Energy storage systems for wind energy

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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 39
- **Storage systems made out of Pump storage** Written by COO Lennart. See section IV page 14

- **Power to Gas**

  Written by CAO Christian. See Section IV page 29

- **Storage systems made out of hydrogen**

  Written by CEO Moritz. See section IV page 22

- **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 Executive Summary

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4.1 Vehicle to Grid

Introduction One 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. Therefore it would be a lot more difficult to convince customers to use bidirectional Vehicle to Grid. At the same time multiple studies have shown, 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 viable 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 would need 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. These 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-elektroauto

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 too expensive and requires too 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 too expensive and requires too 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.

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4.2 Pumped Storage Hydropower

Introduction

References

Situation

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

Parameters

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.

Criteria

For these parameters, the total costs for the storage system is limited to 21.82 billion € over the course of 10 years. The Total efficiency of the system must exceed 70%. The failure rate of the storage system must be lower than 1 ppm (part per million). A statement must be made if it is possible to scale the storage system to the parameters mentioned. Lastly, the technology must be technically feasible within the next 5 years.

https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

Findings

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

https://www.energy.gov/

https://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity and generate electricity.

Cost Overview

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/

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.

Kamath (2016)

May (2018)

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.

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 https://www.lazard.com/

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.

Running costs

The typical running costs of PSH are very low. Lazard 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.

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. Using the the current (26.12.2019) conversion rate at 0.90 € per USD this results in costs ranging from 20.2 to 34.7 billion €.

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

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

Yang (2016)

https://www.energy.gov/

Yang (2016)

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.

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.

https://energyeducation.ca/encyclopedia/Dam_failures/

Response time

The response time of a PSH should be considered, 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.

Safety

The most severe safety concern regarding PSH is dam failure. A major dam failure may lead to loss of life and property damage. Four main causes lead to dam failure: Overtopping due to substandard spillway construction, foundation defects, piping failures and valve failures. A PSH reservoir built to standard will have a failure rate below 1 ppm.

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

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.

Yang (2016)

To create even smaller PSH a different technology

https://en.wikipedia.org/

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.

wiki/Wind_power_in_Germany

Technincal Feasibility

The more pressing issue regarding scalability is that certain terrain contitions must be met. 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.

https://www.ifc.org/

https://www.ifc.org/

Problems encountered

Sustainability

As the PSH is a very large structure and interupts natural waterflow, the environmental impact is significant. 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

Yang (2016)

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.

Current Developments

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.

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.

Solution Discussion

With total costs of between 20.2 and 34.7 billion € over the course of 10 years the PSH system fulfills the cost requirement of 21.82 billion € if costs are optimized. However, the values for running costs are based on PSH systems in the United States, these values may vary for PSH constructed in Germany. The advantage of PSH is that it can remain operational from between 20 to 75 years. This means that the PSH will not need replacing for a long time in which only minimal running costs exist. This makes a PSH more profitable in the long run.

PSH fulfills the efficiency and safety criteria. The efficiency at up to 87% is very high, which in turn also increases the profit the PSH can make. With a very low failure rate, this means that the energy expected to be stored and generated by the system can be depended on. However, if a reservoir were to overflow or a dam were to break, the damage to the surrounding area will be severe. As such, special precaution must be taken to assure a high safety standard.

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

Additionally, PSH can easily be scaled to very high power and capacity. This means that only a small number of large scale PSH systems are required to store the necessary energy. However, Germany does not have the required terrain to build enough PSH systems to store the unused energy from the wind farms. A solution to this problem is to rely on the current developments and use these in conjunction with other technologies mentioned in this paper. However, these technologies may not become viable within the next 5 years. Another solution is to store the energy in a different country. 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.

Conclusion PSH is a costeffective storage system. If given a long time to recoup the investment a PSH system will make profit. PSH fulfills the all the other set requirements, expect for the technical feasibility. Conventional PSH require mountainous terrain for the required elevation difference of the two reservoirs. Germany does not have the water sources and elevation changes to allow for enough PSH systems to be built to store the required energy. PSH technologies currently in development may become technically feasible in the near future and even then it is unclear if they will be economically feasible. At the moment, a conventional PSH solution is not possible in Germany.

Recommendation Conventional PSH systems should be installed alongside other technologies. Current developments, especially seawater PSH, should be further developed. If possible, PSH systems from bordering countries should be developed and used to store energy from wind farms.

4.3 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

4.4 Power-to-Gas

Heading		References
Introduction	Wind power plant power production is volatile and weather-	
Power-to-gas	dependent which leads to fluctuation, because of this, wind power is incapable of providing reliable base load power. To enable the transition to this renewable energy source, large-scale energy storage systems are required to compensate for seasonal imbalances and to save excess power.	https://en.wikipedia.org/wiki/Wind_power
	That can be achieved by converting electrical energy into hydrogen via electrolysis, a process that is called "power to gas". Water gets split into hydrogen and oxygen with the use of electricity. Hydrogen can optionally be converted to methane.	https://en.wikipedia.org/wiki/Power-to-gas
Findings		
	The paper focuses on the restricted energy that comes from wind power plants. It presents the costs, efficiency, safety, scalability, sustainabality and technical feasibility of a Power-to-Gas system. In the first 3 months of 2019 about 3.23 billion kilowatthours (kWh) had to be restricted from wind power plants. This amount is now calculated into a power by dividing the time in hours (2190h). The power now results to 1.495 million kW. This value will be used as basis for upcoming calculations. The technology of Power-to-Gas is now used as a kind of "storage" to safe the excess energy from wind power plants.	https://www.bdew.de/presse/presseinformationen/zahl-der-woche-gut-32-mrd-kilowattstunden/
	There are currently three alternative con-	
Hydrogen use scenarios	cepts for Power-to-Gas systems which all use the method of water electrolysis: • Use of hydrogen from wind power for applications which require hydrogen. For example transportation or industrial applications. • Direct feed-in of hydrogen from wind power into	https://www.journals.elsevier.com/international-journal-of-hydrogen-energy

the gas grid.

