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Li-Ion Battery versus Pumped Storage for Bulk Energy Storage - A Comparison of Raw Material, Investment Costs and CO_2-Footprints

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Abstract

The balancing of load and generation is a major challenge in electricity systems shaped by renewable energy sources. In this context, large-scale storage systems as a temporal flexibility option contribute to the balancing process by participating in portfolio management, energy only markets as well as system reserve markets. Over the past years particularly battery storages experienced a tremendous ‘hype’ in public discussions due to technological innovation and a significant cost decrease. As a result, several new stationary battery storages in the order of magnitude of hundreds of megawatt hours have been constructed during the last decade. However, the question remains whether the falling costs of a stationary battery storage can be competitive with well-established technologies such as pumped storage hydro.

This paper compares the marginal costs given by the specific raw material costs of a representative stationary battery storage with the respective costs of a pumped storage scheme. It is evident that both systems need completely different types and quantities of resources leading to substantial differences in their specific raw material costs. In addition to the raw material costs, annual lifetime investment costs and land requirements for both technologies were examined. Finally, the different contributions to the over-all CO_2-footprint are analyzed. This paper, consequently, contributes to the ongoing and controversial discussions around the different storage technologies for stationary application with respect to their economic efficiency and their environmental impact.

1 Introduction

The German and European transition towards an energy system shaped by renewable energy sources poses many technical and economic challenges. One major technical challenge consists in balancing the electrical generation and demand. In this context, large-scale storages contribute to the balancing process by participating in portfolio management, energy only markets as well as markets for ancillary services.

The substantial cost reduction of battery storages systems (BSS) has led to an increasing amount of installed stationary BSS in Germany during the last years and an installed capacity larger than 120 MW. On the other hand, uncertain market environments in combination with high investment costs and long-term amortization periods discourage investors from developing new pumped storage plants (PSP). Therefore a scientifically justified analysis of these two different storage options is necessary in order to ensure that climate goals are not jeopardized by the utilized storage technology.

2 Investigation Approach

The main goal of this study is to compare a stationary BSS with a PSP regarding key economical and environmental indicators. A first analysis considers the raw material costs of both technologies, as this is the absolute limiting factor with regard to future optimization of component and plant construction. In a second step, the current financial investment sums of both technologies are analysed. Finally, the carbon foot prints are compared as an indication of the environmental impact of the different technologies. The basis for the comparative investigation is a German bachelor thesis [1]. Actual projects in Germany, which were considered in [1] as well, serve as a basis for the following calculations and comparisons. Further related reports are taken into account [2] , [3] to compare and verify the obtained results of this study.

The following two subchapters focus on the specific properties of the two individual projects. The planned 1.4 GW pumped storage project Atdorf serves as an example of a representative PSP whereas the battery power plant located in Schwerin represents a stationary BSS.

2.1 Pumped Storage Plant

For the pumped storage investigations the planned PSP Atdorf located in the southern part of the Black Forest in Germany has been chosen. This PSP is a cavern-type pumped storage with two artificial reservoirs and it is characterized by a projected storage capacity of 13.4 GWh with a maximum power output of 1.4 GW, the power to energy ratio is 1/9.57 W/Wh). The project is in the planning stage and has not been realized, yet. The underground arrangement of the planned PSP is illustrated in Figure 1. It can be seen that the PSP Atdorf has a high civil complexity due to the long tail water tunnel with the sophisticated surge tank as well as the two caverns which are designed to accommodate six units, compared to four units in most other pumped storages.

