-cost energy is used to power pumps that transport water from lower to higher reservoirs. Water is transported from lower to higher reservoirs. When there is a significant demand for electricity, the stored water is released to generate hydroelectric turbines. The system uses solar and wind power photovoltaic electricity to move water from the lower reservoir to the top reservoir. Although initial expenses and the correct location are crucial determining considerations, the procedure is now the most cost-effective method of storing enormous amounts of electricity. The design for almost every pumped storage power plant is severely influenced by the site's distinct attributes. A significant quantity of water is necessary at the site. If the topography and geology of the location are adequate, it is suitable for the building of a PHES plant. Many countries have seen the technology's possibilities and are considering incorporating it into their power systems, particularly to maximize the employment of renewable energy sources.

3. Energy Storage Comparison between two technologies

In this section, we'll look at and compare two very promising energy storage technologies that are both based on pretty simple concepts, concentrating on more general features of these technologies like their designs and the benefits and drawbacks that come with those designs and efficiency. This part will not look at the economics of certain storage technologies because it will be covered in a later section. Gravitational energy storage will be referred to as GES, and pumped hydro energy storage will be referred to as PHES.

3.1. Energy storage comparison

3.1.1 Energy Storage analysis of gravity energy storage.

GES is a relatively new technology that is currently in the early stages of development and implementation around the world. It stores and produces energy using gravitational potential energy. There are various ways to create this type of technology because the underlying concept is so simple, but it is essentially a massive solid mass that moves up and down in a vertical region. Given that gravitational potential energy is mgh, the efficiency of this storage will naturally rise as the height and mass increase. As long as there is enough vertical space, this storage can be installed underground, aboveground, or even offshore. As a result, enormous spaces that would otherwise be unused, such as abandoned mining shafts and large caves, can readily be utilised for storage. Not only that, but the material used to make the enormous mass is also quite versatile; depending on the design choices, the mass can be used as long as it has enough weight. This system is also energy efficient, with a "round-trip power efficiency of 90 percent, i.e. zero to full power to zero, implying only 10 % energy loss" [12]. The need to bring the mass back up, as well as other minor losses, account for the ten percent energy loss.

3.1.2 Energy Storage analysis of classic pumped hydro storage.

PHES is a type of energy storage that has become increasingly popular in recent years. Climate change is one of the key reasons for this, as governments aim to replace their use of fossil fuels with cleaner storage in order to meet their environmental goals. Pumped hydro power accounts for a substantial portion of domestic energy/electricity production and consumption in countries like China, with 30.3 gigawatts of power stored thanks to pumped hydro. "It is a structure of two water reservoirs at different elevations that can generate power as water goes down from one to the other (discharge), passing through a turbine," says the inventor. Pumping water back into the top reservoir necessitates the use of electricity (recharge). PSH works like a big battery in that it can store energy and discharge it when needed" [14]. "Of all renewable energy sources, this type of technology is possibly the most predictable." Such facilities are very efficient, with low maintenance costs and long lifespans," but they have a high percentage of energy loss, because, as previously stated, pumping the water back up to the higher reservoir requires energy, resulting in "a significant loss of energy storage capacity of approximately 30 %" [12].

Pumped hydro has an efficiency of 70 to 80 percent as a result of this. The larger the reservoirs and the difference in elevation between them, the greater the production and storage, which is why this method of storage also necessitates a significant quantity of land and water. Its enormous water use is a cause for concern, although the water consumed does not have to be potable or drinkable. This device, if properly designed, might even operate as a filter, "improving water quality through aeration and other processes" [15].

3.1.3 Comparison of two technologies.

Now it's time to compare and contrast the two technologies. In terms of efficiency, GES has the advantage with roughly 90 % efficiency and just 10 % loss, but PHES has 20 % loss and hence only 70-80 % efficiency. Given that GES largely requires vertical area and very little horizontal area, the geographical demand of PHES is predictably much larger and less adaptable than GES. It can also make use of regions that are normally unsuitable for other purposes. Although PHES has a high requirement for land, its potential as a water purifier may be preferred to some locations over others. Granted, the criterion used here may be a little arbitrary, but additional factors will be investigated later. Both of these technologies are promising and excellent renewable energy sources, but determining which is superior in the long run requires a thorough examination and comparison of their economic implications.

3.2. Economic Comparison

3.2.1. Economic Comparison Approach.

It's never easy to compare and measure two energy storage systems. In this study, LCOE (levelized cost of storage), also known as LCOS (levelized cost of storage), is a cost-based strategy that takes into consideration several factors such as technology lifetime and efficiency [16]. The lifetime cost of energy generation, measured in dollars per kilowatt-hour, is known as the LCOE. Because GES is still in its early stages, there isn't enough data to provide a compelling LCOS at this time, hence estimation of LCOS is employed in this research, along with other assumptions. The size characteristics of GES with a capacity of 100 MWh are provided in Table 1 in this research, which is based on a case study in Germany. PHS is a well-developed technology that has already been applied worldwide, so the LCOS could easily be obtained. In this paper, the data is from U.S Department of Energy [17].