- Methanation of the produced hydrogen with carbondioxide and feed-in of the methane into the gas grid.

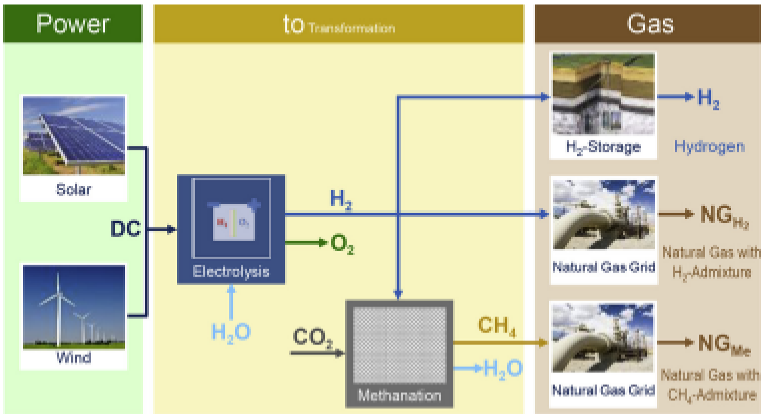

Figure 1: Concepts of power-to-gas systems.

Cost

Power-to-gas transforms electric energy into hydrogen which is used as energy source. So electric energy is technically not stored but transformed into a gas and can then be stored.

The overview for a power-to-gas energy storage in terms of cost will include investment, maintenance and operating costs. Criteria values can be seen in the outline.

https://www.dena.de

Investment costs

https://www.sciencedirect.com/science/article/pii/S0306261918315319

Alkaline investment

PEM investment

Investment costs for a Power-to-Gas system vary greatly on the method that is used for electrolysis. Among these are alkaline water electrolysis with a liquid alkaline electrolyte, Proton Exchange Membrane (PEM) electrolysis, and High-temperature electrolysis with a solid oxide electrolyte.

For alkaline water electrolysis investment costs of large-scale electrolyzers are estimated to be in the range of 800 €/kW to 1,500 €/kW. The cost of alkaline electrolyzers is very size dependent.

PEM electrolyzers are a relativly new method of electrolysis and have issues related to the costs. PEM electrolyzers depend on expensive materials and result in a high investment cost of about 2,000 €/kW to 6,000 €/kW. But there is a cost reduction potential by utilizing alternative materials in the futre.

High-Temperature investment

High-temperature water electrolysis with a solid oxide cell is still in the stage of basic research. More investigation in materials and other characteristics is needed before a reliable value for investment cost can be given.

Estimates

For a simple investment estimate a constant input of 1.495 million kW is assumed (see topic *Analysis*). This ignores any peaks and lows that wind power plants have. An alkaline electrolyzer is used with an average investment cost of 1,150 €/kW. Also, a basic efficiency of 0.7 will be included. This leads to a investment of 2.46 billion € for electrolyzers.

If the produced hydrogen is feed-in into the natural gas grid investment costs are much lower, because gas (as energy source) infrastructure is already well developed in Germany. So a total investment of 2.46 billion € in electrolyzers is needed.

Also, if the methanation process is included after hydrogen is produced, investment costs increase from 2.46 billion € to 3.075 billion € because of lower efficiencies. This does not include additional investment costs for methanation facilities.

Maintenance and operating costs

The maintenance costs are difficult to determine for Power-to-Gas systems because the technology is still in research phase. Therefore, maintenance costs will be set to 5% of investment costs and include the cost of replacing

Prices for scenarios

electrolyzers. Also, even though the power is excess power, it is not free of charge and must be paid for (0.09 €/kWh). In addition, a grid charge (0.02 €/kWh) is included and investment costs. Investment costs will be calculated based on facility lifetime (75,000h). The investment into infrastructure will be set to 1 billion €. The efficiency for electrolysis is set to 0.7 and for methanation to 0.8.

For the first scenario, where hydrogen is feed-in into hydrogen-infrastructure for utilization (Transportation/Industry), the costs of investment would result into 0.03 €/kWh. Maintenance costs would be about 0.017 €/kWh and operating costs would be around 0.13 €/kWh. In this scenario a grid charge is unnecessary. The complete cost for this scenario would be about 0.177 €/kWh.

The second scenario, where hydrogen gets a direct feed-in into the gas grid, the operating costs would be around 0.16 €/kWh and maintenance costs are rougly the same. The costs for investment will be set to 0.02 €/kWh, because additional investments in infrastructure is not needed. The complete cost sums up to 0.20 €/kWh.

https://en.wikipedia.org/wiki/Power-to-gas#Efficiency

In the last scenario, where methane is synthesized, the operating costs are about 0.20 €/kWh because of lower efficiencies and additional feedstock costs. The investment costs also increase to 0.035 €/kWh. Maintenance costs are slightly higher too, but will be set as the same as in the first scenario. The sum of total costs equals to 0.252 €/kWh.

https://www.journals.elsevier.com/international-journal-of-hydrogen-energy

Efficiency

The efficiency of Power-to-Gas depends on electrolysis. The water splitting reaction is endothermic and therefore requires energy. A fraction of the energy that is put in gets lost as heat. Because of the direct injection of created hydrogen there are no real long-term storage losses. As mentioned in the section *costs* there are three different electrolysis methods and all have a different efficiency. The High-Temperature solid oxide electrolysis is still on a very low technological readiness level and will be excluded, because there may be technological innovations which could increase efficiency significantly.