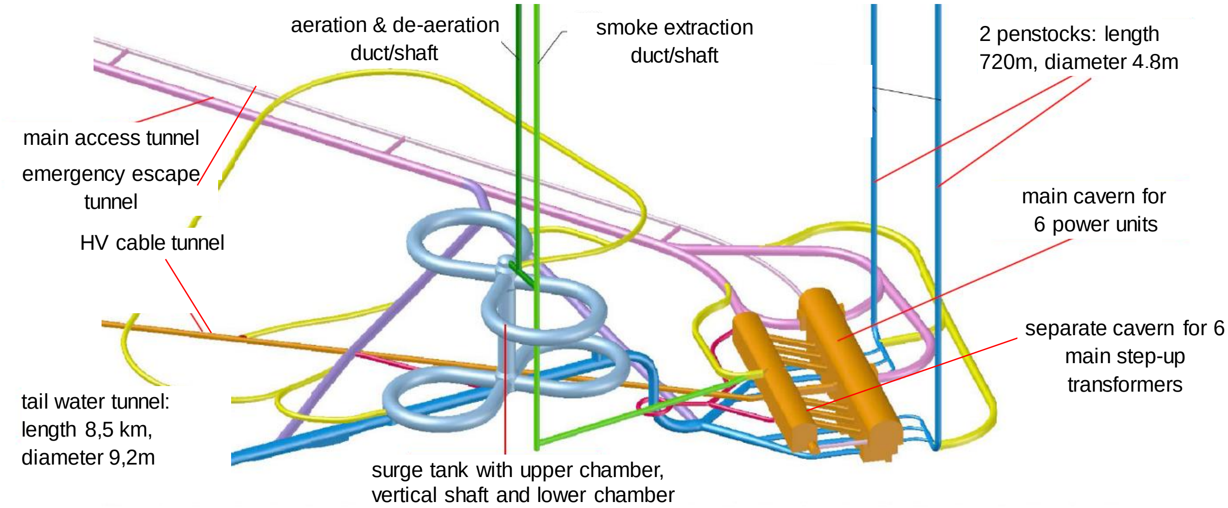

Figure 1: 3D underground arrangement of PSP Atdorf

2.2 Battery Storage

As an equivalent electrochemical storage, the BSS Schwerin erected by the WEMAG group in 2014 is chosen. The BSS has a storage capacity of 5 MWh with a maximum power output of 5 MW, i.e. the power to energy ratio is 1W/Wh. It consists of 25,600 lithium-manganese-oxide cells produced and maintained by Samsung SDI. Samsung offers 20 years of warranty on the cells if a constant temperature of 17°C is maintained by the HVAC system. In addition to the cells, the BSS contains ten DC/AC converters placed in a building which needs a base area of approx. 400 m². Currently, this BSS participates in the German fast balancing energy market particularly for primary control reserve.

3 Investigations

The following subchapters describe the investigations which were conducted within this study. Section 3.1 depicts general aspects relevant for understanding the idea of this comparison. Section **Fehler! Verweisquelle konnte nicht gefunden werden.** examines the differences in terms of raw material requirements for both technologies during the initial installation. On this basis, section 3.3 presents the resulting raw material costs in the initial installation phase and draws a comparison. In a second step the raw material requirements and costs during the lifetime of the storage plants are examined in section **Fehler! Verweisquelle konnte nicht gefunden werden.** and 3.5. As an extension to the work of Mr. Rostetter [1] an examination of investment costs and present values for both technologies follows in section 3.6. Finally, section 3.8 completes this work by analysing the carbon footprint of both technologies.

3.1 General Notes

Storage systems can be generally categorized by the relationship between power and stored energy [4]. With a ratio less than 1/50, storage facilities are classified as long-term storages. With a ratio between 1 and 1/50 storages are considered as medium-term storage systems whereas storages with a ratio greater than 1 are considered as short-term storages. With respect to the two storage systems, which are chosen for this comparison, the ratio of the PSP Atdorf is 1/9.57 W/Wh whereas the ratio of the BSS

Schwerin is 1/1. This difference indicates that the field of application for the two storages differs which has to be taken into account when comparing the results. Other battery technologies like sodium-sulfur (NaS) can offer ratios up to 1/7.2 [5]. Therefore, those technologies are more similar to the PSP in terms of the ratio, but since they are in pilot project stage, there are no in-depth analyses or data available so far.

3.2 Raw Material Requirements during the initial installation phase

In the scope of this study, the input data for respective raw materials of the PSP are not evaluated in detail. Instead, official values of the project developer of PSP ‘Atdorf’ are applied. Table 1 gives an overview about the most characteristic materials. The materials used most are concrete, steel and copper. Concrete is used for erecting dams, tunnels, surge tank and caverns. The vast amount of steel is utilized for the mechanical components of the power plant. Copper is mostly needed in the motor-generator set for producing electricity. The civil construction is strongly characterized by the removal of rock material and large amounts of energy are required. The raw materials used most are diesel fuel for the site vehicles as well as explosives. In general neither for the PSP nor the BSS the raw materials used for the substations are added, since both plants have to be connected with similar switch gears, so that the same values would be added for both technologies.

Material	Usage	Value
Steel	Anchors, hydraulic steel structures, concrete steel reinforcements and miscellaneous mainly for the civil works	70,000 t [8]
Site concrete & shotcrete	Dams, tunnels, shafts, caverns and other buildings	1.748 mil m^3 [8]
Copper	Motor-Generator sets	336 t [9]
Diesel	Construction	149,000 m^3
Explosives	Tunnel and cavern blasting	5,620 t

Table 1: Raw materials requirements for the PSP for the initial installation

The quantification for BSS raw material requirements are based on the following assumptions. The calculation can be divided in the required raw materials for the building on the one hand and for the battery cells on the other hand. First, the paper shows the analysis of the utilized surface area of the BSS building and the corresponding raw material requirements. Thereby, Figure 2 gives a (schematic) top view of the storage system clearly showing that battery cells and converters do not occupy the whole surface area.

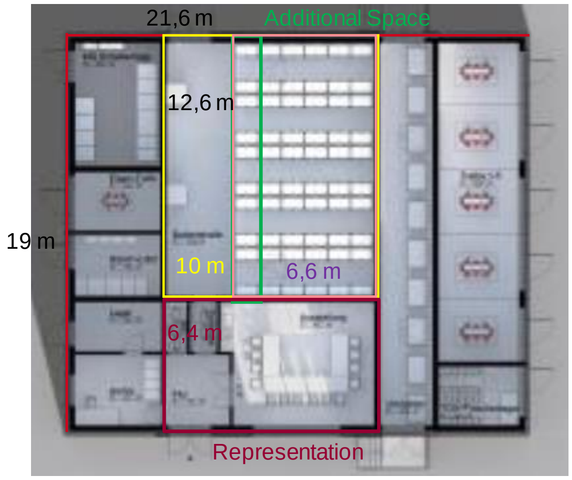

Figure 2: Floor plan use of BSS in Schwerin [6]

Since the BSS in Schwerin was the first large scale BSS in Germany, about 15 % of the whole surface area is used for demonstration purposes. As this area will not be part of future similar BSS projects, it is excluded from the calculations (see Figure 2). 20 % of the surface area has two-levels in the area of the batteries. The Wemag BSS was designed to house a maximum 120 battery racks, however in the first stage only 100 racks were actually installed. The area allocated for further expansion is marked by the green-lined rectangle in Figure 2. The scaling up of the building is based upon a total storage capacity of 6 MWh.

