4CBLA30 Energy Storage and Transport

Self-Study Assignment
Group 46

SSA No.	Description
1	Concept Designs
SSA Owner	
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Introduction

As per discussions in the previous meeting, concept designs must be fabricated once the supply and demand data are properly visualised.

Goal

- To analyze the supply and demand graphs
- To come up with two concept designs based on the analysis

Problems

Conclusion

- A molten salt battery and a pumped hydro storage system was conceptualized
- Using a thermal (molten salt) battery in not ideal due to thermal degradation over long periods (months) of time. Using a gravitational (pumped hydro system) is feasible and ideal due to minimal to negligible energy losses, even over long periods of storage time.

Recommendations

- Neglected factors during calculations need to be considered wherever required (such as frictional and viscous losses) in future mathematical models, to obtain at a more accurate representation of the energy storage system

1 Elaboration

1.1 Analysis of Supply and Demand Graphs

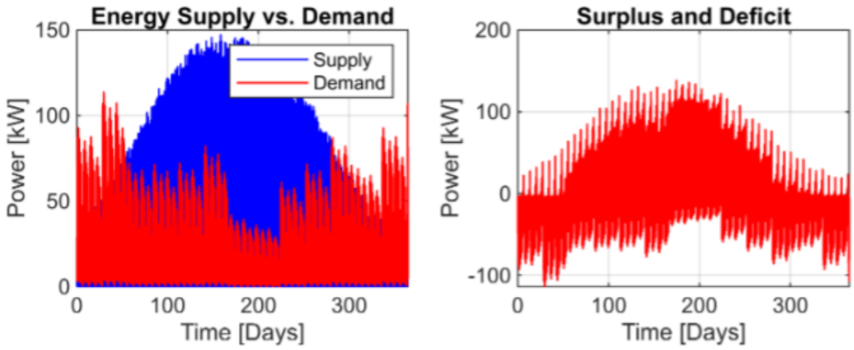

Figure 1: Supply and Demand Graphs

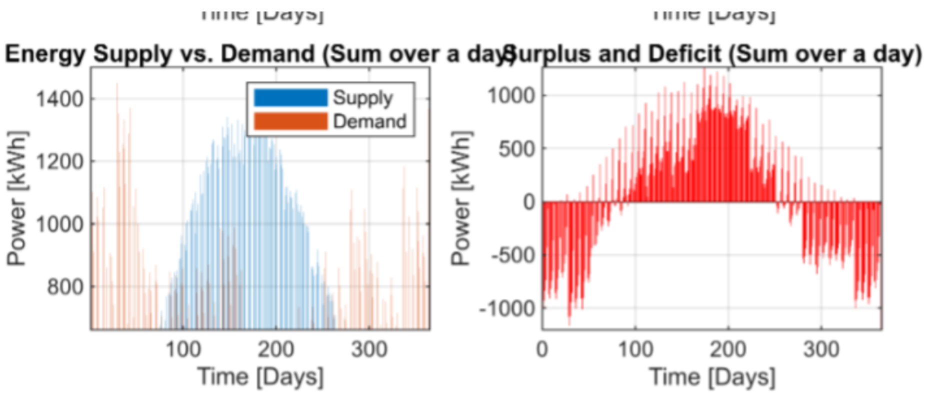

Figure 2: Supply and Demand Graphs with More Information

The above graphs were received after compiling the supply and demand data.

The standout from this graph is the clear differences in supply and demand surpluses. From day 90 (as confirmed in figures 3 and 4) to day 245 nearly (as confirmed in figures 5 and 6) there is a clear supply excess. This period lasts nearly 155 days and the demand surplus lasts nearly 210 days.

The largest amount of energy that needs to be stored in a day is of the order 10^2 kW, the largest power excess is in the order of 10^3 kWh and the largest power deficit is in the same order (around day 10 as seen in fig. 2).

