Cover

1 Project Statement: Utilizing unused renewable Energy

References

Current Situation

Each year the electricity generated by using renewable energies like solar and wind makes up a bigger part in the energy-mix [1]of Germany. But the amount varies because of seasonal or just daily fluctuations. This is especially true for wind. In 2018 wind energy was the main renewable source with about 48%, which made up around 19% of the overall consumption.

1 Source: `https://strom-report.de/strom`

Need

Because of the significant mismatch in grid power demand, the need for a solution is becoming more acute. It's a well-established problem for the industry, and there are a number of energy management and storage systems in the pipeline today, which could solve this problem. But few offer a complete solution allowing wind energy to be seamlessly plugged into the grid.

Problem

Today, the importance of transitioning into a sustainable and cost-effective energy sector is more important than ever. Fossil fuels won't last for ever and are straining the environment too much. The state will on the long-term ban or at least heavily restrict the usage to meet its own agendas therefore the solution for efficiently using renewables is of utmost importance.

Energy production by wind power is intermittent and fluctuates. Currently one of the main challenges is the adaptability of different energy storage or management systems to daily and annual fluctuations as well. This paper will investigate which is the best solution to those problems.

Method and Criteria

The new solution must be more cost-efficient than just shutting the wind turbines off, or buying energy from other countries. It has to be able to be integrated into the current grid of wind turbines. The factors to rate our solution therefore include:

- **Costs** Must be equal or lower than 21.82 billion €over 10 years: including investment, maintenance and operating costs. Otherwise, it is cheaper to than just shut the wind turbines off, or buy energy from other countries.
- **Efficiency** Must be equal or higher than70 %: including kwh lost while transforming and lost while saving over one year.
- **Safety** in %: failure rate per year must be lower than 1 ppm (part per million)
- **Scaling** yes or no: Is it reasonable for an input of 1,495 GW per hour and saving 36 GWh?
- **Technical Feasibility** yes or no: Implementable in the next 5 years? Is the technology viable or is something better obtainable in the next years? Is it possible in the geographic area?

Aspects covered

The most promising Solutions are covered in this analysis:

- **Storage systems made out of batteries**
  Written by CFO Annabelle. See section IV page ???
- **Storage systems made out of Pump storage**
  Written b COO Lennart. See section IV page ???

- **Power to Gas**

  Written by CAO Christian. See Section IV page 21

- **Storage systems made out of hydrogen**

  Written by CEO Moritz. See section IV page 14

- **Storage systems made out electric vehicles**

  Wtitten by CTO Kai. See sectition IV page 7

References and Informations

[energy-mix] Der deutsche Strommix: Stromerzeugung in Deutschland.
https://strom-report.de/strom/.
Last accessed 21.11.19

2 ExecutiveSummary

ExecutiveSummary

3 Tabel of Contents

Contents

4 The Working Papers

4.1 Vehicle to Grid

Introduction A solution to utilize unused renewable energy, which does not rely on building additional storage systems is to use EVs (Electric vehicles) and PHEVs (Plug in Hybird) as a storage system. When the power output of the grid/the offshore parks is low, the EVs can throttle their charging rate or even return power to the grid. The EVs could also delay their charge and use the peaks in the power output of offshore parks to charge their batteries.

https://en.wikipedia.org/wiki/Vehicle-to-grid

Charging direction There are two fundamental ideas in Vehical to Grid. Bidirectional Vehical to Grid where the EVs also return power to the grid or unidirectional Vehical to Grid where the EVs only store the power but do not return power to the grid. Bidirectional Vehicle to Grid requires special hardware. This results in a system, that is far more complex and expensive than unidirectional Vehicle to Grid. It also results in a lot of additional wear in the EVs batteries. It would therefore be a lot more difficult to convince customers to use bidirectional Vehicle to Grid. At the same time multiple studies showed, that the profit is not significantly higher than with unidirectional Vehicle to Grid. Because of this unidirectional Vehicle to Grid is superior and will therefore be the object of the following calculations.