The raw material requirements for the battery cells are based on the weight of one single cell and the corresponding power and storage capacity. The respective values are in accordance with publications by Samsung SDI [7] due to similar technology and design. Scaling up the power and storage capacity of this single cell to the storage capacity and power of the BSS results in the requirements for an equivalent BSS. Gaines [8] analyzed the technical composition of lithium-ion batteries in his study and provided the percentage of battery mass for each individual raw material. The result is illustrated in Figure 3, but only the raw materials with a share equal to or larger than one percent of the overall mass are illustrated. Based on these proportional factors and the overall mass of the batteries the requirements are estimated.

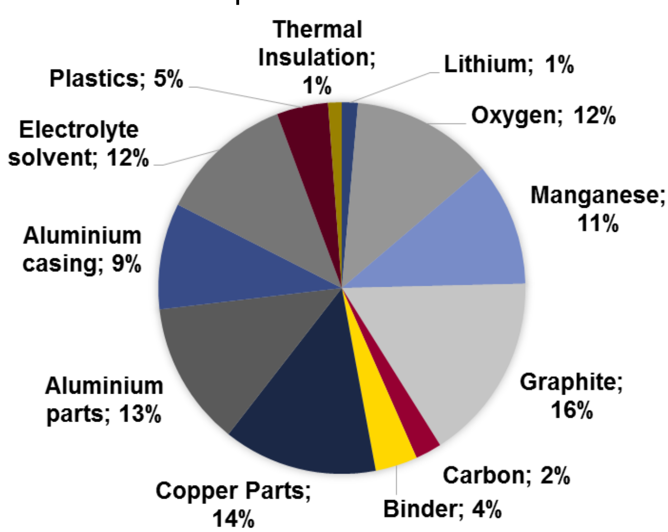

Figure 3: Battery Parts (with a share above or equal 1% of mass) of Lithium-Ion Batteries [8]

Table *2* illustrates the different raw materials used for the BSS. The first column states the various raw materials taken into consideration. The second column explains, where the respective raw material is used in the BSS. The third column depicts the demand for the different materials used in the BSS in Schwerin. The fourth and fifth column represent the required materials for a BSS with the same power and respective capacity as the PSP. In the following only the amount of materials needed for an equal storage capacity will be taken into account. For this storage capacity the amount of crude oil for the transportation by cargo vessel from the production of the battery cells in Korea to Germany are calculated.

Material	Usage	Tonnage for Schwerin with 5 MW [t]	Tonnage for 1.4 GW and 1.4 GWh [t]	Tonnage for 13.4 GWh [t]
Steel	Fundament, support, racks, ceiling, battery module	90.01	21004.44	201042.48
Concrete	Fundament	960	224000	2144000
Copper	Racks	5.95	1665.89	15944.94
Plastic	Racks and battery module	1.89	529.62	5069.19
Lithium	Battery module	0.51	141.84	1357.63
Manganese	Battery module	3.87	1084.08	10376.18
Graphite	Battery module	5.90	1651.45	15806.71
Mercury	Battery module	$3.26 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	0.01
Cadmium	Battery module	$8.32 \cdot 10^{-5}$	0.02	0.22
Lead	Battery module	$2.9 \cdot 10^{-5}$	0.01	0.08
Carbon	Battery module	0.83	233.03	2230.39
Aluminum	Battery module	7.85	2198.55	21043.29
Rock wool	Battery module	0.43	121.58	1163.68
Electrolytic solvent	Battery module	4.27	1195.53	11442.89
Binder	Battery module	1.34	374.87	3588.03
Crude Oil	Cargo Vessel	-	-	1529

Table 2: BSS Initial Raw Material Requirements

3.3 Raw Material Costs during the initial installation phase

Based upon the raw material requirements in Table 3, the costs of those materials can now be evaluated to make a comparison of the two technologies. Table 3 illustrates the respective costs for each raw material, as well as the source (where the values are extracted from). It is obvious that there is a huge range of costs for the different raw materials, especially some of the raw materials used in the BSS are highly cost intensive.

When considering those costs, the difference in raw material costs between BSS and PSP becomes evident (cf. Figure 4). As it is shown, the BSS is about 3.7 times more cost intensive compared to the PSP regarding raw material costs for the same storage capacity of 13.4 GWh. Figure 4 indicates that for the Battery Storage the costs for the batteries itself exceed the costs for the building by far. Furthermore, Figure 4 illustrates, that the main driver for raw material costs for the PSP are the costs for diesel fuel for the construction process.