https://www.sciencedirect.com/topics/engineering/alkaline-water-electrolysis

Alkaline efficiency

The formula for the energetic efficiency is:
$\eta = \frac{E_{use}}{E_{input}} = \frac{E_{hydrogen}}{E_{el}} = \frac{V_{H2} * H_s}{U * I * t}$.
V: volume of created hydrogen in cubic meter
H: energy volume of hydrogen in Joule/cubic meter
U: voltage in Volt
I: current in Ampere
t: time in hours.

https://en.wikipedia.org/wiki/Polymer_electrolyte_membrane_electrolysis#PEM_Efficiency

PEM efficiency

The alkaline water electrolysis is available on large and small scales, with lifespans of about 10 years. The efficiency of the hydrogen production is 67%. Assuming all excess wind power energy in Germany would be put in Power-to-Gas systems, a value of 9.17 billion kWh would result for a duration of one year. This means 3.75 billion kWh would be lost.

https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/10/Power-to-Gas-Linking-Electricity-and-Gas-in-a-Decarbonising-World-Insight-39.pdf

Safety

The Proton Exchange Membrane electrolysis is only availabe on a small scale, with lifetimes of less than 10 years. It is still a young technology, so the efficiency could be improved in the future. The efficiency in a PEM electrolysis is higher than in an alkaline water electrolysis, because of higher temperatures inside the PEM electrolysis the waste heat can be redirected to make steam and create a higher overall efficiency. This results into efficiencies of about 80%. On the same assumption as in the alkaline water electrolysis, a value of 10.05 billion kWh would result. This leads to a loss of 2.87 billion kWh.

Power-to-Gas is a reliable and safe method for transforming electrical energy into hydrogen. The only real safety threats are high hydrogenconcentrations in gas grids and oxyhydrogen reactions while electrolyzing water. High hydrogenconcentrations can damage gas pipelines, compressors and other steel components that are in contact with hydrogen. This is because of hydrogen embrittlement, which makes material fatigue happen much faster. To prevent damage the gases have to stay very pure. Gas crossover takes places in every electrolyzer, but if oxygen occurs at the cathode, where hydrogen is produced, a spontaneous combustion can happen if the mixture reaches a oxygen content of over 4 vol% . So, the maximum value of oxygen in hydrogen is set to 2 vol% . If this is respected, a safe operation of Power-to-Gas systems is guaranteed.

https://de.wikipedia.org/wiki/Power-to-Gas# Wasser-stoff einspeisung_ versus_ Methanisierung

http://epub.sub.uni-hamburg.de/epub/vollte /2014/35363/pdf /Masterthesis_Bastian_Hey _Power_to_Gas.pdf

Scalability

The scale of the Power-to-Gas facility depends on the size of the wind farm and on economic aspects. Generally the size of the electrolyzer is the most important component that has to be adjusted for a given amount of excess wind energy.

https://en.wikipedia.org/wiki/Electrolysis_of_water #Equations

Sustainability

This is made possible through stacking single-cells and connecting them in a series. A issue with alkaline electrolyzers is that electrolyzers have a limited part-load capability of 20-40%. Single electrolyzers have a power range from 5 kW up to 3400 kW. Multiple electrolyzers can be used in parallel operation.
PEM electrolyzers in comparision with alkaline electrolyz-

ers have some advantages like a lower limited part-load capability of 0-10% and slightly higher efficiencies but also have lower lifetimes. Currently, single electrolyzerers have a power range up to 150 kW.

In order to rate the sustainability through water and carbon dioxide consumption, all that is needed are the respective chemical reactions. The chemical equation for a water electrolysis:

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

$$2\,H_2O_{(l)} \xrightarrow{\text{electrolysis}} 2\,H_{2(g)} + O_{2(g)}$$

The amount of hydrogen that is needed can be calculated through the energetic efficiency and stoichiometry. If a hydrogen production of 2 kg is assumed and the molar masses are respected:

H_2O : 18 g/mol

O_2 : 32 g/mol

H_2 : 2 g/mol

a calculation is possible with

https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/10/Power-to-Gas-Linking-Electricity-and-Gas-in-a-Decarbonising-World-Insight-39.pdf

$$n = \frac{m}{M}$$

The chemical equation tells that 2 mol of water is needed to receive 2 mol of hydrogen and 1 mol of oxygen. This leads to:

$$1000\,mol\,H_2O- > 1000\,mol\,H_2 + 0.5 * 1000\,mol\,O_2$$

Technical feasibility

Therefore, we need 18 kg of water to produce 2 kg of hydrogen. Because of efficiency a mass of 25.72 kg is needed.

For the optional step of methanation the amount of carbon dioxide can be calculated through stoichiometry too. The chemical equation for hydrogen methanation :

https://www.sciencedirect.com/science/article/abs/pii/S0360319915001913

$$CO_{2(g)} + 4\,H_{2(g)} \xleftrightarrow{\text{methanation}} CH_{4(g)} + 2\,H_2O_{(g)}$$

The 2 kg of hydrogen that have been produced are used to produce methane. The math is the same as in the electrolysis step and will be excluded.

https://www.sciencedirect.com/science/article/pii/S0360319912026481

For the synthesis of 4 kg methane, a mass of 11 kg carbon dioxide and 2 kg hydrogen is needed. Because of efficiency a mass of 13.75 kg carbon dioxide and 2.5 kg hydrogen is needed.

Problems and Solutions

The technical feasibility for Power-to-Gas depends on the use. Because of the diverse use of hydrogen there are various ways to utilize the technology. Hydrogen can be used for heating, as energy carrier and as a fuel. Right now the best use for hydrogen is using it as a fuel for transportation and industry because these are the most profitable ways to use the technology.
The most important technical aspect is electrolysis. In general, alkaline water electrolysis is the most developed method for Power-to-Gas systems and is ready to be used. PEM electrolysis is also in a technical feasible state, but in comparision to alkaline water electrolysis in a much more undeveloped state. High-Temperature electrolysis with a solid oxide electrolyte is currently not technically feasible.