https://www.isi.fraunhofer.de/content/dam/isi/dokumente/sustainability-innovation/2010/WP4-2010_V2G-Valuation.pdf

https://www.erneuerbar-mobil.de/sites/default/files/publications/anhang-optum-ap6_1.pdf

Findings For the purpose of a large scale storage system for unused wind energy unidirectional Vehicle to Grid is not a resalable option. The necessary system should have a regulating power of 1495 MW and a capacity of 36 GWh is needed. This equals the average unused power in the first months of 2019. The capacity equals the amount of this power over 24 hours. Since the system is not only storing power but also constantly using it to drive the vehicles this should be enough capacity.

https://www.bdew.de/presse/
presseinformationen/zahl-der-woche-gut-32-mr

The unidirectional Vehicle to Grid system necessary to achieve this size would need over 10 million EVs or PHEVs. The problem is not the power. The necessary power output would only require a little more than 1.7 million EVs or PHEVs. But the storage to power ratio in Vehicle to Grid is a lot smaller than the necessary ratio. This results in a system with the necessary 36 GWh of storage capacity, but 9000 MW of regulating power. This system needs over 10 million vehicles. It is unlikely that this amount of EVs and PHEVs will be available in the next five years.

Hypothetically scenario

But even with 10 million EVs and PHEVs in the year 2025 the necessary infrastructure for a system this large would take a lot longer than five years to be built. In order to include 10 million vehicles in the system more than 10 million chargingstations would be necessary (not including the chargers at home). This can not be implemented in the next five years. But assuming that we could built the charging and communication infrastructure in 5 years the cost would be 47.7 billion euros in investment cost and 4.8 billion euros a year in running cost. Over five years this adds up to 71.7 billion euros.

Solution Discussion

Scaling

On average a vehicle spends over 90 percent of the day parked. Given the infrastructure a EV could be connected to the grid and function as a storage system in this time. In Germany are over 83000 EVs and almost 67000 PHEVs (01 Jan 2019) and this number is growing exponentially. The Government has the goal to increase this number to 1 million by 2022. A study by the Frauenhofer institute from 2010 showed with simulations, that a Vehicle to Grid System could provide up to 3.5 kWh of capacity and 0.875 kW of regulation power per Vehicle. This study is now almost 10 years old and the capacities for batteries in EVs have increased a lot since then. But this study uses a very complex simulation which does not just use averages but accounts for different driving behavior at weekends, battery degeneration, dispatch time, different charges at day and night, and a whole lot more. Because of this its results are still viable today but it should be clear that the numbers will increase with improved batteries.

`https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/b_jahresbilanz.html`

`https://www.isi.fraunhofer.de/content/dam/isi/dokumente/sustainability-innovation/2010/WP4-2010_V2G-Valuation.pdf`

This would mean that today the system would have a theoretical capacity of 525 MWh and a regulation power of 131.25 MW. This numbers a relatively low but the number of EVs and PHEVs in Germany is growing. With 1 million vehicles in the system it would have a theoretical capacity of 3.5 GWh and a regulation power of 875 MW. Assuming that 90 percent of germanys vehicles (42 million vehicles) would be EVs or PHEVs it would result in a theoretical capacity of 147 GWh and a regulation power of 36.75 GW.

Cost In order to operate such a system additional infrastructure is needed. Wherever the EV is parked it needs a connection to the grid via a chargingstation. This means that additional to the fast charging gird on the highway a lot more charchingstations in the cities, at work and anywhere a car might get parked are needed. These chargingstations also need to communicate with the gird in order to make the regulation and storage system work. At the moment there are 17500 charchingstations in Germany, but 83000 EVs and 67000 PHEVs (01 Jan 2019).

https://de.statista.com/statistik/daten/studie/460234/umfrage/ladestationen-fuer-elektroautc

https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/b_jahresbilanz.html

Cost per station With the help of numbers provided by Volkswagen we can calculate the costs. Assuming that every owner of an EV or and PHEV already has a charchingstaion at home we only need to install additional ones at workplaces, car parks and public places. But the ones at home still need a connection for the load management. Using the example given by Volkswagen a charchingstation, which provides place for 22 vehicles would have an investment of about 105000 Euro and 250 Euro upkeep every month. The connection for the charger at home would cost about 350 Euro a year.

https://www.volkswagenag.com/presence/konzern/group-fleet/dokumente/Compendium_Electric_charging_for_fleets_DE.pdf

Total costs To ensure that the EVs and PHEVs can connect almost everywhere they park we would need about 9100 charchingstations from the example. The cost would then add up to about 960 million Euros of investment cost and 27.5 million per year to run them. And an additionally 52.5 million per year to run the charginstations at home. If we assume 1 million vehicles in the system the cost would add up to 6.4 billion in investment cost and 532 million per year to run all the charchingstations.