For easy access later on, a basic requirement list is made below, the chosen energy storage system must

- Be able to store energy in the order of 10^3 kW
- Store the energy for nearly 155 days with minimal losses
- Discharge the energy over a period of nearly 210 days

7794000	1.709618
7794900	1.664196
7795800	1.683865
7796700	1.604485
7797600	4.80927
7798500	4.681497
7799400	4.736824

Figure 3: Demand at the start of 90th Day (Time in seconds on the left and Power in kWh on the right)

7794000	3.689618
7794900	8.020909
7795800	13.31471
7796700	19.25018
7797600	25.66691
7798500	32.24406
7799400	38.8212

Figure 4: Supply at the start of the 90th Day (Time in seconds on the left and Power in kWh on the right)

21225600	46.78992
21226500	45.5468
21227400	46.08509
21228300	43.91259
21229200	46.16585

Figure 5: Demand during the 245th Day (Time in seconds on the left and Power in kWh on the right)

21225600	34.48991
21226500	28.55444
21227400	22.45855
21228300	17.32516
21229200	12.03136

Figure 6: Supply during the 245th Day (Time in seconds on the left and Power in kWh on the right)

This was the basic analysis performed to gain a foundational idea on what type of energy storage system may be suitable for the given use-case scenario.

1.2 Concept Design Research

To cement onto a conceptual design, research was performed. Firstly, the graph shown in the PSL (Fig.7) was looked at to gain a basic ballpark of what kind of system may apply to this scenario.

Based on the set requirements (in the above subsection), it is practical to consider **thermal energy storage**. It minimally meets all the requirements, and is in scope of this project. Secondly, a gravitational energy storage or pumped hydro storage system can be looked into as well, even though the graph finds it applicable out of scope for energy levels dealt by the given use-case scenario. They are found to be more efficient (as read in [11]) but definitely take up more physical space (as read in [2]).

For now, first a thermal energy system will be devised. Followed by an attempt at conceptualizing a gravitational battery and/or a Pumped Hydro Storage system.

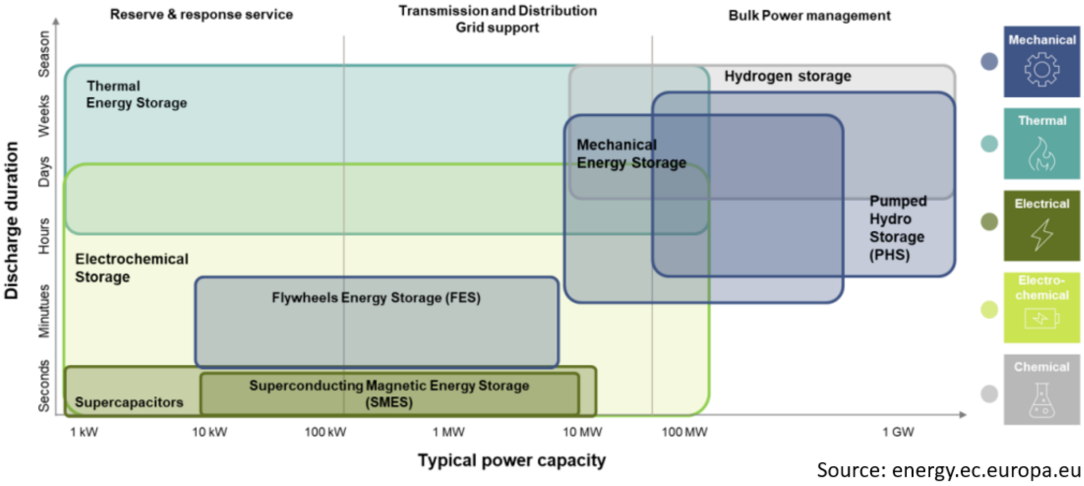

Figure 7: Rule of Thumb Graph

1.3 Thermal Energy Storage

A rough average of the amount of energy that needs to be stored every day for the 155 days of supply surplus can be roughly calculated by subtracting the average surplus from the average demand in that period. The supply averaged to nearly 47.7 kW (as averaged in excel from supply data, shown in fig. 8) and the demand averaged to be nearly 21.8194 kW (as shown in fig. 9). The maximum and minimum was also found, to understand the range of the values and perhaps accomodate for them in some manner. This is shown in fig. 10 and 11. The power data is given in time increments of 900 seconds. It is assumed that the Power demand/-supply stays the same over a complete day.