Power-to-Gas has currently the biggest issues related to its cost. There are also some minor issues with scalability. The problems in terms of cost are:
1. How produced hydrogen is used as a energy carrier.
2. The electrolyzers that are used for hydrogen production.
Depending on the use of produced hydrogen, a lot of investments are needed to get full use out of hydrogen. For example, if hydrogen is used as a fuel for traffic

or industry, investments for electrolyzers, pipeline grids, geological storages and refueling stations are needed. If investments into infrastructure and peak loads are taken into account, a investment cost of 86-102 billion € is estimated by scientists. For the optional methanation step scientist estimate a value of 76 billion € as investment costs. This makes Power-to-Gas a very expensive technology to implement.

Conclusion

The only way to reduce these immense investment costs are currently just up to commercialising and research into other electrolyzing methods. Right now PEM and High-Temperature electrolysis have still potential to reach a better € per kilowatt ratio, because these methods are still very young and new innovations could reduce costs. For alkaline electrolysis the cost per kilowatt probably will not change significantly in the future, but currently is the cheapest electrolysis method (see section *Alkaline investment*).

The problems for scalability are the geographical and political conditions that come with wind power plants. Overall Power-to-Gas is a scalable technology, but in regards of using wind power there are limitations. Wind power plants are restricted to areas with high wind velocities and few settlements. To reach a maximal supply of excess wind power, a Power-to-Gas facility needs to be close to a wind power plant. Therefore the conditions that count for wind power plants also count for a Power-to-Gas facility and need to be respected before a wind power plant and a Power-to-Gas facility can be build.

https://www.sciencedirect.com/science/article/pii/S0196890415004343

https://www.sciencedirect.com/science/article/pii/S2352152X15300311

The conclusion will look into if a Power-to-Gas system is reasonable to implement with a budget of 15 billion € and in a span of about 10 years.

None of the mentioned scenarios (see section *Findings*) are economical feasible (see section *Maintenance and operating cost*) with this budget. For comparison the market prices for electrical power are about 0.04 €/kWh. The capacity that is needed during 10 years, with a constant use of 1.495 million kW, would result to 130.96 billion kWh. The costs in 10 years would be...

... for the first scenario 23 billion €.

... for the second scenario 26.2 billion €.

... for the last scenario 33 billion €.

This assumes a alkaline water electrolysis because it is currently the cheapest and most reliable method to use (see section *Technical feasibility*) for a Power-to-Gas system in this time range, but in the future may be substituted with one of the two other electrolysis methods. If the technology would be used right now, it would not be reasonable. Power-to-Gas in its current state is uneconomic, because of high investment costs, electricity prices and expensive electrolyzers. Despite this, it may become a viable method for any electrical power input in the future, since it is easy scalable for a given amount of excess power and hydrogen has diverse uses. Scientific researches show that commercialization and lower prices for power can make Power-to-Gas a reasonable application in the next 15 to 20 years.

4.5 Batteries

Intro

Today's electricity is more and more produced by renewable sources such as wind turbines. Because of the intermittent power supply, due to fluctuating winds, there is a need for storing surplus electricity. In some cases wind turbines need to be taken of the grid to avoid an overload. Additionally Germany pays other countries to take its surplus electricity while still paying 1.5 billion € per year for importing energy in case of electricity shortage.

A major portion of today's energy storage systems for portable electronic devices, such as mobile phones or electric vehicles, are rechargeable batteries. They contain an anode, a cathode and different kinds of electrolytes, which affect their specific field of application.

This research will concentrate on 5 types of batteries to determine which kind is most suitable for storing wind energy under the given requirements. Starting with costs, which is the most important criteria, because it determinates if the storage system can be built at all. In a time span of 10 years the investment, maintenance and operating costs cannot exceed 21.82 billion €for a capacity of 36 GWh. Next is efficiency, the aim is to retain at least 70 % of the initial energy. Another aspect to energy storage, which needs to be fulfilled, is the capability to adapt the system for single wind turbines or a whole wind park. This should be achievable while also being safe and implementable in the near future. Regarding Batteries there are a few particularities concerning their limit in energy density, ability to hold electricity over a long period of time and life cycle durability.

energystorage.org

Findings

Types of Batteries and their advantages

Lithium-ion battery Lithium-ion battery (short LIB) is the umbrella term for batteries which transfer an intercalated lithium compound through an electrolyte between the electrodes during the discharge and charge process. Typically the anode (negative electrode) consists of lithium titanate or graphite and the cathode (positive electrode) consists of lithiated metal oxides or phosphates. Compositions with a higher cell voltage (around 3.6 V to 3.7 V) and high energy density are less safe than cells based on lithium iron phosphate or lithiated metal oxide. Therefore the energy density and the voltage (between 3.2 V and 2.5 V) is a lot lower. LIB have a low self-discharge and don't suffer from a memory effect. Compared to newer technologies such as sodium sulfur batteries, they have shorter cycle life and for that reason are less profitable in a large scale energy storage.

circuitdigest.com

wikipedia.org

Nickel-Cadmium battery Nickel-cadmium batteries (NiCd batteries) have a nickel positive and a cadmium negative. They excel at maintaining voltage (around 1.2 V) and delivering their full rated capacity at high discharge rates. Some of their disadvantages are the cost-intensive materials, which they are made out off and their high self-discharge rates. Because NiCd batteries are best stored discharged, they are not suited as an energy storage system, even though they over a lot of advantages.

wikipedia.org

energystorage.org

Sodium-Sulfur battery A sodium-sulfur battery (NaS battery) is a molten-salt battery. The anode (sodium) and cathode (sulfur) are liquid and the electrolyte membrane is a solid ceramic (sodium alumina), which also separates the electrodes. Two features are the high operating temperature between 300 and 350°C and the fast corrosion of the sodium polysulfides. Therefore, the NaS batteries are primarily used as stationary energy storage applications. They offer a lot of advantages, such as high energy density, high efficiency (around 89%), long cycle life and affordable materials for the construction. The cell voltage amounts to 2 V.