Raw Material	Costs in EUR/t	Source
Steel	430	[9]
Concrete	8	[10]
Copper	5,070	[11], [12]
Plastic	1,444	[13]
Lithium	8,000	[14]
Manganese	1,760	[15]
Graphite	5,000	[16]
Mercury	37,640	[1]
Cadmium	1,912	[17]
Lead	1,862	[18]
Carbon	48	[19]
Aluminium	1,682	[20]
Rock wool	2,650	[1]
Electrolytic solvent	21,010	[1]
Binder	54,200	[1]
Diesel fuel	790	[21]
Explosives	3,000	[22]
Crude Oil	299.7	[23]

Table 3: BSS Specific Raw Material Costs

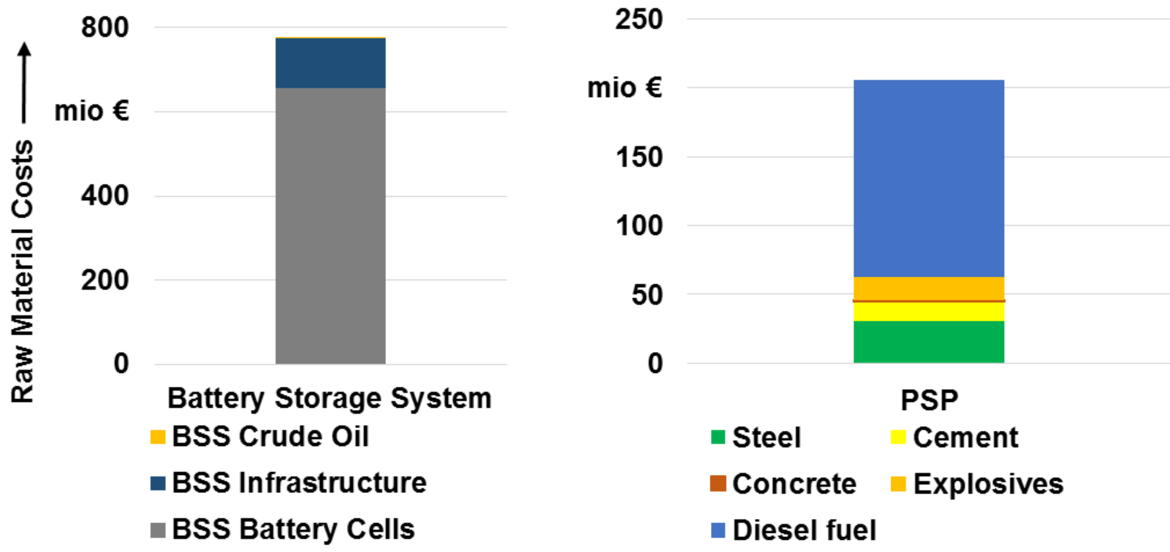

Figure 4: Comparison of Initial Raw Material Costs

3.4 Lifetime Raw Material Requirements

Operating and maintenance costs of BSS are at first glance very low. There are no rotating components and no direct interfaces with the environment, which demand constant vigilance and attention. Further analysis shows, however, that the lifetime raw material requirements of the two technologies are quite different. With an assumed lifetime of about 100 years, parts of the PSP and the BSS have to be replaced meanwhile. For the PSP the 6 motor-generator sets as well as the runners of the pump turbines have to be replaced after 40 years. This information is based on estimates by experts [24] and results in replacements after 40 and 80 years. Replacing the motor-generator set results in an additional requirement for steel as well as copper, as indicated in Table 4 below.

Material	Usage	Tonnage for one exchange	Tonnage for two exchanges
Steel	Replacement of runners, steel components & ferromagnetic sheets for rotors and stators	4,586	9,172
Copper	Replacement of the windings for the motor-generators sets	336	672

Table 4: Lifetime PSP raw material requirements

In contrast to the PSP, the battery modules already have to be replaced after the guaranteed lifetime of 20 years. Identical raw materials requirements as for the initial battery modules installation are assumed. For the buildings, a lifetime of 100 years is assumed and therefore the building raw materials are not taken into account in this calculation. The results are shown in the following Table 5. The values shown in the fourth column of Table 5 represent the corresponding requirement for raw materials for one battery modules exchange. Assuming a lifetime of 100 years, replacement will occur every twenty years and therefore the battery modules will have to be replaced four times.

Material	Usage	Tonnage for Schwerin with 5 MW [t] (one exchange)	Tonnage for a capacity of 13.4 GWh [t] (one exchange)	Tonnage for a capacity of 13.4 GWh [t] (four exchanges)
Steel	Fundament, support, racks, …	0.04	96.97	387.9
Copper	Racks	5.03	13479.34	53917.4
Plastic	Racks and battery module	1.63	4363.82	17455.3
Lithium	Battery module	0.51	1357.63	5430.5
Manganese	Battery module	3.87	10376.18	41504.7
Graphite	Battery module	5.90	15806.71	63226.8
Mercury	Battery module	$3.26 \cdot 10^{-6}$	0.01	0.04
Cadmium	Battery module	$8.32 \cdot 10^{-5}$	0.22	0.9
Lead	Battery module	$2.9 \cdot 10^{-5}$	0.08	0.3
Carbon	Battery module	0.83	2230.39	8921.6
Aluminium	Battery module	7.85	21043.29	84173.2
Rock wool	Battery module	0.43	1163.68	4654.7
Electrolytic solvent	Battery module	4.27	11442.89	45771.6
Binder	Battery module	1.34	3588.03	14352.1
Crude Oil	Cargo Vessel	-	1529	6116