Table 1. The Parameter Used in GES Case Study [15].

Parameter	Height (m)	Diameter (m)	Thickness (m)
Container	500	5.21	7.6
Piston	250	5.21	-
Return Pipe	500	0.6	0.083

3.2.2. Economic analysis of gravity energy storage.

The initial cost of GES is made up of the cost of excavation, the cost of materials for the container, piston, and return pipe, the cost of auxiliary equipment, and miscellaneous charges.

The cost of excavation ranges from 220 k$/m^3 to 462 k$/m^3 [18], but in this situation, the median cost, which is 341 k$/m^3, is used to establish the cost of excavation. The volume of the container shaft and the volume of the return pipe are then multiplied. Excavating the container will cost around 2.19*107 dollars, and building the return pipe will cost $75500 dollars.

The other factor is the cost of materials. Because of its high density and low cost, iron ore should be the optimum material for the piston [16]. By translating its density of 7870 kg/m^3, the volume in this case is 5347 m^3, or 42,084,813 kg. As a result, the estimated cost is 2.2 million dollars [16]. Reinforced concrete is the optimum material for the container and return pipe walls since it can withstand high inner pressure. The estimated costs of the container and return would be 9.24*106 $ and 1.023*103 $, respectively [16].

When compared to battery storage technologies, GES has a smaller number of equipments. Turbine, pump, motor, and generator are all included. The total cost is 4.95 million dollars [16]. Figure 3 depicts the percentage of each component of the GES prime cost. So, if we sum the total cost above and divide by 100 MWh, we get a total cost of 383.8 $/kWh, ignoring any system costs and generator efficiency losses.

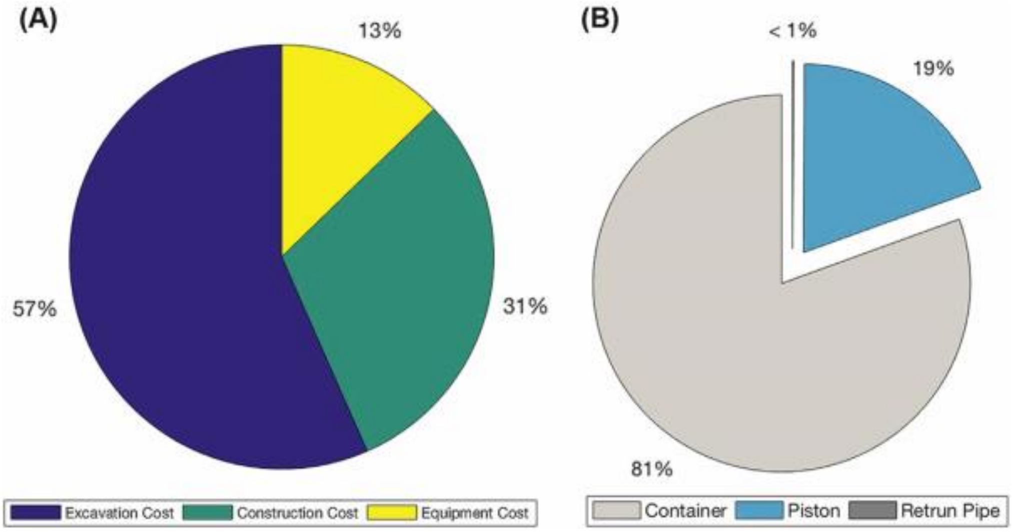

Figure 3. Percentage of capital cost of GES [5].

Another key component that impacts the overall effectiveness of the system is discharge time. Because the electric system discharges twice in an 8-hour period in most circumstances, the discharge duration is set to 4 hours in this scenario, and the capital cost might be 1535.2 $/kW. To make a more accurate comparison, we leave the excavation cost out of the total cost calculation because areas like disused mines may not require much excavation.

3.2.3 Economic analysis of classic pumped hydro storage.

PHS's cost is reasonably steady over the world because it is a well-established technology that has been developed for several decades. The data for this study comes from a report by the US Department of Energy. The paper assumes a capacity of 100 MW, a 16-hour PHS discharge period, and a capital cost of PHS ranging from 1700 $/kW to 3200 $/kW. And the overall project's proportional total cost is 165 $/kWh [17].

3.2.4 Comparison of two technologies.

Because PHS is made up of two distinct reservoirs, and the LCOS does not account for the cost of construction of the two reservoirs, the cost of GES excavation should be neglected as well. The LCOS of GES changes from 383.8 $/kWh to 164 $/kWh when the capital cost of GES is reduced. The excavation cost accounts for a significant portion of the total capital cost, accounting for more than half of the total. So, if GES could be erected on an existing structure, such as a decommissioned mine, the LCOE would be reasonably low.

Furthermore, any system costs or Operations and Maintenance (O&M) expenses are not included in the LCOE of GES estimated above. As a result, the LCOE would almost certainly rise as a result. In comparison to well-developed PHS, it does not exhibit a strength in LCOE as a freshly developing technology. PHS, on the other hand, has tight regional restrictions. It necessitates the elevation difference between two reservoirs. As a result, the location options are limited. PHS is also relied on two reservoirs, which means that if the reservoirs are not built, the capital cost will be considerably higher than any other storage strategy.