Technical Feasibility

The time needed to build all this new chargingstations is comparable to the construction of the Tesla Superchargers. Since 2012 Tesla built almost 15000 individual superchargers at 1650 locations and an additional 24000 destination chargers at hotels worldwide. This would mean for less than 40000 charchingstations it took almost eight years. The superchargers have a power output higher than the ones needed for Vehicle to Grid. Furthermore, the stations are created worldwide. A Charchingsolution in Germany with less powerful chargers would be quicker to realize. The numbers we used form the volkswagenag suggest a time of less than 5 months from planing to finishing the construction of one of the charchingstions from our example. When we keep all this in mind it becomes clear, that it would take approximatly ten years to built all the chargingstions needed for the EVs and PHEVs today. This does not take into account, that the number of EVs and PHEVs is rising exponentially.

https://en.wikipedia.org/wiki/Tesla_Supercharger

Effciency

Unidirectional Vehicle to Grid does not require multiple conversions form AC to DC and vice versa like bidirectional Vehicle to Grid would. The efficiency is comparable to the normal charching efficiency which is on average 65 – 75 percent. This loss efficiency is explained by the different design criteria of the converters. When the charger and the cars converter design match each other, efficiency can be as high as 90 percent. Since the EVs and PHEVs constantly use their charge to drive it is not necessary to include the efficiency losses by hold-

https://backend.orbit.dtu.dk/ws/portalfiles/portal/137328554/efficiency_paper.pdf ing the charge.

Substainability The environmental effects of Vehicle to Grid are hard to calculate, since it mostly relies on hardware, that already exist. With unidirectional Vehicle to Gird the additional wear on the battery is negligible. There are no numbers to be found how much Co2 and water the construction of a chargingstation consumes. But with the high amount of chargers needed it should not be ignored.

Safety The safety of this system is comparable to the safety of an EV or PHEV charging on a normal chargingstaion. This already controlled and regulated by German law and can therefore be regard as safe.

https://www.bmwi.de/Redaktion/DE/Downloads/V/verordnung-ladeeinrichtungen-e pdf?__blob=publicationFile&v=3

Conclusion Vehicle to Grid is not viable for a system this large. It may fulfill the chosen criteria in Efficiency and Safety but it is to expensive and requires to much new infrastructure to function properly. And even if it would be cost efficient it would not be reasonable to build that many chargingstations. Furthermore, it is not even possible to build that many chargingstations in the given amount of time.

Recommen - dations Based on the analysis it is recommended, that Vehicle to Grid should not be implemented. It is to expensive and requires to much new infrastructure to function properly. On a small scale there may be cases where Vehicle to grid makes sense. For example a small city, that already has lot of EVs or PHEVs could use a Vehicle to grid system to for its local wind or solar power plants. Or an owner of an owner of a small solar power plant on the rove of its house could use his EV as a storage system for its own power production. Given these requirements a Vehicle to Grid system should be considered. But it is not good solution to utilize the unused renewable energy in Germany.

Personal Comments At first glanz Vehicle to Grid seems like a brilliant idea. But as this analysis showed it is neither economical nor technical feasible. It also comes with a social problem, that has not been described in the analysis yet. All calculations assume that the owner of an EV or PHEV has no problem with a software deciding when to charge his car. This could come with problems such as People having an important meeting and not having enough charge, just because the software assumed that the driver wasn't going to work this early. The drivers of PHEVs could end up driving with gasoline most of the time, because the software can completely discharge them. Other than EVs PHEVs can drive with an empty battery, but this does not mean, that the driver is willing to drive with an empty battery.