Flow battery A flow battery, more precisely a reduction-oxidation flow battery (redox flow battery), mainly consists of two liquid electrolyte solutions which flow through electrochemical cells and are separated by a ion-selective membrane. There are various types of flow batteries such as hybrid redox flow batteries or redox batteries without a membrane. Compared to a conventional battery the difference is that energy is stored in the electrolyte rather than in the electrode material. The cell voltage is specific to the chemical components involved in the reactions and the number of cells that are connected in series. In practical applications it reaches 1 to 2.2 V. The amount of energy stored is depending on the amount of active chemical species present in the electrolyte. Therefore the capacity can be easily amplified by expanding the size of the storage tanks. Because the amount of electrolyte flowing in the electrochemical cells is usually only a small fraction of the total amount, uncontrolled energy release only concerns this small portion. Another advantage are the unrivalled cycle life (compared to other batteries) of 15,000 to 20,000 cycles for vanadium redox flow batteries (VRFB), which are the most commonly used redox flow batteries. The main issue up to this date is that flow batteries are less powerful and have a more lavish structure.

wikipedia.org

nature.com

John R. Miller and Andrew F. Burke (2008)

Federal Network Agency and Federal Cartel Office

energiefirmen.de

Electrochemical An electrochemical capacitor (EC), also known as supercapacitor or ultracapacitor, stores energy using ion ad-

Capacitor sorption or surface redox reactions. For storing energy over night, meaning 1 cycle per day, an asymmetrical EC with a lead oxide positive electrode and an activated carbon negative electrode is most suitable. Even though its energy density (around 20 $Whkg^{-1}$) is lower compared to batteries and its best adapted for a short duration of storing energy, it offers a lot of different advantages. Such as a 10 to 100 times higher capacity (energy per unit volume or mass), fast acceptance and delivery of power, good reliability and unmatched cycle life (over 500,000).

Problems encountered Trying to decide which battery or capacitor is the most suitable, is not an easy task. Nickel-cadmium batteries are eliminated from the selection quickly because they have a high self discharge rate and cannot keep up with newer technology in this instance. Deciding whether or not LIBs are a viable option is not that easy. There is a lot more research and practical applications for LIBs on which one can build upon. Still, they are not a long term solution. It's not the aim to find a storage system which needs to be renewed every 3 years, but to find a durable and adaptable one.

Another problem is that the operating costs are unknown. For most sources it's not clearly stated if the operating cost is included in the price per kWh. Estimating the costs is quit complicated, thus the batteries are ranked from least to most cost-intensive. The EC ages slowly and has a temperature range from -40 to +70 °C, so it's not high-maintenance. Vanadium redox batteries do not need to be cooled because they have a integrated cooling system due to the flow of electrolytes which dissipates heat. Therefore they don't need a fire protection system either. Most maintenance is needed for the sodium-sulfur battery. It's prone to corrosion of the insulators and growth of dendrites, which increases self-discharge.

Current Developments

Another issue is, that there's still a lot of research done compared to more established battery types such as nickel-cadmium or lithium-ion batteries. Especially ECs are in development and can be further optimized. In a few years time those technologies will be more affordable and sophisticated, as the demand will increase. Nevertheless an investment at this point is reasonable.

Solution Discussion

Costs

Determining the Budget

The expenses for covering Germany's demand of electricity in case of an electricity shortage amounts to around 1.5 billion € in 2017. In this year Germany exported 83.4 billion kWh, imported 28.4 billion kWh and produced 105.5 billion kWh of energy with wind turbines. Consequentially there is an excess of electricity, which can be stored. Because there are no specific values for how much energy is needed at a time, the minimum capacity can be deduced from the quantity of lost power per month. According to the BDEW (Federal association of energy and water economy) approximately 3.23 billion kWh could not be fed into the grid from January to March of 2019. So on average this amounts to 1.495 GW of nominal capacity and a storage capacity of 36 GWh (one day of full nominal capacity). Adding the price per kWh for the additional 12,92 TWh gives a budget of 2.18 billion € per year and 21.82 billion € for 10 years. Overall this adds up to 131 TWh over 10 years, presuming that Germany will still be producing as much electricity in 10 years as now.

Investment costs

Taking the values from table 1 (475 € for NaS, 330 € for

VRFB and 18,000 € for EC), the most affordable option are vanadium redox flow batteries with investment costs of 11.88 billion €. Next up are sodium-sulfur batteries with 17.1 billion € and lastly electrochemical capacitors with 648 billion €. The costs for the ECs might be unrealistic compared to the other options, because one needs to consider their high cycle life, which makes them more lucrative over a longer period. 10 years are only 3650 cycles, assuming that batteries discharge over the day and charge over night when wind increases.

Operating costs Because corrosion of insulators and growth of dendrites, which increases self-discharge, are an issue with sodium-sulfur batteries, operating costs are potentially higher. VRFB do not need to be cooled because of the flow of electrolytes which dissipates heat, nor do they need a fire protection system.

Efficiency Both batteries are rather efficient (NaS 85% and VRFB around 75%), so they fulfil the criteria. NaS batteries operating temperature is around 290 °C, but they do not need to be heated, because one cycle per day heats the battery enough due to ohmic loss. This leads to 2% loss per 300 cycles self-discharge rate. For the vanadium redox flow battery no self-discharge rate could be found, but it's possible that the 75% efficiency includes this aspect.

