Cost analysis of Underground Pumped Hydro Storage

Foreword

This white paper is conducted on behalf of Pumped Hydro Storage Sweden AB. The analysis presented in this paper is a continuation of a previously published report called "Cost models for battery energy storage systems" (Börjesson & Larsson, 2018) which includes a cost analysis on energy storage with battery technology. The aim with this paper is to expand the previous analysis to include pumped hydro storage that utilizes sub-surface reservoirs.

Executive summary

The ability to store excess energy efficiently is an important factor in reaching the COP21 targets of limiting the increase in global temperature. Breaking the world's fossil fuel dependency and achieving a sustainable energy sector requires further adoption of renewable energy production, which in turn require excess energy to be stored in order to be flexible and reliable.

While pumped hydro storage (PHS) accounts for over 94% of the world's installed storage capacity today, battery energy storage (BES) has received a lot of attention recently as demand for batteries to power portable consumer electronics and electric vehicles has increased substantially. However, PHS still possess several key advantages when it comes to large-scale energy storage. Long project lifetime, large storage capacity, mature and well-known technology and high energy-to-power ratios are examples of characteristics that make PHS an attractive technology. The required difference in height between the two reservoirs however makes PHS facilities highly dependent on land availability and favorable topography. Therefore, exploring the possibilities of underground pumped hydro storage (UPHS) that uses abandoned mine pits and quarries as reservoirs could increase site availability, improve environmental impacts and reduce capital costs.

This report provides a cost analysis of UPHS where the Levelized Cost of Storage (LCOS) is used as a metric. The results are compared to battery storage technologies and shows that UPHS is a highly cost-efficient technology for large-scale energy storage today, and for a foreseeable future. These results combined with environmental advantages highlights the importance of initiating new projects that can enable this technology to be explored and developed further.

Introduction

Since the United Nations climate change conference in Paris 2015, the energy sector has continued its shift from fossil fuel to renewable energy sources. However, this transition poses a challenge since renewable energy sources such as solar and wind are intermittent sources that cannot match their production over time to variations in demand. Therefore, the ability to store excess energy can be considered a key in increasing the adoption of renewable energy and improving its efficiency, flexibility and reliability.

In 2018, PHS represented over 94 percent of total installed energy storage capacity globally (International Hydropower Association, 2018). A PHS system consist of two reservoirs located at different heights which enables energy to be stored in the form of gravitational potential energy of water. During low electricity demand periods, water is pumped from the lower reservoir to the upper and during periods of high demand, water is released from the upper reservoir through a turbine. The turbine is then used to drive a generator that converts the mechanical energy to electricity.

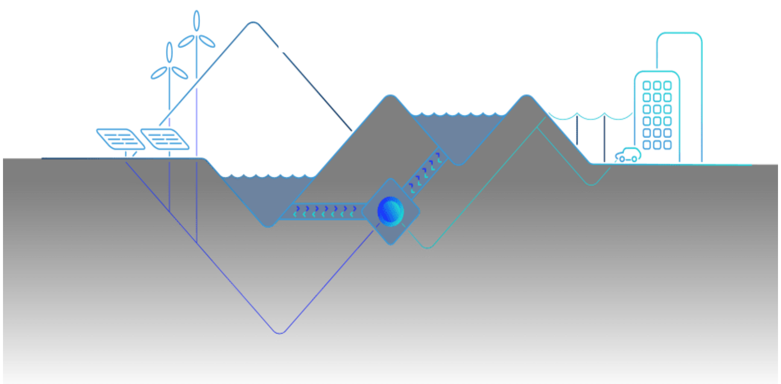

Figure 1. Schematic view of a PHS system

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Pumped hydro storage use cases

PHS systems can provide a range of different services such as frequency regulation, energy arbitrage, black start and voltage support.