Revised: 16 Jan 2020

4.2 Hydrogen as an Energy Storage System

Introduction

The share of renewables in the energy-mix continues to grow as more countries pledge themselves to achieve net-zero carbon-output in their power production in the next decades. This seemingly free power manifests with no possibility to regulate its output to the demand of the market. This is especially true for wind energy from off-shore platforms. Windy days can be followed by days with little to no wind. A system with 100% renewables offers therefore no grid security without methods to overcome the immense mismatch in supply and demand. A feasible solution to that problem is to store excess energy and release it again when needed. One medium which gained a lot of momentum in last years is Hydrogen. Hydrogen energy storage is another form of chemical energy storage in which electrical power is converted into hydrogen. This energy can then be released again by using fuel cells. Hydrogen can be produced from electricity by the electrolysis of water, a simple process. The hydrogen must then be stored, potentially in underground caverns for large-scale energy storage, although steel containers can be used for smaller scale storage.

https://www.researchgate.net/publication/336527927_Hydrogen_Energy_Storage

https://en.wikipedia.org/wiki/Grid_energy_storage#Hydrogen

This report presents the basics of hydrogen energy storing systems, a framework to rate and compare this system to other forms of storing energy and finally quantifying the system itself. This discussion underpins the preliminary recommendation that completes the report.

Findings

To understand the methods to rate the system, the framework itself, we first need to understand how hydrogen is produced, stored and then converted back to electricity. Hydrogen can be considered as the simplest element in existence. Hydrogen is also one of the most abundant elements in the earth's crust. However, hydrogen as a gas is not found naturally on Earth and must be manufactured. This is because hydrogen gas is lighter than air and rises into the atmosphere as a result. Natural hydrogen is always associated with other elements in compound form such as water, coal and petroleum. Hydrogen has the highest energy content of any common fuel by weight. On the other hand, hydrogen has the lowest energy content by volume. It is the lightest element, and it is a gas at normal temperature and pressure. Hydrogen is considered as a secondary source of energy, commonly referred to as an energy carrier. Energy carriers are used to move, store and deliver energy in a form that can be easily used. Electricity is the most well-known example of an energy carrier.

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

Electrolysis

Since hydrogen does not exist on Earth as a gas, it must be separated from other compounds. The most common way for the production of hydrogen is electrolysis. Electrolysis involves passing an electric current through water to separate water into its basic elements, hydrogen and oxygen. Hydrogen is then collected at the negatively charged cathode and oxygen at the positive anode. Hydrogen produced by electrolysis is extremely pure, and results in no emissions since electricity from renewable energy sources can be used. Unfortunately, electrolysis is currently a very expensive process, but costs may fall if the cost of electricity to carry out the procedure also falls. There are also several experimental methods

https://www.azocleantech.com/article.aspx?ArticleID=29 of producing hydrogen such as photo-electrolysis and biomass gasification.

Storage Technologies

Hydrogen, which has been created like this must then be stored. Hydrogen as an energy storage medium of the future has this specific advantage. It can be stored in large volume in a number of different ways, including compressed hydrogen in tanks, through chemical compounds that release hydrogen after heating or underground hydrogen storage. The last of which offering the cheapest solution. Underground caverns, salt domes and depleted oil and gas fields can provide the needed space. This possibility is especially cost-effective because almost no construction work is required and also the maintenance practically goes to zero. This method is of course locally restricted.

https://en.wikipedia.org/wiki/Grid_energy_storage#Hydrogen

The Fuel Cell

Fuel cells directly convert the chemical energy in hydrogen to electricity, with pure water and heat as the only by-products. Its main components are an anode and a cathode which are separated by an electrolyte and a catalyst like platinum. Hydrogen which is pressure fed into the fuel cell on the anode-side first hits the catalyst. It splits H2 into two ions and two electrons. The electrolyte is a proton exchange membrane so it only lets the ions pass. The electrons are picked up by the anode and travel through a cable to the cathode. This electrical current is used to power the grid. On the cathode-side the electrons and ions are reunited and combined with O2 to create water. Hydrogen-powered are not only pollution-free, but a two- to three-fold increase in the efficiency can be experienced when compared to traditional combustion technologies.