Table 5: BSS Lifetime Raw Material Requirements

3.5 Overall Raw Material Costs during Lifetime

During the lifetime of 100 years the raw material costs for the two bulk energy storage options are very different. Due to the frequent replacement of the battery cells and their high raw material costs, the running material costs are much higher compared to the running material costs for machinery in the PSP. The running raw material costs (excluding initial raw materials) of BSS is about 357 times more cost intensive over 100 years. Overall, over 100 years, the raw material requirements of BSS are approximately 18 times more cost intensive than PSP.

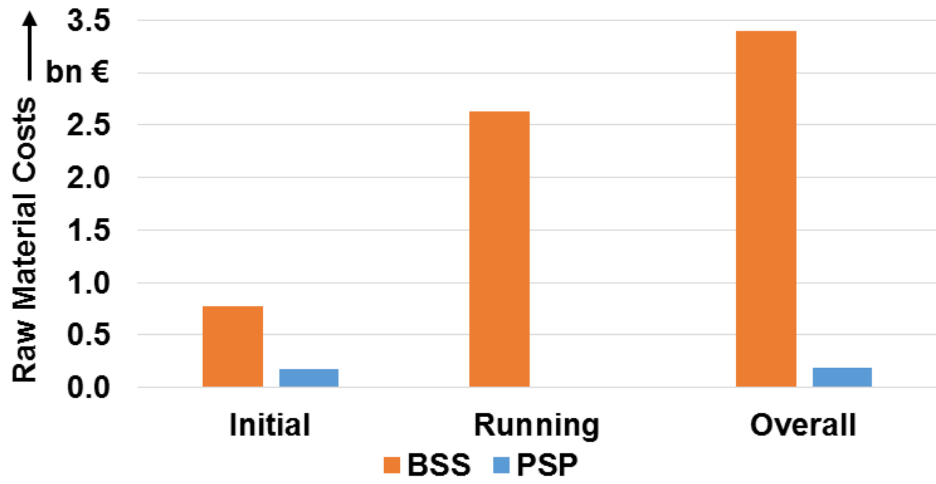

Figure 5: Comparison Raw Material Costs during the Assumed Lifetime of 100 Years

3.6 Capital and Operational Expenditures

For both technologies, the raw material costs represent a relatively small proportion of the overall investment costs. The overall investment includes planning, energy, manufacture, erection and grid connection costs as well as operation and maintenance costs. In the following calculations of the investment costs, a depreciation period of 40 years for the PSP (replacement of machinery) and 20 years for battery replacement in the BSS are assumed.

The PSP has investment costs in the order of magnitude of 1.6 bn EUR [1]. Those comprise costs for raw material, planning, erection and grid connection. The yearly operating costs for this storage can be separated in fixed costs and operating costs. The fixed costs are 2.86 EUR/ (kW a) [1] which amounts to 4,004,000 EUR/a when being multiplied with the installed power of 1.4 GW. The variable operating costs are numbered by 0.56 EUR/MWh [1]. With the assumption of a yearly generation of 2.5 TWh/a [24] the variable operating costs are estimated with 1,400,000 EUR/a. Under the assumption of a depreciation period of 40 years and an interest rate of 4 % that results in a yearly annuity of 82.25 mio EUR/a.

The BSS 'Schwerin' has investment costs of 6 mio EUR [6] including costs for raw materials, manufacture, planning, erection and the grid connection. The annual operating costs are around 116,000 EUR/a with an inflation rate of 1.5 %/a, as stated in [6]. These values with the assumption of a depreciation period of 20 years and an interest rate of 4 % result in an annuity of 573 mio EUR/a. When scaling the storage capacity to the capacity that the PSP provides, the annuity increases to 1,535 mio EUR/a.

The result is similar to the difference in raw material costs as stated in section 3.2. The difference between the annuities between the two technologies is a factor 18, making the PSP 18 times more cost efficient as shown in Figure 6.