4. Conclusion

Energy storage technology has been developed for about a century with the widespread use of electricity and the increasing demand for electricity. With the prevalence of a new coronavirus infection disease (COVID-19 virus) and the dramatic increase in prices, the global shortage of natural gas and oil has focused attention on energy storage technologies to solve the global energy crisis. In this paper, we introduce the working principles of both PHES and GES technologies and then compare the two technologies. In terms of efficiency, the efficiency of GES is about 90 % and the loss is only 10 %, while the loss of PHES is about 10 % more than that of GES, which shows that the efficiency of GES is higher than that of PHES. in addition, the geographical requirement of PHES technology is much more and less functional than that of GES because GES requires mainly vertical area and very little horizontal area. This paper shows the benefits of GES technology and the promise of GES. Some case studies may not show a convincing trend in GES development, but it can still be used to compare the current level of technological development. The technology is also studied to help the world reduce the pressure of the energy crisis and to alleviate the environmental problems associated with stored energy.

References

[1] United Nations (2015) Resolution adopted by the General Assembly on 25 September 2015, Transforming our world: the 2030 Agenda for Sustainable Development (A/RES/70/1 Archived 28 November 2020 at the Wayback Machine)

[2] "Will China's Energy Crisis Make It More Reluctant to Fight Climate Change?". Time. 30 September 2021.

[3] Clarke, Energy. "Energy Storage". Clarke Energy. Archived from the original on July 28, 2020. Retrieved June 5, 2020.

[4] Gravitypower, 2011. Gravity Power Module. Energy Storage. Grid-scale Energy Storage. Available at: http://www.gravitypower.net/

[5] A. Berrada, & K. Loudiyi, (2019). Chapter 2—Technical Design of Gravity Energy Storage. In A. Berrada & K. Loudiyi (Eds.), Gravity Energy Storage (pp. 25–49). Elsevier. https://doi.org/10.1016/B978-0-12-816717-5.00002-5

[6] J. Benzu,, 2013. Civil Engineering Projects, Reinforced Circular Water Tank/Design of RCC Structures [online]. Available at: http://www.civilprojectsonline.com/building-construction/reinforced-circular-water-tank-design-of-rcc-structures/

[7] A. Berrada, K. Loudiyi, & I. Zorkani, (2017). System design and economic performance of gravity energy storage. Journal of Cleaner Production, 156, 317–326. https://doi.org/10.1016/j.jclepro.2017.04.043

[8] S. Rehman et al. / Renewable and Sustainable Energy Reviews 44 (2015) 586–598

[9] Y. Chi-Jen. Pumped hydroelectric storage Duke University; 2012 [accessed: 12 February, 2012].

[10] F. Blaabjerg, A. Consoli, J.Ferreira, J.van Wyk . The future of electronic power

[11] S. MacLaughlin, M. Leahy, D. Connolly. Processing and conversion. IEEE Trans Power Electron 2005;20(3):715 –20. Development of a computer program to locate potential sites for pumped hydroelectric energy storage. Energy 2010;35:375–81.

[12] T. Husseini. "Tower of Power: Gravity-Based Storage Evolves beyond Pumped Hydro." Power Technology, Power Technology, 7 Mar. 2019, www.power-technology.com/analysis/gravity-based-storage/.

[13] P. Roger, et al. "Hydroelectricity (Waterpower) and Pumped Storage." Analysis of Resource Potential and Scenario Assumptions, Pembina Institute, 2011, pp. 22–28, http://www.jstor.org/stable/resrep00259.9. Accessed 9 Apr. 2022.

[14] "Pumped Storage Hydropower." Energy.gov, 2021, www.energy.gov/eere/water/pumped-storage-hydropower#:~:text=Pumped%20stor age%20hydropower%20(PSH)%20is,)%2C%20passing%20through%20a%20turbin e..

[15] Y. Chi-Jen, and J. Robert B. "Opportunities and Barriers to Pumped-Hydro Energy Storage in the United States." Renewable and Sustainable Energy Reviews, vol. 15, no. 1, Jan. 2011, pp. 839–44,https://doi.org/10.1016/j.rser.2010.09.020.

[16] A. Berrada, & K. Loudiyi, (2019). Chapter 3—Economic Evaluation and Risk Analysis of Gravity Energy Storage. In A. Berrada & K. Loudiyi (Eds.), Gravity Energy Storage (pp. 51–74). Elsevier. https://doi.org/10.1016/B978-0-12-816717-5.00003-7

[17] K. Mongird, ,V. Viswanathan, V. Balducci, P. J., Alam, M. J. E., Fotedar, V., Koritarov, V. S., & Hadjerioua, B. (2019). Energy storage technology and cost characterization report (No. PNNL-28866). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

[18] R. Madlener, & J. Specht, (2013). An exploratory economic analysis of underground pumped-storage hydro power plants in abandoned coal mines.