https://www.hydrogenics.com/technology-resources/hydrogen-technology/fuel-cells/

Solution Discussion

Energy storage technologies are generally compared in terms of their cost, efficiency, scalability, safety and technical feasibility. Hydrogen Energy Storage are also often compared based on application-specific benefits and specific characteristics of interest; however, such comparisons did not take into consideration their financial competitiveness. Financial competitiveness of energy storage system is to define the price of stored energy per kWh over 10 years of the energy storage system. We chose 10 years as most machines had to be replaced by then. The cost is compared to the approximated money spent on imported electricity. The system has of course be as cheap or cheaper than buying the electricity. In all other cases financial feasibility can not be achieved. The Electric Power Research Institute has developed and documented a method that analyses the costs associated with grid connected energy storage applications. It includes the capital and operational expenditures including the upfront capital costs, the fuel expenses, the operating and maintenance charges, the financing costs, etc. Levelized costs can be done using limited input data, thus useful for evaluating technologies with limited operating experience or available data. The Hydrogen energy storage system has not been included in the Electric Power Research Institute analysis or in other cost analysis modeling techniques available in literature. Hydrogen energy storage system appears to be commonly excluded from the cost comparative studies due to its high capital cost and low turnaround efficiency compared to other bulk energy storage systems. Therefore the cost are calculated in the next chapter. 100 % of the H2 gas stored is as electricity injected back

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

https://www.researchgate.net/publication/336527927_Hydrogen_Energy_Storage to the power grid through the FC electricity generation. The by-product O2 is sold. Efficiency was chosen even if it is somewhat represented in costs because it also gives context for sustainability and scalability. Systems that achieve 70% round-trip efficiency are in the following considered as efficient. Scalability has be taken in account to review the field of usage for this technology. The model was inspired by the energy loss on Off-Shore platforms in the northern part of Germany. The energy loss was determined to be 3.23 TWh. The median for the power loss therefore comes to down to 1.5 GW. To able to save one day worth of energy to achieve grid safety, the system needs to be able to save 36 GWh of energy. Peaks will not be accounted for otherwise cost-effectiveness could also not be achieved. For any energy storage technology safety has be taken into account. It factors in into possible human causalities, loss of revenue stream and grid security. Finally the system has to be able to be integrated into the grid in the next five years. This narrow time window is chosen for this technology would have to be integrated first to enable future rapid expansion of rewenables.

https://www.nrel.gov/docs/fy10osti/48360.pdf

Cost

Typically, the capital costs of an energy storage facility are expressed as €/kW installed, where it includes all expenses involved in the purchase and installation of facility. The €/kW capital expenditure multiplied by the size of the facility produces the total cost of the project. In the proposed analysis, all the costs related to an energy storage facility are expressed as total €/kW of usable discharge capacity (in kW) and total €/kWh of usable energy storage capacity. Energy storage technology with deeper Depth of Discharge and higher turn-around

https://www.researchgate.net/publication/336527927_Hydrogen_Energy_Storage efficiency will have a lower unit cost of usable power and energy. The electrolyzer costs 2500 €per kW and the fuel cell 4000 €for each kWh needed as capital cost. The storage costs are minimal because of the usage of underground hydrogen storage. The costs are factored in with 3 €per kWh. The Operation costs are as follows 50 €per Kw for the electrolyzer, 100 €per kWh for the fuel cell and 0.2 €per kWh for the storage. The sold 02 was priced with 3000 €per ton. The levelised cost for one kWh is therefore 22 cents. Comparing that to the price which was paid for importing the electricity the cost is almost four-times as high. (0.0528/kWh to 0.22/kWh)

Efficiency

The round-trip efficiency measures up to 45 % which explains the high cost. The system is therefore not efficient. The efficiency of the electrolysis and the fuel cells is high, but by combining many processes the efficiency quickly goes down. Their efficiency can be increased by utilizing the output heat from electrolyzers and fuel cells in process heating. Additionally they do not only store the electrical energy for future re-use like all other conventional energy storage systems, but also allow both hydrogen and oxygen gases to be sold as commodities thus increasing the system economic efficiency. The 3:1 increase in revenue options, opens the potential for downstream applications like car fuelling, fertilizer production, and high and low-grade heat applications in addition to electricity.

https://bit.ly/364Wv1p

https://en.wikipedia.org/wiki/Combined_cycle_power_plant

Scaling

Hydrogen storage technology is fully scalible. The power-output is not depended on the energy storage capacity. Our model is therefore achieveable with hydrogen, thus fulfilling the criteria.