Safety In the safety criteria the VRFB is leading, because it is non-flammable and inherently safe. There is no accident known, unlike with NaS batteries. One accident happened 2011 in the Tsukuba plant, leading to a fire, but a statistic stating what percentage the risks are, is not public.

Scaling Again the VRFB offers a distinct advantage compared to the sodium-sulfur battery. Power and energy are completely separated and can be scaled up or down and are highly flexible. If the demand for storage options expands, VRFB can easily be upgraded by adding bigger electrolyte tanks.

Technical Feasibility It was not possible to find data stating how much time it would consume to build either of the battery types. Most definitely the construction of a VRFB would cost more time because of its sophisticated structure. Altogether the implementation of both batteries should not take more than 5 years considering that there are some companies in Europe producing them.

VRFB vs NaS battery VRFBs reaction time to frequency changes is rather slow. The frequency can be restored after a over-stressing of the grid with its help. Sodium-sulfur batteries have such a quick reaction time (1 ms), that they can prevent any frequency irregularities altogether. This makes both of them helpful additions to the grid. Concerning the charging and discharging performance the vanadium redox flow battery is superior to a NaS battery. It can discharge up to 20 hours while NaS batteries only last about 6 hours. Additionally VRFB are able to replenish charge and provide power simultaneously.

Sustainability The options at hand might not be the most sustainable options due to their use of rather rare metals, but sodium sulfur is a non toxic battery and vanadium can be recycled.

Conclusion Sodium-sulfur batteries and vanadium redox flow batteries both offer great advantages, which makes deciding which one is the most suitable complicated. Considering that the demand for energy might expand greatly, the VRFB is the best decision for the future. A storage system for 36 GWh costs 11.88 billion €and will last approximately 40 years. Operating costs still have to be applied but should be moderate.

Recommendation It is recommended to start construction of a vanadium redox flow battery as soon as possibly. Due to the shutdown of nuclear power plants, renewable electricity will become a major source of electricity in Germany. To be energy-self-sufficient must be an objective. The best implementation is one big storage facility near a wind park which has enough space for later expansions.

Personal Comments It was not easy to find consistent data concerning the price per kWh for any of the battery types. The spectrum reached from 0.05 $ per kWh to 20,000 $ per kWh for electrochemical capacitors. Some of those values refer to a cost projection after an unspecified amount of years, making it incomparable. The reason a lot of the sources are wikipedia sources is that a lot of articles cost money and I was not up to pay 35 $ per PDF. So I learned not to double check every value I found with another source, but to accept insufficient research.

Table 1: Specific values of different battery types

	NaS battery	VRFB	EC
Cycle life (90% capacity drop)	15 years and 4.5k	12k-20k	500k
Investment costs [$ per kWh]	50-525	364.44-1078	0.05-20,000
Investment costs [€ per kWh]	45-475	330-970	0.04-18,000
Operating costs	high	middle	low
Efficiency of conversion	85% DC	65-80% (commonly 75%)	75-95%
Specific energy [Wh per kg]	150-240	10-20	0.5-15
Energy density [Wh per L]		15-25	50
Operating temperature [°]	270-360	-5-50	up to 65
Speed of charge/discharging	6 h discharge	20 h	5 h
Features	non toxic	need a lot of space	
	start up speed of 1 ms	non flammable, inherently safe	

Sources

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solarbay.com.au

wikipedia.org

Journal of Advanced Chemical Engineering: Mark Moore... 2015

RWTH Aachen 2018

Haisheng Chen: Storing Energy 2016

Saurabh Tewari: Energy storage for smart grids 2015

5 Analysis Summary

Topic and Contributions Due to climate change and air pollution, an energy revolution is needed. The energy market has to transform into a sustainable yet safe and economically feasible future. To achieve grid security, while having a high percentage of renewables that fluctuate in energy production, energy storage are of utmost importance. This report focused on five of these solutions.

- Vehicle-2-Grid — Kai
- Pumped Storage Hydropower — Lennart
- Hydrogen storage technology — Moritz
- Power-to-Gas — Christian
- Battery Storage Technology — Annabelle

Findings

Vehicle-2-Grid — Vehicle-2-Grid offers great resource efficiency but is heavily limited by the quantity of cars connected to the grid. It is too expensive and requires too much new charging infrastructure to function properly. However, it is a safe and efficient technology which could work on a small scale. For our use-case it fails the requirements. see Page 7

Pumped Storage Technology — Pumped Storage Hydropower is a mature and safe storage system but is limited by geographical restraints. For the required power and capacity a conventional Pumped Storage Hydropower System meets the cost requirement, assuming optimal to good system prerequisites. Additionally PSH stores energy efficiently and is easily scalable for high power and capacity systems. However, a conventional PSH solution is not technically feasible in Germany as the necessary terrain to accommodate a see Page 14

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 systems can also be used or expanded, a solution using PSH is feasible.

Hydrogen Storage Technology

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 scalable 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.

see Page 22

Power-to-Gas

Power-to-Gas in its current state is uneconomic, because of high investment costs, electricity prices and expensive electrolyzers. Despite this, it may become a viable method for any electrical power input in the future, since it is easy scalable and safe for a given amount of excess power. Additionally Power-to-Gas is efficient and has diverse uses. With the right infrastructure it could be used as fuel or directly fed into the gas grid. Scientific researches show that commercialization and lower prices for power can make Power-to-Gas a feasible application in the next 15 to 20 years.

see Page 29

Battery Storage Technology

Finally Battery Storage Technology offers great adaptability to any given change in requirements, is cost-effective however fails in respects to sustainability. Currently vanadium redox flow batteries are the most suitable solution to the problem. They are easily scalable and provide an expected round-trip efficiency of 75 %. Because of its early stage of development problems in construction could occur. The best implementation is

see Page 39

one big storage facility near a wind park which has enough space for later expansions.