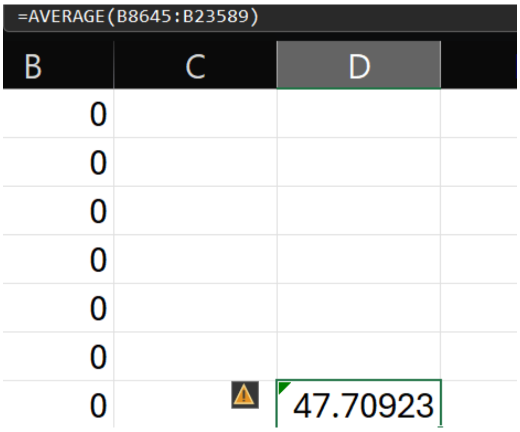

Figure 8: Average Supply over 155 day period

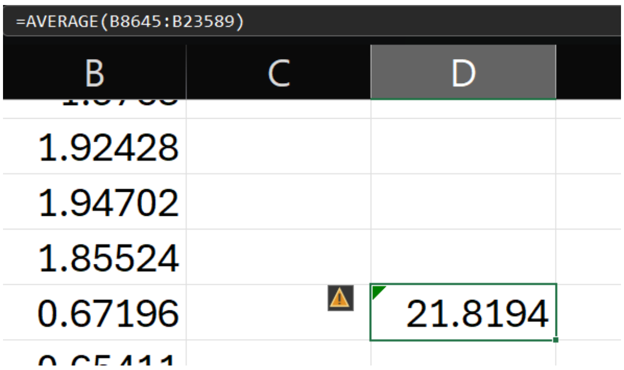

Figure 9: Average Demand over 155 day period

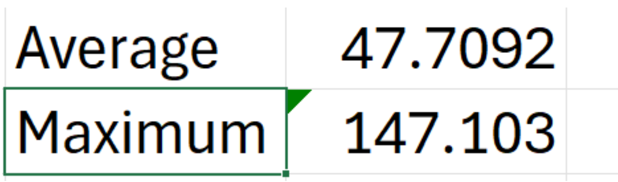

Figure 10: Maximum Supply over 155 day period

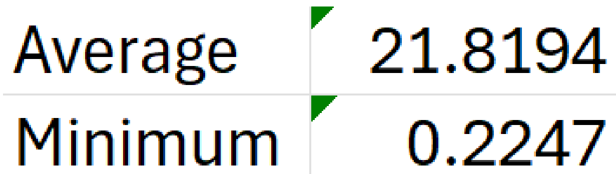

Figure 11: Minimum Demand over 155 day period

Total Average	16.83324
Min	0

Figure 12: Average and Minimum Supply over the rest 210 days

Total Average	31.2725
Maximum	113.67

Figure 13: Average and Maximum Demand over the rest 210 days

The desired thermal system should be able to store about 25 kW a day for 155 days. Accommodating for the maxima and minima for every day may not be practical, since storing nearly 150 KW a day is very exhaustive (energetically it comes upto 360 MWh for 100 days only, which is already quite a lot). Also, the maxima of supply and minima in demand may/may not occur on the same day. However, it is good to accommodate power-wise for this extreme-case scenario, but not energy wise.

The desired thermal system should be able to deploy the required amount of energy (15 kW a day on average) as per the demand during the 210 day period. The extreme case scenario of maximum demand and minimum supply is ideal to accommodate for.