- *Frequency regulation*; the main purpose is to maintain the stability and accuracy of the system.
- *Energy arbitrage*; energy is stored when the electricity price is low and used or sold when prices are high.
- *Black start*; when the grid gets disconnected, energy storage can be used to restore the power system without pulling electricity from the grid.
- *Voltage support*; this means maintaining the necessary voltage level in the grid and its stability.

The most common source of revenue for a PHS system is benefitting from energy arbitrage opportunities. For this to be economically viable, there need to be significant volatility in the electricity wholesale price. The price on electricity used for pumping has to be considerably lower than the selling price to make up for energy losses (Deane, et al., 2010).

Underground pumped hydro storage

The required difference in height between the two reservoirs makes PHS technology highly dependent on land availability, favorable topography and correct geotechnical conditions (Pujades, et al., 2017). There are also environmental impacts associated with PHS systems as they require a great deal of land resources. Conventional PHS systems that uses a river, or a sea as lower reservoir may obstruct fish mitigation, change natural water temperature, water chemistry and river flow characteristics (Kobler, et al., 2018). To minimize these environmental impacts, pumped hydro storage can instead utilize underground reservoirs, such as abandoned mine pits and quarries, as lower dams. Underground pumped hydro storage (UPHS) systems that utilizes abandoned mines can also have great economic advantages. Some sites might already have existing infrastructure such as tunnels and grid connection points at high voltage level and some sites might also have the possibility of using the quarry as the upper reservoir, leading to a reduction in capital costs. However, it is important to recognize the technical considerations required for each unique situation which makes cost estimations of PHS systems highly project-specific (Davidson & Khan, 2016).

Like traditional PHS, the main advantages with UPHS are: high cycle efficiency, capacity to deliver large scale power over a long period of time and long project life-time (European Energy Research Alliance, 2018). As previously mentioned, UPHS also has the advantage of not requiring high surface topography since it offers the possibility of using existing cavities (European Energy Research Alliance, 2018). Therefore, the closed loop configuration would have no effect on surface water flow, ecological systems or landscape views.

Battery technology

Even if PHS represents a large part of total installed energy storage capacity in the world, there are other technologies available as well. Lithium-ion (Li-ion) batteries are perhaps the most notable storage technology as demand for batteries to power portable consumer electronics and electric vehicles has increased substantially in recent years. Also, the world's largest battery project (100 MW) was commissioned in 2017 and is located in South Australia. While innovation is contributing to improvements in performance and cost reduction of Li-ion batteries, PHS maintains several distinct advantages.

Storage capacity

PHS is characterized by its ability to provide a wide range of power and energy capacities. Large scale PHS systems benefit from the large amount of energy that can be stored, generating high energy-to-power ratios. Typical power capacity generally ranges from 100 to 1000MW while Li-ion batteries and other rapid response technologies are traditionally suited to smaller scale systems with power capacities in the kW to MW range (International Hydropower Association, 2018).

PHS systems can typically generate up to 10 hours of power output, meaning that a system can deliver maximum power during that time before the stored energy runs out (International Hydropower Association, 2018). In comparison, batteries usually provide short discharging times which means that each cycle has a much shorter duration time (Börjesson & Larsson, 2018). For instance, the previously mentioned battery of 100MW in South Australia has an energy capacity of 129 MWh, meaning it has the capacity to deliver 100MW of power during a little over an hour.

Project life-time

The construction of a PHS system can usually take several years from project state to being in full operation. However, PHS is the storage technology that lasts the longest in terms of project life-time, typically ranging from 60 to 100 years (International Hydropower Association, 2018). In comparison, batteries can be produced much quicker but are limited to shorter life-time due to degradation. The rate at which a battery degrades depends on which conditions it is operated at. Amount of cycles, depth of discharge and operating temperature all affect the life-time of a battery which is usually up to ten years (Börjesson & Larsson, 2018).