Criteria / Systems	Cost	Efficiency	Safety	Scalability	Technical Feasibility
V2G	-3	1	3	-2	-3
PSH	1	3	2	2	-2
HST	-2	-3	2	3	3
P2G	-2	1	2	3	3
Battery	3	2	2	3	2

Good +3 +2 +1 -1 -2 -3 Bad

Criteria Discussion The given framework to rate each system is weighted as follows:

references

- Cost [3x]
- Efficiency [1x]
- Safety [1x]
- Scalability [2x]
- Technical Feasibility [3x]

This results in -20 for Vehicle-2-Grid, +6 for Pumped Storage Hydropower, +8 for Hydrogen Storage Technology, +12 for Power-to-Gas and +25 for Battery Storge Technology.

During the process it was noticed that the infrastructure of each energy carrier such as Hydrogen or Electricity is additionally an important factor that should be taken into consideration.

Recommend Solutions It is recommend to start the construction of a Battery Storage Facility as soon as possible. The facility should be planned and constructed in stages to incorporate further development in Battery Technology.

Rapid development in the infrastructure and usage of

Hydrogen could alter the outcome. It is recommend to commission another analysis report if such a development signalizes.

Revised: 20 JAN 2020

6 Resources

6.1 A. Personnel Qualifications List

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, Kitzingen
2009 - 2015	Jakob-Stoll-Realschule, 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 – Thought 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

Kai Braungardt 21 NOV 2019

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

Personal Qualifications List

Education:

Since Oct 2017 - Karlsruher Institute of Technology (KIT)
Bachelor studies, major in physics

2009 - 2017 - Secondary Education
Otto-Hahn-Gymnasium, Landau in der Pfalz

Work Experience:

Since July 2019 - Job at the 'Schülerlabor TUN'
Supervising and helping children during experiments

2018 - Worked at different venues as a waitress
arranged tables for formal dinners and served food at fairs

2017 - Worked as a waitress in a restaurant
decorated, made cocktails, cleaned, dealt with a lot of stress and served customers

2016 - Worked for an ice cream parlor
delivered ice cream to the customer on time

Special Skills:

- Language skills: - German (Mother Tongue)
  - English (C1) Proficient
  - French (A1) Basic

Personnel Qualifications List

Education:

Since Oct 2017	—	Karlsruhe Institute of Technology (KIT) Chemical and process engineering
Sept 2014 to Jun 2017	—	Secondary Education (A-Levels) BBS Technik 1, Ludwigshafen am Rhein

Work Experience:

Mar 2018 to Apr 2018	—	Inorganic-chemical internship at KIT Qualitative and quantitative analysis, identification of unknown substances based on functional groups
Jun 2016 to Aug 2016	—	Summer Job at Gaststaette Große Blies Helped out the cooks, cleaned the kitchen and served food

Special Skills:

Programming	—	C++ CAD MS Office
Languages	—	German (Mother Tongue) Russian (Mother Tongue) English (C1 – proficient) Spanish (A1 – basic)

Christian Geier 20 Jan 2020

Personnel Qualifications List

A. Education:

since October 2018	Karlsruher Institute of Technology (KIT) Mechanical Engineering, Master Studies - Mechatronics – "Mechatronik" - Information Technology – "Informationstechnik"
October 2014 – October 2018	Karlsruher Institute of Technology (KIT) Mechanical Engineering, Bachelor of Science - Development and Design – "Konstruktion und Entwicklung"
	Secondary Education (A-levels)
2012 – 2014	Bilingual International Baccalaureate at Zurich International School, Adliswil, Switzerland

B. Work Experience:

since October 2019	Math tutor at Studienkreis Karlsruhe-Mühlburg – teaching Students up until the 12/13 grade in Math and physics
April 2018 - November 2018	Bachelor thesis at ZF Friedrichshafen AG, Department for Advanced Development of Drivetrains "Conception and Design of a Co-Rotating Transmission Part for the Actuation of a Dual Clutch with Low Actuation Forces on the Engagement Bearing"
May 2017 – October 2017	Internship at ZF Friedrichshafen AG, Department for Advanced Development of Transmissions - Researched projects - Designed and evaluated patents - Created mathematical models with MATLAB - Created 3D-models and animation with Creo 2.0 - Created calculation tools with Visual Basic in Excel

March 2016 – April 2016	Basic Metalworking Techniques at Institut für Angewandte Verschleißforschung (IAVF) Antriebstechnik GmbH - Filed, Grinded Milled, Turned, Welded, Drilled, Bent, Measured, Sawed, Installed; Metal Parts

C. Special Skills and Awards:

Programming Skills:	PTC Creo 2.0
	MathWorks MATLAB
	MS Office
	Visual Basic (Basic Knowledge)
	Java (Basic Knowledge)
Language skills:	German = Mother Tongue
	English = Second Mother Tongue
	French = DELF B1

6.2 B. Resources

Vehicle to Grid	https://en.wikipedia.org
	https://www.isi.fraunhofer.de
	https://www.erneuerbar-mobil.de
	https://www.bdew.de
	https://www.kba.de
	https://de.statista.com
	https://www.volkswagenag.com
	https://backend.orbit.dtu.dk
	https://www.bmwi.de/
Pumped Storage Hydropower	https://en.wikipedia.org
	https://www.bdew.de
	https://www.hydropower.org
	https://www.energy.gov
	https://www.tep.com
	https://www.lazard.com
	https://books.google.co.uk
	https://phys.org
	https://www.ifc.org
Hydrogen as an Energy Storage System	https://www.researchgate.net
	https://en.wikipedia.org
	https://www.irena.org
	https://www.azocleantech.com
	https://www.hydrogenics.com
	https://www.nrel.gov
	https://publications.jrc.ec.europa.eu
Power to Gas	https://en.wikipedia.org
	https://www.bdew.de

https://www.elsevier.com

https://www.dena.de

https://www.sciencedirect.com

https://www.oxfordenergy.org

http://epub.sub.uni-hamburg.de

Batteries

https://energystorage.org

https://circuitdigest.com

https://www.wikipedia.org

https://www.nature.com

http://www.energiefirmen.de

https://batteryuniversity.com

https://solarbay.com.au

6.3 C. Costing

Manhours The manhours are split into two categories. Work done individually, such as research and technical writing, is mentioned in total work hours. Work done together, such as team meetings and the work done on the presentation, is mentioned in hours per person. At a rate of 12.50 € per person the total costs for manhours comes to 2,150 €.