Safety	Also safety is fully achieved with less than one in a million fuel cells fail. Even less failures happen in the process of electrolysis or storage.	
Technical Feasibility	Hydrogen is technical feasible. With the technology being fully matured a system with such requirements can be implemented in two to three years.	https://www.nrel.gov/docs/fy10osti/48360.pdf

Conclusion Based on the discussion above Hydrogen storage technology as a closed system can not be economical feasible. Even if the cost can be reduced by using a combined cycle it is still significantly higher than the market price. Nevertheless, Hydrogen can be made safely from renewable energy sources, is fully scalible and is virtually non-polluting. It will definitely join electricity as an important energy carrier in the future but not as an energy storage medium. We do not recommend the implementation of the system.

Revised: 16 Jan 2020

4.3 Pumped Storage Hydropower

References

PSH (Pumped Storage Hydropower) is an electrical storage technology that has been used since the 1890s. It works on the principle of changing the gravitational potential energy of water. This is done by first pumping the water from a place of low elevation to a higher one to store energy and then, when electrical energy is required, releasing that water to run through a turbine and generate electricity.

`https://en.wikipedia.org/wiki/Pumped-storage hydroelectricity`

Unused energy

In Quarter 1 of 2019 an estimated 3,230,000,000 kWh were produced by wind turbines in Germany that could not be used or transported to a location where it could have been used. This means that an average of 1,495 MWh are left unused every hour. Germany already has 6,806 MW of existing PSH. However, as this is already used for load balancing it will not be taken into account for still existing unused power.

`https://www.bdew.de/`

`https://www.hydropower.org/country-profiles/germany`

Requirements

To calculate an example of the required storage system in Germany the power requirement for such a storage system is set at the average unused power of 1,495 MW. A days worth of this average unused power comes to 35,880 MWh of required stored energy. This value will be used as the required capacity. Additionally this storage system should have a lifetime of at least 10 years.

Costs

For conventional PSH the initial capital costs are very high while the operational costs are low. With a typical life cycle of 20 to 50 years and for some locations even up to 75 years, this means that PSH will pay dividends only after a long running time.

`https://www.energy.gov/`
`https://en.wikipedia.org/wiki/Pumped-storage hydroelectricity`

Capital costs

Typical upfront capital costs include the acquisition of the land, the machines required to generate electricity and pump water, the structure that regulates the flow of water to the reservoir, and the infrastructure to connect the PSH to the grid.

A german study of 11 such structures found the upfront capital cost to be 1850 USD per kW of power generated. This value takes into account an energy to power ratio (E/P) of between 6 to 20. This means that for every 1 kW of power generation between 6 to 20 kWh of storage capacity is installed. Assuming 1495 MW is left unused at all times, this would result in an upfront capital investment of 2.8 billion USD. A storage capacity of 40 GWh is required which, at 1495 MW, results in an E/P of 26.8. This is above the typical E/P values and thus may result in higher costs.

`https://www.energy.gov/`

Capacity capital costs range between 70 to 230 USD per kWh according to Kamath and 250 to 350 USD per kWh according to May. Using these values, a capacity of 35.9 GWh may range from 2.5 billion USD to 12.6 billion USD.

Kamath (2016)
May (2018)

Small scale PSH

However, these values are only estimates for large PSH at roughly 500 MW. For PSH with 100 MW or lower the capital costs steadily increase. A small scale PSH by Shell Energy North America (SENA) rated at 5 MW and with a capacity of 30 MWh cost a total of 22.3 million USD in capital costs. This translates to a much higher rate of 4,400 USD per kW and 743 USD per kWh. This makes conventional PSH cost inefficient for small scale endeavours. As the technology improves and costs decrease this may be a suitable solution in the near future.