Storing 25 kW a day for 155 days is requires a storage power of 93000 kWh or 93 MWh (Since energy is $Power * Time$ and here time is 155 days, or 3720 hours).

After some research, **molten salt batteries [3] and Pumped Storage Hydropower** [**4**] were worked upon further.

Molten salt batteries are commonly used in solar energy plants to store energy for moderately long durations, this corresponds with the requirement list set up earlier. Pumped Hydro Storage was also investigated, since thermal batteries could face significant amounts of energy losses due to thermal degradation over long durations of time. These systems can store energy for extremely long durations of time, hence complying with the requirements set up earlier.

1.4 Molten Salt Thermal Batteries

Molten salt batteries take advantage of the high specific heat capacity of molten metal nitrate salts (for eg, sodium nitrate has a specific heat capacity of 1.6-1.75 J/gK) paired with high melting and decomposition temperatures. This provides efficient heat transfer and operation in high and big temperature ranges, (for eg: sodium nitrate can be used in a window of 308 [7] to nearly 600 degrees celcius [8] before it decomposes). These molten salts are also usually phase change salts, which have a high heat of latent fusion, ie; they take up a lot of energy to change from their solid to liquid phase (Sodium nitrate requires nearly 178 kJ/kg to change between its solid and liquid phase [9]), allowing for further energy storage.

1.4.1 Conceptual Design

For the given use-case scenario, a conceptual design needs to be put in place. Firstly, calculations for the temperature range of the sodium nitrate salt need to be done. Here, a cylindrical thermal tank is used, so that the heat transfer in the insulation layers is maximally uniform. The most commonly used insulators in any industry application are the following [12]:

- Coated Fabrics
- Fiberglass Textiles
- Silica Textiles
- Coated textiles with Silicone, Graphite and Carbon
- Ceramic Coated Textiles

Ceramic Coated Textiles can handle thermal shock and withstand extremely high temperatures (upto 1260 degrees celcius [1]) making them ideal for the innermost layer of insulation. Here, **Basalt Fibre cloth** will be used for further calculations.

To minimize space usage and maximize temperature range usage (of the molten salt), the following conditions and assumptions are set to find the dimensions of the tank:

- The heating in the molten salt will be uniform
- The salt used for calculations will be homogeneous Sodium Nitrate
- Currently, only the basalt fibre cloth will be used as conductive insulation.
- The temperature of the molten salt should go upto 550 degrees celcius (not 600 degree celcius since that is the decomposition temperature)
- The energy supplied to the molten salt is 150 kW (To accomodate for extreme-case scenario)
- The temperature on the outside of the tank should be 60 degrees celcius (as described by a common guideline to prevent burns upon contact [6])
- The entire system is in steady state
- The thermal coeffecient of heat transfer of Basalt Fibre is 0.034 W/mK
- Height of the tank is assumed to be one metre
- Specific heat capacity of Sodium Nitrate is assumed to be 1600 J/kg K in molten state and 1210 J/kg K in solid state
- Melting temperature of sodium nitrate is assumed to be 308 degrees celcius
- Latent heat of fusion (l_f) for sodium nitrate is 178 kJ/kg
- Room temperature (T_{room}) is defined as 20 degrees celcius
- The density of sodium nitrate is 2250 kg/m^3 in its solid form, and it reduces to 1560 kg/m^3 in the liquid form. The tank should accommodate for the increase in volume of sodium nitrate, hence the liquid density will be used when calculating the volume of the molten salt tank.