Manhours-Type	Hours
Research	37h
Technical Writing	45h
Team meetings	15h p.p.
Presentation	3h p.p.

Total Costs Printing costs are split into two parts. The costs per page of a one-sided black and white print at the AStA printing office is 0.03 €. The cost of the plastic binding is 0.50 €. This results in a total of 2.60 € for the entire paper.

Cost-Type	Cost
Manhours	2,150,00 €
Printing Costs	2.60 €

7 Glossary

Vehicle to Grid	V2G: Vehicle to Grid EV: Electric Vehicle PHEV: Plug in electric Vehicle
Pumped Storage Hydropower	PSH: Pumped Storage Hydropower E/P: Energy to power ratio
Power-to-Gas	PEM: Proton Exchange Membrane
Batteries	LIB: Lithium-ion-battery VRFB: Vanadium redox flow battery EC: Electrochemical capacitor BDEW: Federal association of energy and water economy

8 Evaluation

Evaluation

9 ReferenceList

Pumped Storage Hydropower

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3. https://www.hydropower.org/country-profiles/germany
4. https://www.energy.gov/sites/prod/files/2019/07/f65/Storage%20Cost%20and%20Performance%20Characterization%20Report_Final.pdf
5. Kamath https://www.tep.com/wp-content/uploads/2016/04/12-TEP_UNSE-2017-IRP-Workshop-Energy-Storage-EPRI.pdf
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7. https://www.lazard.com/media/438042/lazard-levelized-cost-of-stor pdf
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10. https://phys.org/news/2016-10-pumped-storage-hydroelectricity.html
11. https://www.ifc.org/wps/wcm/connect/79ad4356-6f18-4955-bf35-adcc GPN_EHSHydropower.pdf?MOD=AJPERES&CVID=mR5BwAV
12. https://en.wikipedia.org/wiki/Wind_power_in_Germany

Vehicle to Grid

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3. https://www.erneuerbar-mobil.de/sites/default/files/publications/anhang-optum-ap6_1.pdf
4. https://www.bdew.de/presse/presseinformationen/zahl-der-woche-gut

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

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

10. https://backend.orbit.dtu.dk/ws/portalfiles/portal/137328554/efficiency_paper.pdf

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pdf?__blob=publicationFile&v=3

10 Other

10.1 Presentation

Karlsruhe Institute of Technology

Utilizing unused renewable energy

1

Problem

- Wind power plant power production fluctuates and is weather dependent
- 3.23 billion kilowatthours were restricted in the first quarter of 2019
- Is it possible to store or use this restricted energy?

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2

Introduction

1. Vehicle to grid
2. Hydrogen as an energy storage system
3. Pumped storage hydropower
4. Power-to-Gas
5. Batteries

Rocket Science // Moritz, Kai, Annabelle, Lennart, Christian 3

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Vehicle to grid

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KIT – die Kooperation von
Forschungszentrum Karlsruhe GmbH
und Universität Karlsruhe (TH)

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

Universität Karlsruhe (TH) Forschungsuniversität • gegründet 1825

Hydrogen as an energy storage system

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Pumped storage hydropower

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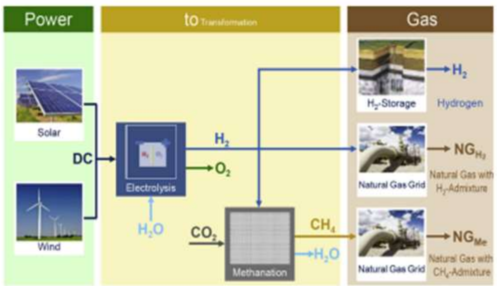
Power-to-Gas



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Batteries

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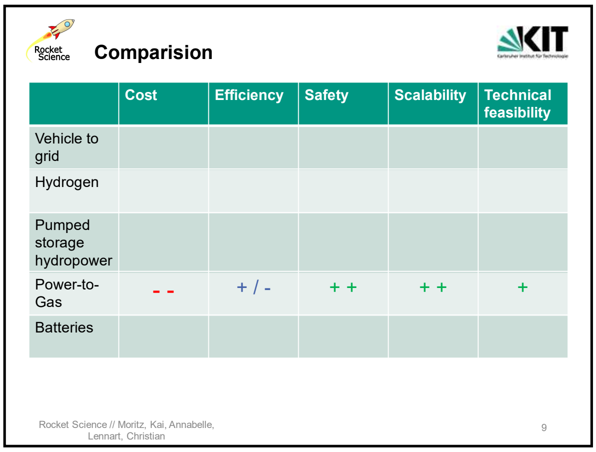
Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Universität Karlsruhe (TH)
Forschungsuniversität • gegründet 1825


Comparision

	Cost	Efficiency	Safety	Scalability	Technical feasibility
Vehicle to grid					
Hydrogen					
Pumped storage hydropower					
Power-to-Gas	- -	+ / -	+ +	+ +	+
Batteries					

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Conclusion
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Recommendations
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