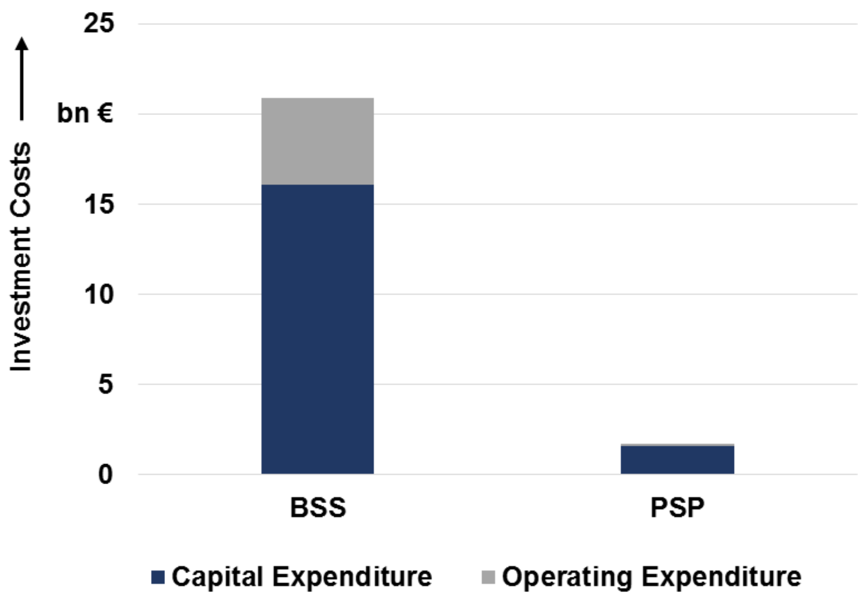

Figure 6: Comparison of Investment Costs

3.7 Spatial Requirements

Another interesting comparison with respect to the environmental impact is the spatial requirement of both technologies. According to the operator, PSP ’Atdorf’ requires an area of approx. 1.086 km². Scaling up the BSS ‘Schwerin’, results in an area of 0.759 km², approximately 30% less than PSP ’Atdorf’. This is illustrated in Figure 7.

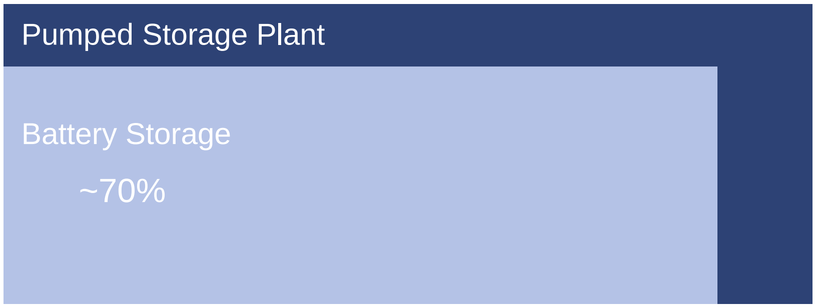

Figure 7: Land use of PSP and BSS

Within the calculations for the BSS ‘Schwerin’ it is assumed that 85 % of the ground area of the building are necessary for technical equipment, whereas the other 15 % are used for demonstration purposes. Furthermore, the building is supposed to offer a capacity of 6 MWh and a power of 6 MW. However these calculations are limited to the land use in Germany. When expanding the geographical scope to a global level, it becomes obvious that especially the battery storage needs huge areas for the mining process of the required raw materials, which are not taken into consideration in Figure 8. A benefit of BSS regarding the land use in Germany is the type of land cover required for BSS. BSS can be erected in a decentralized way on brown-field site whereas pumped hydro storage has to be located in less developed areas, with convenient topologies regarding head difference and reservoir capacities.

3.8 Carbon Footprint

The carbon footprint of the two technologies is evaluated by comparing the carbon emissions for the production of the raw materials. Additionally for the PSP the carbon emissions related to the erection of the facility are taken into account, due to the huge amount of CO_2 emitted during this process. As for the PSP, the CO_2 intensive transport of the battery cells from Korea to Germany via Cargo Vessel it taken into account. The carbon footprint is compared for the lifetime of 100 years for both technologies. The carbon footprint is analyzed with respect to the Ecoinvent database [26]. Therefore, the demand of raw material is multiplied with the greenhouse gas potential of the respective raw material.

The corresponding CO_2 emission factors of all materials are depicted in Table 6. All emission factors are derived from the Ecoinvent database [25].

Material	Steel	Concrete	Copper	Plastic	Lithium	Manganese	Graphite	Mercury	Cadmium	Lead	Carbon	Aluminum	Rock wool	Electrolytic solvent	Binder
GWP in kg CO_2-eq/kg	1.47	0.092	3.72	1.10	58.88	3.33	2.06	13.23	3.84	1.25	0.34	10.50	1.44	2.29	1.59

Table 6: Global Warming Potential (GWP) of different materials

Table 7 presents an overview of the necessary energy consumption during the complete construction and erection phase of the PSP, which needs to be considered when calculating the carbon-footprint. The values arise from in depth analyses, conducted by an experienced consulting agency for the plan-approval process.

Energy	**Usage**	**Value**	**CO_2 Emission Factor**
electricity	Energy demand during the construction phase for construction & site equipment, logistics, production, transport and delivery of building materials	880 GWh [10]	564 gCO_2/kWh [27]
fossil fuels (Diesel)	construction machines using combustion engines	149,000 m^3 [11] [1]	2650 gCO_2/l [28]
Explosives	Rock blasting underground and at the surface	5620 t [8]	2320 gCO_2/kg [29]

Table 7: Energy consumption during the construction and erection phase for the PSP

Focusing on the BSS, the major contribution to the CO_2-footprint from the erection phase arises from the CO_2 intensive transport of the battery cells. Most battery cells today are produced in Korea, therefore the transport via sea from Korea to Germany is taken into consideration. This results in the following values, emerging from GaBi

[1] The volume of fossil fuels was calculated using the following assumptions: average efficiency of construction machines of 0.2; density of fossil fuels 833 kg/m³; heat value of 11.8 kWh/kg

software for Life Cycle Assessments for different sections of the transport chain. The 117,000 t of battery cells, can be commissioned in 5850 containers (twenty-foot equivalent unit) and with overall CO_2 emission of 8,267 t. During its lifetime, the batteries in the BSS have to be replaced four times, therefore the CO_2 emission are 4 times the emissions given in Table 8.