These conditions lead to the following back of the envelope calculations:

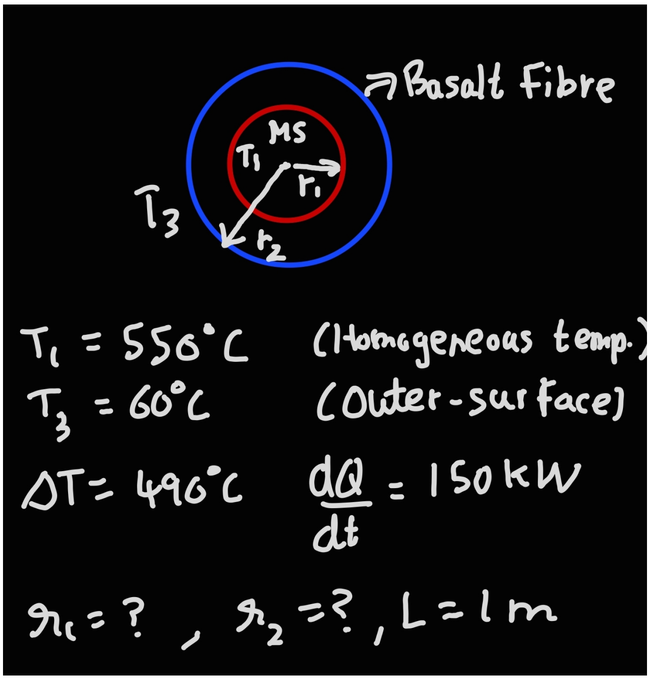

Figure 14: Initial Setup and Diagram

By conservation of energy:

$$Q_{in} = Q_{out}$$

$$\therefore 311{,}040(10^6) = m_{salt} \cdot \left[c_{solid} \cdot \Delta T_1 + c_{molt} \cdot \Delta T_2 + l_F\right]$$

$$\therefore m_{salt} = 340{,}425.53 \text{ kg}$$

Figure 15: Conservation of Energy

$$\frac{dQ}{dt} = 2\pi k_{Basalt} L \frac{\Delta T}{\ln\left(\frac{r_2}{r_1}\right)}$$