`https://www.energy.gov/`

Running costs

The typical running costs of PSH are very low. Lazard

`https://www.`

estimates the levelized costs as 152 to 198 USD per MWh. Levelized costs are calculated by dividing the total maintenance costs by the total energy produced over the lifecycle of the PSH. Considering 1,495 MW are lost on average this results in a total of 131 TWh lost over the course of 10 years. If all of this energy is to be stored, this results in 19.9 up to 25.9 billion USD of running costs.

lazard.com/

Total costs

In total the lowest estimate predicts 22.4 billion USD including investment and running costs over a 10 year period. The highest estimate predicts 38.5 billion USD. If small scale PSH are used this value will increase significantly.

Efficiency

PSH lose energy at many points of the storage process. The first losses occur at the entrance to the pump and at the pump. The pump then transports the water over a large distance to a higher elevation. At this point, friction with the pipe walls cause losses. To minimize losses due to friction the pipe must be constructed accordingly by increasing the diameter, reducing the friction coefficient with the pipe wall, reducing the flow rate and reducing the pipe length. Since the last two are important factors to the power generation, the diameter and pipe surface composition can be optimized. If the water is stored in an open container, such as a reservoir lake, evaporation can cause some of the water to be lost.

https://en.wikipedia.org/wiki/Darcy%E2%80%93Weisbach_equation

Total efficiency

Considering all the losses, state of the art PSH have an overall efficiency of 80%. Other sources estimate the round-trip efficiency at 70 to 87%. PSH is a very mature technology due to its age. This means that much of the efficiency gains have already been put into use.

Yang (2016) https://www.energy.gov/

Response time

The response time of a PSH should be considered,

Yang (2016)

as this influences power left unused and therefore the overall efficiency of the PSH as a storage system. A short response time to a surge or shortage of electricity is important, as in the time in which a storage system is not online valuable power will be left unused or demand of electrical power will be left unfulfilled. PSH boasts a time of 60 to 220 seconds from offline to electricity generation and 300 to 360 seconds from offline to pumping.

Scalability

PSH are easily scalable towards the high end of power generation. As mentioned, costs for low power generation increase drastically to make small conventional PSH less economically feasible. As mentioned in the Costs section, PSH as small as 5 MW can become feasible in the future.

To create even smaller PSH a different technology is required. The Goudemand building in France has an open water container on its roof connected to a very small scale PSH. However, the concept of PSH does not translate itself well to this size as much of the otherwise high efficiency and economical feasibility is lost. An additional challenge in this urban situation is the access to a very large amount of water.

`https://phys.org/news/2016-10-pumped html`

Sustainability

PSH systems are environmentally sustainable system as they require create virtually no emissions during their operation. The emissions created during construction are also negligible. However, specifically open-loop PSH can create issues with the existing wildlife in the area. A dam can interrupt the downstream flow of sediment in the water. The sediment piles up at the location of the dam the erodes the existing habitat of the species found there. Additionally the existing fish species may

`https://www.ifc.org/`

not be able to travel upstream to their breeding ground, possibly causing vast populations to perish. To counter this, proper bypasses should be built.

The flow of water in an open-loop PSH along a river should be regulated to avoid sudden large volumes of water travelling downstream. Also, the flow of water should be increased during breeding months of fish to allow for fish to travel upstream. The dependence upon a source of water for these systems is critical. As such a drought or too much rain can have large impacts on the ability of the system to store energy.

`https://www.ifc.org/`

Technical feasibility

Conventional PSH are located in areas with high elevation changes. Typically an elevation difference of 200 to 300m is required. Additionally access to a large amount of water is required to fill the reservoirs. Southern Germany has these required elevation changes and water sources. Subsequently 80% of all Hydropower is located in Bavaria and Baden-Württemberg. However, this is an issue since the wind energy is mostly produced in northern Germany and has to therefore be transported over long distances. To overcome this geographical restriction of requiring very mountainous terrain, other technologies can be put to use.