Cost models

When comparing costs of energy storage technologies, it is important to distinguish between the energy and the power capacity of a system (Mayr & Beushausen, 2016). The amount of energy that can be stored is the energy capacity of the system, and the rate of which the energy flows in and out of the system, is the power capacity. Power can be measured in watts (W), and energy can be measured in watt hours (Wh). This means that when estimating costs in terms of USD/kW, the cost is based on the power capacity of the system. For example, a PHS system is assumed to have a size of 100MW/800MWh. If the capital cost of the system is MUSD 200, the cost based on the energy and power capacity become:

- MUSD200/100MW = 2000 USD/kW
- MUSD200/800MWh = 250 USD/kWh

If the system then is changed to a size of 100MW/400MWh with the same total cost, the cost in terms of energy capacity will not be affected while the cost in terms of power capacity will be doubled. Therefore, system size and specific use case are important to keep in mind when evaluating and comparing costs of energy storage (Mayr & Beushausen, 2016).

Levelized Cost of Storage

When comparing costs of different technologies for energy generation such as wind and solar power, the Levelized Cost of Electricity (LCOE) is the most commonly used metric (Belderbos, et al., 2017). The LCOE formula can be defined as *"the fictitious stable electricity price needed to make the present value of the sum of all costs and all revenues over the entire operational life of the unit equal to zero"* (Belderbos, et al., 2017). A version of the LCOE for calculating costs of energy storage systems is called Levelized Cost of Storage (LCOS). The LCOS can be defined as *"the fictitious average electricity price during discharging needed over the lifetime of the storage plant to break even the full costs for the investor"* (Belderbos, et al., 2017). The LCOS formula can be computed as follows:

$$LCOS = \frac{CAPEX + O\&M \cdot \sum_{n=1}^{N} \frac{1}{(1+r)^n} - \frac{v_{res}}{(1+r)^{N+1}}}{c \cdot DoD \cdot RC \cdot \sum_{n=1}^{N} \frac{1-DEG \cdot n}{(1+r)^n}} + \frac{p_{elec}}{\eta}$$

$CAPEX$	= Capital expenses
$O\&M$	= Operating and maintenance costs
DoD	= Depth of discharge
c	= Number of cycles per year
RC	= Rated capacity
DEG	= Annual degradation
N	= Lifetime of system
r	= Discount rate
P_{elec}	= Charging cost
η	= Round-trip efficiency
v_{res}	= Residual value

The charging cost is the cost of which the electricity is bought to be stored. The value of this parameter varies depending on the price of electricity at the specific location of the system. The price can include cost carriers such as the spot price in the region, network charges, taxes and electricity certificates. Therefore, it is important to know which cost to include in the charging cost to get a relevant LCOS for a specific use case. Some cost estimations available in open literature has set the charging cost to zero. These cases are expected to have storage facilities in near location or co-operated with wind farms or solar-PV. However, a charging cost of zero is only true when there is no demand on the grid and the electricity otherwise would be dissipated as heat. To achieve an accurate LCOS if the storage unit is coupled with an energy generation source, the LCOE of that source could be used as the charging cost.

Method

This paper has based its analysis on eight different old mines and quarries sites which is presented in the appendix. The sizes of the projects range from 24MW to 300MW. Seven of the sites have either been commissioned, are in a start-up phase or gone through a feasibility study. One of the sites, Asturian in Spain, is based on the paper "Underground pumped-storage hydro power plants with mine water in abandoned coal mines " (Menendez, et al., 2018). For some of the projects, values on efficiency and lifetime have been assumed since there was no available information, and these were set to values commonly used by the industry. However, specific values on size and CAPEX were found for each project. OPEX has been set to 2% of CAPEX since this has shown to be a commonly used value in hydro power projects.

One of the objectives of this study is to present benchmark values on the LCOS for UPHS versus traditional PHS and Battery energy storage systems (BESS). This is done by calculating an interval that contains the LCOS for each analyzed project, indicating a high-low end for UPHS technology. Additionally, a mean value case is displayed that can be used as a reference to compare with Lazard's Levelized Cost of Storage Analysis 2.0 (Lazard, 2016) for traditional PHS and with Lazard's Levelized Cost of Storage Analysis 4.0 (Lazard, 2018) for wholesale BESS. Since traditional PHS is based on a mature and well know technology, no major improvements of costs, structure or transformation efficiencies are anticipated in the future (IRENA, 2017). The use of Lazard's 2.0 analysis is therefore considered valid as a reference for traditional PHS. Lazard's 4.0 analysis is based on interviews, latest industry data and extensive research on BESS.