$$150(10^3) = \frac{2 \cdot \pi \cdot (0.034) \cdot (490)}{\ln(r_2/r_1)}$$

$$\ln\left(\frac{r_2}{r_1}\right) = 6.98 \cdot (10^{-4})$$

$$\frac{r_2}{r_1} = 1.0006 \quad \text{—— (1)}$$

Figure 16: Equation 1

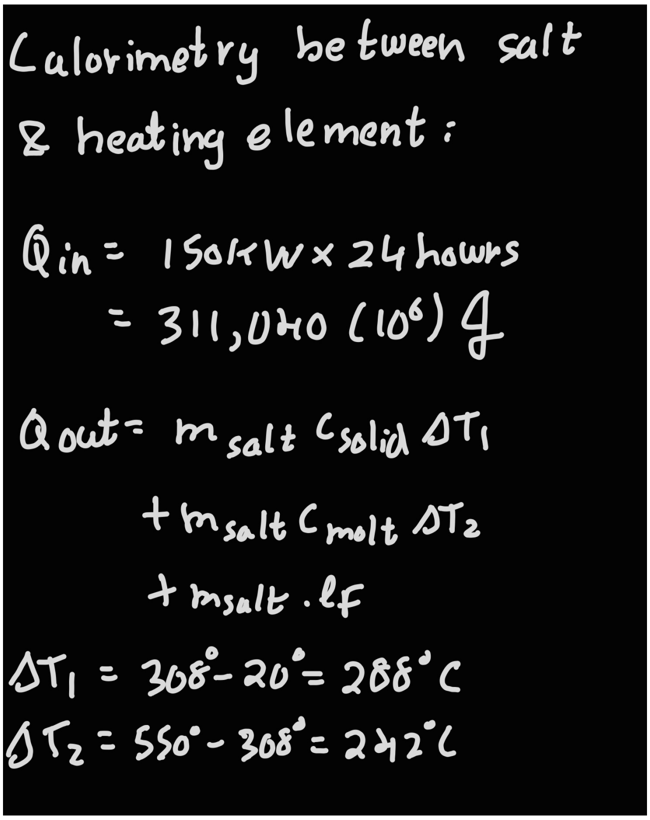

Figure 17: Calorimetry

$$\rho_{salt} = \frac{m_{salt}}{Vol.}$$

$$\therefore \quad Vol. = \frac{m_{salt}}{\rho_{salt}}$$

$$Vol. = 218.221\, m^3$$

This is the vol. of the MS tank, hence

$$Vol. = \pi r_1^2 L$$

$$\therefore \quad r_1 = \sqrt{\frac{Vol.}{\pi L}}$$

$$r_1 = 8.334\, m$$

$$r_2 \simeq r_1 \quad [\text{From eqn. (1)}]$$

Figure 18: Volume of Molten Salt Tank

This conceptual modelling led to a tank that has a total radius of **8.339 m** (using the factor of 1.0006), and an inner radius (holding the molten salt) of **8.334 m**. This concept uses only one layer of insulation (basalt fibre), which is **0.005 m thick**.

Converting this stored energy back into electrical energy can be conceptualized by a thermoelectric generator [10]. After reading through some common industrial-use generator types [10], a steam cycle generator is conceptualized further. The heat from the molten salt can be put through a heat exchanger [13] used to heat up water in a chamber, which would eventually pressurize the chamber by creating enough steam. This pressurized steam can be used to spin a turbine and generate electricity.

A big advantage of this concept is that the insulator is very effective and makes the storage system much more compact (w.r.t radius). Molten salt batteries are usually quite huge, hence a significant volume (nearly 218 m^3) is valid for such a molten salt battery. The supply of energy (from the storage) in the days of a supply deficit can be moderated by controlling how much of the molten salt is put through the heat exchanger, how much steam is pressurized or by controlling the size of the steam chamber by using different sized chambers.

The biggest con of such a system is the thermal degradation that can occur over longer periods of time. Other cons are the loss of energy between the heating element and molten salt, followed by any conversion losses that may occur when converting the heat energy back to electrical energy since it is first converted to pressure energy and then into mechanical energy. Finally, this concept cannot be used to instantaneously supply energy since the thermoelectric generator is not instantaneous in its function.

1.5 Pumped Hydro Storage

This energy storage system is a type of gravitational battery involving water. During a supply surplus, water is pumped up to a relatively higher altitude and stored in a reservoir. When required, the reservoir is opened. As the water makes its way down, it spins a turbine that generates electricity.

For some back of the envelope calculations, the atitude of the water storage system was assumed to be 50 metres. The entire system itself is conceptualized as shown below in fig. 19

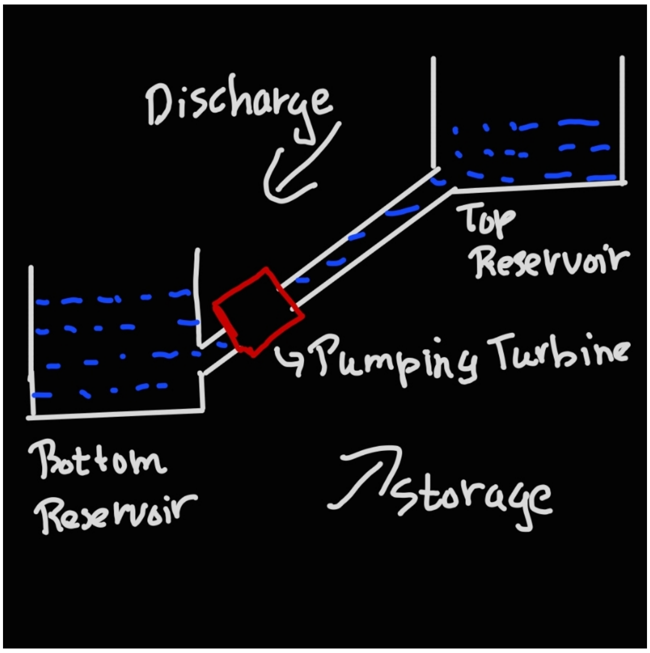

Figure 19: Concept

Here a pumping turbine [5] is used to pump the water during a supply surplus and generate electricity when the water transfers from top to bottom reservoir.