Yang (2016)

`https://en.wikipedia.org/wiki/Wind_power_in_Germany`

Seawater PSH

Along the coast seawater PSH can be used. In this situation the upper reservoir is the ocean's sea level and the lower level is a reservoir far below sea level. Ideally this is done in areas where the land is already below sea level, such as behind dikes. A major issue with this concept the corrosion due to seawater. However, this allows for the PSH to be situated near the coast and near overshore wind turbines.

Yang (2016)

Mine PSH

Old abandoned mines and quarries may be used for

PSH. A reservoir on the surface and a second lower reservoir in the mine can be used to create the required gravitational potential.

Closed container PSH

A PSH with closed containers may be used, where one is filled with compressed air. This requires no elevation change, since the pressure in one container creates the required potential. This PSH is however limited in its size.

Underwater PSH

An underwater PSH may be used for offshore wind turbines. In this system a container is lowered to the ocean floor. Since the pressure outside of the container is much higher than in the container, pumping water out of the container will require energy, while filling the container with water from outside will generate energy with the use of a turbine. For this technology corrosion is once again a major factor. However, the location so close to the offshore wind farms will prove useful.

Conclusion

All of these technologies may become feasible in the near future. At the moment, however, a conventional PSH solution is not feasible in Germany as the necessary terrain to accommodate a storage system of the required size does not exist. Germany is already serviced by its neighbours Luxembourg, Switzerland and Austria to store electrical energy in PSH systems. If Norwegian PSH system can also be used or expanded, a solution using PSH is feasible.

`https://www.hydropower.org/country-profiles/germany`

5 AnalysisSummary

AnalysisSummary

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6 Resources

6.1 A. Personnel

Section VI -A

Personnel Qualifications List

A. Education:

since October 2018	Karlsruher Institute of Technology (KIT) Electrical Engineering and Information Technology, Bachelor studies
	Secondary Education (A-levels)
2015 – 2018	Armin-Knab-Gymnasium in Kitzingen
2009 - 2015	Jakob-Stoll-Realschule in Würzburg

B. Work Experience:

since October 2019	Math tutor at Studienkreis Karlsruhe-Mühlburg – teaching Students up until the 12/13 grade in Math and physics
August 2018 - September 2018	Summer Job at Service and ElectroMechanical Devices (semd) Rottendorf – built wireless switches – used laser engraving machine
2016 – 2018	Math tutor at Schülerhilfe Ochsenfurt – teached Students up until 10 grade in Math and physics

C. Special Skills and Awards:

August 2018	Prize of the German Physics Association (DPG)	
March 2018	Cambridge Certificate	
	Programming skills (C++)	
	Language skills:	German = Native Speaker English = C1 - proficient Spanish = B1 - Independent

Section VI -A

Personnel Qualifications List

A. Education:

since October 2018	Karlsruher Institute of Technology (KIT) Electrical Engineering and Information Technology, Bachelor Studies
	Secondary Education (A-levels)
2009 - 2017	Casper-Vischer-Gymnasium, Kulmbach
2014 - 2015	Exchange Year in Justin, Texas
2011 – 2012	German School Moscow, Russia

B. Work Experience:

May 2019 - Sep 2019	Delivery Driver at Takeaway N.V. - Delivering food - Customer care
Oct 2017 – Oct 2018	Electrical Mechanic on board the frigate “Schleswig-Holstein” with Deutsche Marine, Bundeswehr - Maintenance and repair of the cooling system - Technical guard duty
Jul 2017 – Sep 2017	Postman with Deutsche Post AG - Sorting and delivering mail - Customer care

C. Special Skills and Awards:

2019	Social Youth Group Leader
2018	Fire fighter certificate
2017	Live saving skills and coach with DLRG
	Elected representative of the pupils of the school
	Lead and head of Big Band
2016	Head of swim team
	Programming skills (C++)
	Language skills: German = Native Speaker English = C1 - Proficient French = B1 - Independent

7 Glosary

Glossary

8 Evaluation

Evaluation

9 ReferenceList

ReferenceList

10 Other

10.1 Presentation

Presentation