Freight for the battery cells from Korea	Twenty-foot Equivalent Unit container (TEU)	Distance [km]	CO_2 [t]
Cargo ship	5850	20,525	8,267.36

Table 8: CO_2 emissions during the transport of the battery cells

Evaluating all of these values leads to a GWP of about 2.6 million t CO_2-equivalent for the BSS over a lifetime of 100 years, just caused by raw materials. The predominant part of the CO_2-equivalent arises from the raw materials, while transport is responsible for only 5%. In contrast to this, the GWP of the PSP sums up to 1.1 million t CO_2-equivalent, divided up into about 0.82 million t CO_2-equivalent resulting of the energy consumption during the erection process and about 0.3 million t CO_2-equivalent based on the raw materials. Figure 8 shows the different GWPs of the two technologies, and illustrates that the GWP over the lifetime of the Battery Storage is about twice the GWP of the PSP.

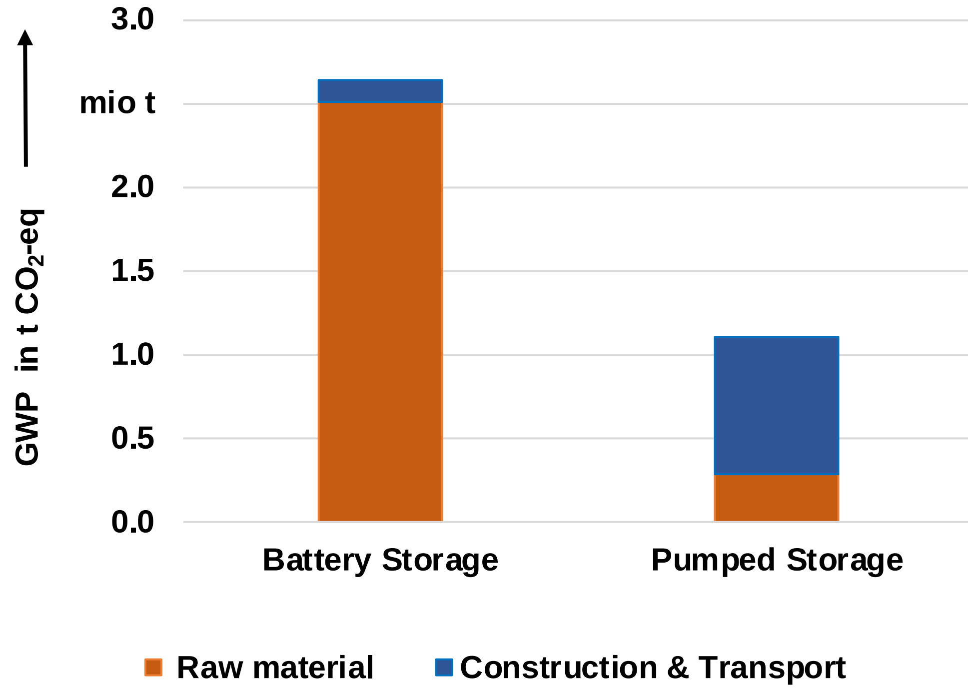

Figure 8: GWP of the two technologies

Concluding Remarks

A fundamental difference between the evaluated technologies is the power to stored energy ratio. For a PSP, this ratio can be easily tailored to the individual project needs. Typical values for PSPs are smaller than 1/7. The factor for PSP Atdorf is 1/9.6.

The Power to Energy ratio for a BSS depends on the type of chemical battery:

- Li-Ion: 1/3 ... 1/0.5
- Lead: 1/6 ... 1/3
- NaS: 1/7

Another important factor to be mentioned is the capacity deterioration of Li-Ion batteries. Depending on the operation mode Li-Ion batteries can suffer a significant capacity deterioration, which can reach up to a 2 digit percentage of the initial installed capacity after 20 years of operation. The capacity deterioration of Li-Ion batteries includes a cycle deterioration (e.g. number of cycles) and a storage deterioration (depends on the storage time from completion of charging to the start of discharge) [31]. In order to overcome this, the initial capacity installation has to be over-sized thus leading to additional costs for the battery cells. These costs have been not considered in Figure 5.

If the focus of a project is bulk energy storage, then as we have seen, the chemical battery is a very expensive solution, partly due to the fact that it is also capable of delivering comparably high values of power according to its individual Power to Energy coefficient mentioned above.

Stationary BSS facilities are ideally suited to fast and short duration applications (< 1...1.5h) like UPS, peak shaving, governor response mode (European terminology: primary frequency control), high-voltage grid booster, etc. BSS can be implemented in areas like Schwerin, where there are no naturally occurring head differences.

The different power and energy trading opportunities in the German electricity market are illustrated in
Figure ***9***.