During the storage part of the cycle, the pressure provided by the pump transfers into the potential energy stored in the top reservoir. Since this a preliminary concept, viscous and frictional losses during the transfer of the water from bottom to top reservoir are neglected.

The pressure provided by the pump comes from the surplus power of 25 kW (on average). The power going into the pump can also be written as:

$$\begin{aligned} P_{in} &= \rho_{water} * g * h * Q \\ Q &= \frac{Volume}{Time} \end{aligned} \tag{1}$$

Here Q is an indication of the volume of water that needs to be stored in the top reservoir. The total volume that could potentially be stored in the top reservoir over 155 days is given by:

$$\begin{aligned} Volume &= \frac{P_{in} * t}{\rho_{water} * g * h} \\ &= \frac{25 * 10^3 * 13392 * 10^3}{10^3 * 9.81 * 50} \\ &= 682,568.8\ m^3 \end{aligned} \tag{2}$$

This is a significant volume of water, and storing it could become a challenge in constrictive spaces.

Working on this concept in a more minimalistic approach would be to accommodate exactly for the the supply deficit over the 210 days. Based on the power averages, clearly a smaller amount of water needs to be used to meet the power demand during that period.

The power required is 15 kW on average and 113 kW in an extreme case scenario (over a day). The system should be able to deploy 113 kW in one day and 15 kW on average:

$$\begin{aligned} P_{out} &= \rho_{water} * g * h * Q \\ 113 * 10^3 &= 10^3 * 9.81 * 50 * Q \\ Q &= 0.23\ m^3/s \end{aligned} \tag{3}$$

Hence the maximal volume that the top reservoir should be capable of transferring to the bottom reservoir in one day

$$\begin{aligned} Volume &= Q * t \\ &= 20,736\ m^3 \end{aligned} \tag{4}$$

For the final dimensions of the tank:

$$\begin{aligned} P_{out} &= \rho_{water} * g * h * Q \\ 15 * 10^3 &= 10^3 * 9.81 * 50 * Q \\ Q &= 0.03\ m^3/s \end{aligned} \tag{5}$$

$$\begin{aligned} Volume &= Q * t \\ &= 544,320\ m^3 \end{aligned} \tag{6}$$

Even with a minimalist approach, the required volume of water seems to be quite large. However, the average area requirement of a Pumped Hydro Storage is 10 hectares of land (100,000 m^2), this would mean that this reservoir falls below the average (5.44 hectares of land if the reservoir is 1 metre deep). This is a good indication of the concept being feasible.

The pros of such a system is that there are negligible to no energy losses in the system during the storage period. The system is quite straightforward and undergoes a more effecient energy conversion, ie; gravitational (potential energy) to mechanical (pressure) to electrical energy. The deployment of energy is fairly fast since it is moderated by the amount of water released from the reservoir.

The only possible cons of this system is the scalability. The water storage scales with the amount of energy being stored, making it geometrically challenging to accommodate depending on available space. The geometric challenges can be overcome by using multiple reservoirs, hence removing the requirement of one big piece of land. Using underground caves can also help save costs and delimit space constrictions.

Overleaf Link to this SSA

https://www.overleaf.com/read/vbbwhynfkhmt#08ac9d

References

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[2] *Mix Mountains and Gravity Batteries for Long-Term Energy Storage*. URL: https://spectrum.ieee.org/mix-mountains-and-gravity-for-longterm-energy-storage. (accessed: 25.04.2024).

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[11] *What are Gravity Batteries?* URL: https://www.thegreenage.co.uk/what-are-gravity-batteries/. (accessed: 25.04.2024).

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