The mean value case is calculated by using the mean average energy capacity of the eight different old mines and quarries sites as well as the mean average of total capex. Regarding the charging cost and WACC, this report uses an electricity price of 0.033USD/kWh and a WACC of 11.2% which is the numbers used by Lazard in their cost analysis of PHS and BESS. The mean value case is presented in the table below.

Mean value case				
LCOS(USD/kWh)	WACC	CAPEX (MUSD)	Charging cost USD	System size kW/kWh
0,111	11,2%	167	0,033	142/920

The projected LCOS for BESS in 2024 is based on a cost projection by Lazard, estimating a 28% decrease in CAPEX for Li-ion and 38% for VFB (Lazard, 2018). The paper "cost models for battery energy storage systems" (Börjesson & Larsson, 2018) estimates that a percentage decrease of CAPEX corresponds to an approximately equal reduction in LCOS for both battery technologies.

Three different sensitivity analyses were conducted on the LCOS formula in order to identify which factors that contribute the most to a cost reduction of UPHS. In the first analysis, four parameters (CAPEX, OPEX, WACC and cycles) were iterated from -40 % to 40 % individually while the other remained constant. The second analysis is two-dimensional and shows an absolute value on LCOS when changing CAPEX and WACC simultaneously. A sensitivity analysis was also conducted on the charging cost, displaying different LCOS for different prices on electricity.

Results

In this section, the resulting LCOS for UPHS in relation to other storage technologies are presented, as well as the sensitivity analyses.

Figure 2 shows the capital cost for each project in terms of energy capacity in relation to power capacity. The graph illustrates how the initial investments of the different projects compare to each other when the energy to power ratio is accounted for.