In the past thermal power plants were usually supplying primary frequency control (PFC) in Germany (US terminology for PFC is governor response mode). Nowadays, these thermal power plants have to be shut-down several times per day or week in order to integrate solar and wind generation, which have a higher feed-in priority. For this reason these thermal power plants cannot guarantee the PFC service for a continuous week, since the product is traded and has to be guaranteed for an entire week without interruptions. This new situation led to a new business case for chemical batteries.

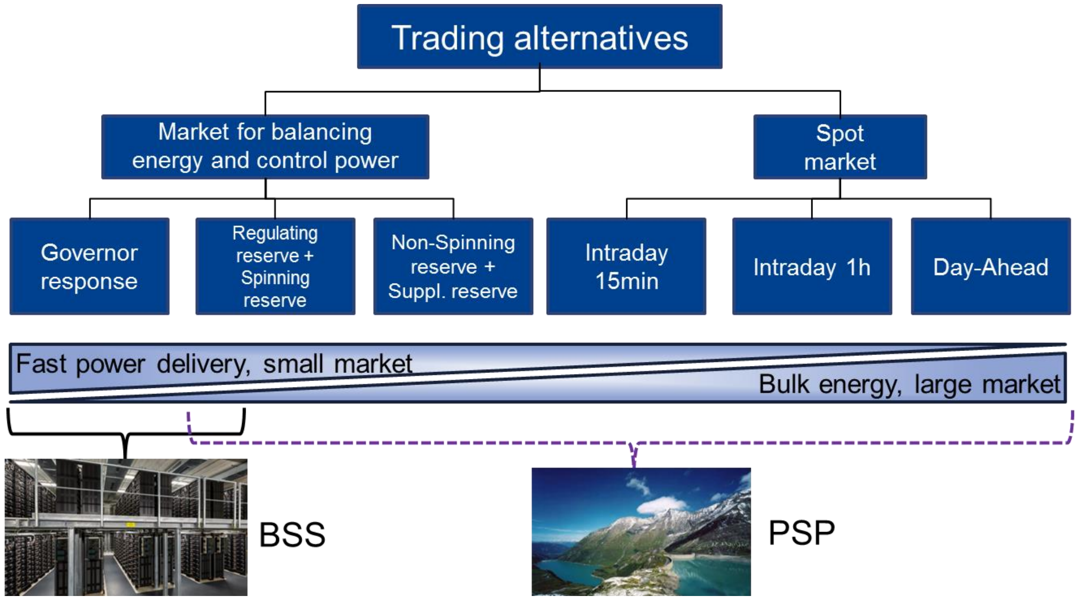

Figure 9: Power & Energy Trading Opportunities for Batteries & Pumped Storages in Germany

There are new references in Germany, where new chemical Li-Ion batteries are integrated in existing PSP or in switchyards of existing thermal power plants and supply PFC services for the TSOs. These references are:

- PSP Reisach (3 x 35 MW) built 1954/1961 plus a new Li-Ion battery with a power of 12.5 MW and a capacity of 13 MWh (in operation since December 2017),
- PSP Herdecke (153 MW) since 1989 in operation plus a new Li-Ion battery with a power of 7 MW and a capacity of 7 MWh (in operation since February 2018).
- STEAG large scale batteries with 6 x 15 MW and a total capacity of 120 MWh are since 2017 in operation. The six locations are: Lünen, Herne and Duisburg-Walsum in North Rhine-Westphalia, then Bexbach, Völklingen-Fenne and Weiher in Saarland.

It should be pointed out, that the PFC market is limited to approx. +/- 500 MW in Germany. Furthermore the average price for 1 MW PFC per week dropped from approx. 4,000 € in the year 2015 to values below 1,600 € per MW and week in 2018 due to the very competitive market situation [30].

4 Summary

This study presents a comparison between the PSP 'Atdorf' and a fictitious large scale BSS with a stationary battery technology of Schwerin, which was scaled up to the power and energy capacity of the PSP. The aim was to identify relevant characteristics of both technologies in order to compare those. Furthermore, calculations in previous studies are evaluated and improved.

The first analysis focuses on the raw material requirements for both technologies. Based on these, the raw material costs of both technologies as well as the carbon footprint are compared. The investment and operating costs over an assumed lifetime of 100 years are evaluated.

With respect to the raw material requirements it becomes obvious that the two technologies have completely different needs. While PSP ’Atdorf’ predominantly requires huge amounts of steel and concrete for the reservoirs and the underground tunnels and caverns, the BSS in Schwerin requires a diverse array of expensive raw materials such as mercury, binder and electrolytic solvent.

In terms of raw material cost, it can be summarized, that the PSP ’Atdorf’ proves itself by relatively cheap raw materials, whereas certain components of the battery cells are highly cost intensive. As a consequence, the overall raw material costs for the initial installation for the BSS scaled to the same power and energy storage capacity are about 3.7 times higher compared to the PSP for the initial installation. Over a lifetime of 100 years the overall raw material costs are about 18 times higher for the BSS. The capital investment and operating costs of the BSS are 18 times higher than for the PSP.

Due to the high greenhouse gas potential of certain raw materials of the battery cells, the carbon footprint of the BSS turns out to be double the footprint of the PSP.

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