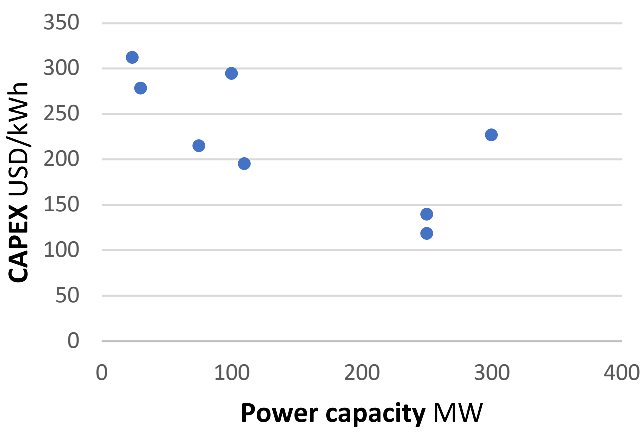

Figure 2. CAPEX USD/kWh to power capacity

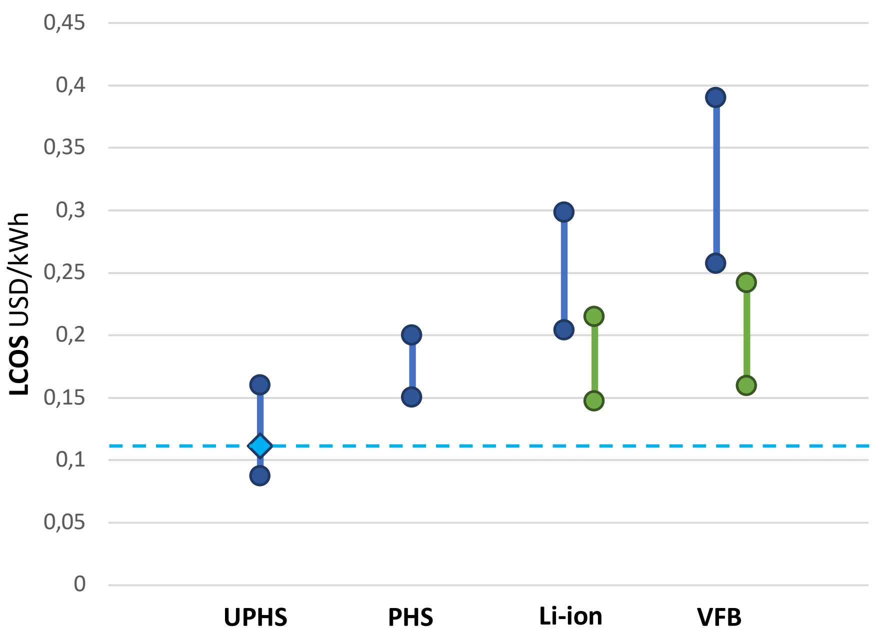

Figure 3. LCOS for different technologies – present & 2024

Figure 3 shows the levelized cost of storage for all four technologies: Underground pumped hydro storage (UPHS), traditional pumped hydro storage (PHS), Lithium-Ion (Li-Ion), and Vanadium-Flow batteries (VFB). The cost intervals show that UPHS is, and will most likely remain, the most cost-efficient technology for large-scale energy storage in a foreseeable future.

Sensitivity analysis

Figure 4 shows that cycles have the largest impact on the LCOS formula. CAPEX and WACC also has a large impact, in this case the change is almost identical which is due to the long lifetime of UPHS systems.

The two-dimensional sensitivity analysis on CAPEX/kWh and WACC is displayed in figure 5. The blue color indicates a lower LCOS and the red area indicates a higher LCOS.

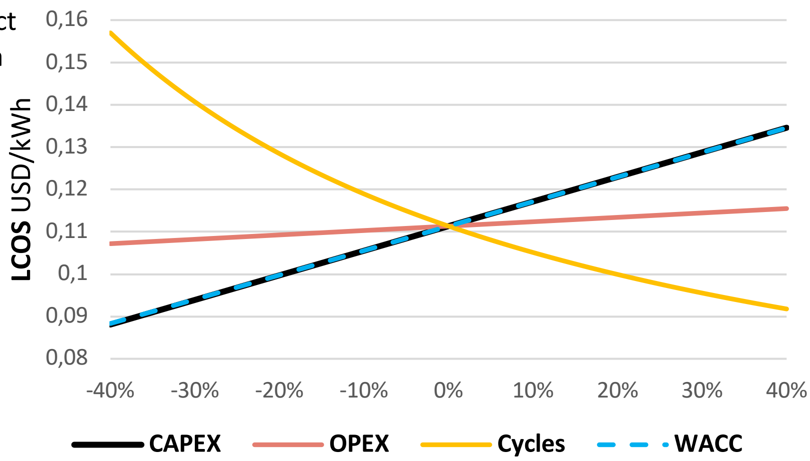

Figure 4. Sensitivity analysis on LCOS

CAPEX/kWh	WACC 6%	7%	8%	9%	10%	11%	12%	13%	14%
100	0,068	0,071	0,074	0,077	0,08	0,083	0,086	0,089	0,093
150	0,08	0,085	0,09	0,094	0,099	0,103	0,108	0,113	0,117
200	0,093	0,099	0,105	0,111	0,117	0,124	0,13	0,136	0,142
250	0,105	0,113	0,121	0,128	0,136	0,144	0,152	0,159	0,167
300	0,118	0,127	0,136	0,145	0,155	0,164	0,173	0,183	0,192
350	0,131	0,141	0,152	0,163	0,173	0,184	0,195	0,206	0,217

Figure 5. Two-dimensional sensitivity analysis on LCOS

Figure 6 shows how a change in charging cost will affect the LCOS.

Charging cost (USD)	0,00	0,02	0,04	0,06	0,08	0,10	0,12	0,14	0,16
LCOS (USD/kWh)	0,069	0,094	0,12	0,146	0,172	0,198	0,224	0,25	0,276

Figure 6. Sensitivity analysis on LCOS showing the impact of charging cost

Conclusion

The results in this report suggests that the implementation of UPHS projects that utilizes abandoned mine pits or quarries is an attractive option for large-scale energy storage, both in terms of cost and environmental impacts. Other advantages are that it is based on a well-known and established technology with high efficiency, and with long operational lifetime.

The LCOS analysis shows that UPHS is a highly cost-effective storage technology that has the potential of remaining competitive in the foreseeable future compared to other storage technologies, even though batteries are estimated to experience large improvements in terms of capital costs.

UPHS key advantages

- Low LCOS in comparison to BESS
- Low environmental and social impacts
- Mature and well-known technology
- Long project lifetime
- High efficiency
- Very low landscape impact
- Flat areas can be utilized

In this analysis, 350 cycles per year are used for UPHS, which is the same amount of cycles Lazard used in their analysis. However, 350 cycles annually for UPHS can for some use cases be considered as low. Unlike batteries, the amount of lifetime cycles in UPHS systems are not limited by impaired performance after each charging cycle. Given the character of UPHS systems, lifetime cycles are actually technically unlimited (European Energy Research Alliance, 2018). The sensitivity analysis shows that cycles has a large impact on LCOS and it is therefore important to keep this in mind, as more cycles would reduce LCOS for UPHS.

One other important factor to consider when calculating LCOS for a specific project is the fluctuations in the electricity prices during the day. The business case of a storage facility is to store energy when it is cheap and to sell it when there is higher demand and more lucrative. This paper, as mentioned in the method, uses the charging cost that Lazard provides in their cost analysis of PHS and BESS. Depending on the location of a system, network charges, taxes, electricity certificates and fluctuations in the spot price during the day varies. It is therefore essential to analyze these parameters since the charging cost has a large impact on the LCOS. If the reader wants to use a different charging cost than this paper does, the sensitivity analysis can be used to get an indicative change in how this would affect the resulting LCOS.

The results provided in this report are intended to be viewed as indicative values on how UPHS compares to other technologies in terms of cost. As previously mentioned, the data on the development projects are based on preliminary studies and liable to change. It is therefore important to recognize that UPHS systems are highly project-specific and dependent on several different parameters. However, since the data is gathered from real projects that have either been commissioned, are in a start-up phase or gone through a feasibility study, the results can be regarded as benchmark values that are market based and up to date.

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Appendix

Project name	Country	Power capacity (MW)	Energy capacity (MWh)	CAPEX (MUSD)	OPEX (2% of CAPEX)	CAPEX (USD/kW)	CAPEX (USD/kWh)	Efficiency (%)	Lifetime (years)
1. Asturian Coal Basin	Spain	24	141	44	0,88	1833	312	78*	80*
2. Bendigo UPHS	Australia	30	180	50	1	1667	278	70	30
3. Pyhäjärven	Finland	75	530	114	2,28	1520	215	77	50
4. Glyn Rhonwy	UK	99,9	700	206	4,12	2062	294	81	125
5. Middlebank Ranges	Australia	110	660	129	2,58	1173	195	78	80*
6. Kanmantoo	Australia	250	1800	250	5	1000	139	78	80*
7. Kidston	Australia	250	2000	236	4,72	944	118	78*	80
8. Highbury	Australia	300	1350	307	6,14	1023	227	78	80*

*Indicates that assumptions have been made

1. (Menendez, et al., 2018)
2. (Arup pty LTD, 2018)
3. (Longi, 2017)
4. (Snowdonia Pumped Hydro, 2017) (Modern power systems, 2017)
5. (ARENA, 2018) (Department for Energy and Mining, 2018)
6. (Department for Energy and Mining, 2018)
7. (Queensland government, 2019)
8. (Tilt Renewables, 2019)