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The impact of storage units and renewables extension on power transmission grid in context of a power-to-fuel plant integration assessed by linear power flow optimizations with focus on Schleswig-Holstein

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List of Abbreviations

IPCC: Intergovernmental Panel on Climate Change

RES: the renewable energy sources

PtL: Power-to-Fuel

PtL: Power-to-Liquid

H2: Hydrogen

CO2: Carbon dioxide

PtG: Power-to-gas

P2J: Power to Jet

AE: Alkaline Electrolysis

PEM: Proton Exchange Membrane

SOEC: Solid Oxide Electrolysis Cell

VRE: Variable Renewable Energy

HTEL: High Temperature Electrolyser

CAES: Compressed air energy storage

GT: Gas Turbine

PHS: Pumped hydro storage

BESS: battery energy storage systems

PbAc: lead-acid batteries

Redox flow batteries: RFBs

Li-ion: lithium-ion

BNEF: Bloomberg NEF

UGS: underground natural gas storage

PyPSA: Python for power system analysis

eGo: electricity grid optimization

EHV: Extra-high voltage

HV: high voltage

LOPF: linear power flow optimization

CAPEX: Capital Expenditure Costs

OPEX: Operational Expenditure Costs

1 Introduction

Climate change is one of the most pressing issues of the twenty-first century. According to the analysis of the intergovernmental Panel on Climate Change (IPCC), the global CO2 intensity declined by 0.3 percent year between 2010 and 2019.In 2018, 89% of global CO2 emissions came from fossil fuels and industry, because of that one of the major factors on climate change is energy [1] [2],see Figure 1.Climate change is affecting environment ,consequently also the renewable energy sources (RES) because they depend on climate [3]. This leads to an increase of RES in the system, and this leads to challenges regarding grid operation. The latter is also amplified by future development as PtF plants. Energy may be divided into two main categories: renewable and non-renewable, Non-renewable energy sources are in limited supply, because it takes a time for them to replenish. These nonrenewable resources have the benefit of allowing the power plants that utilize them to produce additional electricity on demand. The non-renewable energy resources are Coal, Nuclear, Oil, Natural Gas and the major RES including Biomass, Hydro, Geothermal, Solar, and Wind. RES is weather-dependent and, hence, restricted at any given time, despite the fact that they have a limitless supply in the long run [4].Germany’s target to reduce using of Coal in Future ,see Figure 2 .

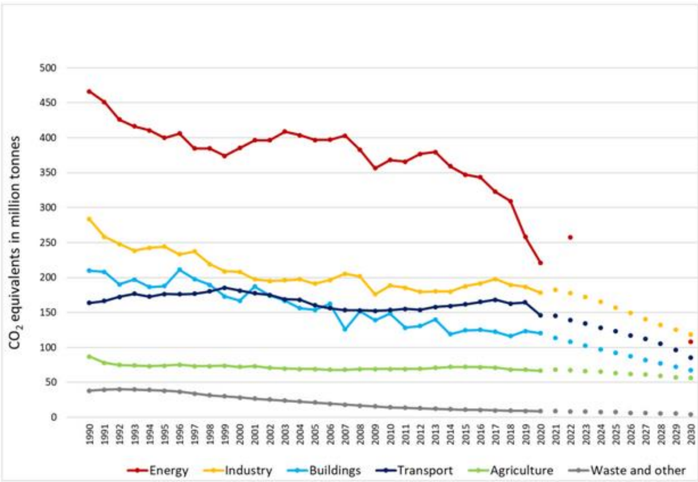


Figure 1:German greenhouse gas emissions by sector 1990-2019 [3]

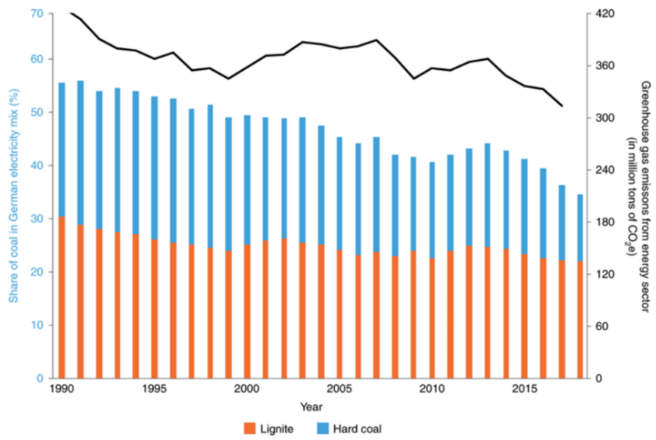


Figure 2:Share of coal in German electricity Mix and energy-related greenhouse gas emissions,

As increasing of RES, the variability of renewable generation can pose challenges for grid operators, because in case wind or solar generation increases when load falls (or vice versa) so the system will be unbalanced [5]then grid operators face a constant problem in balancing power systems, which is growing increasingly with the introduction of large-scale intermittent RES. To achieve the necessary grid balance, there are a number of options, including grid conversion and expansion, demand side control, generation-side policies, and more energy storage facilities [6] [7].

The first option is to extend the grid capacity physically, but this will need significant capital investments thus this option is not optimal. The second option is to regulate the power output of wind turbines but in case of high wind power leads to curtailment power, it means reduction of power generated by the wind turbine below what it could produce but it causes waste of Energy because it will be unused .The third option to store excessive surplus energy in different types of storage technologies and also it could be conversion to other forms energy as hydrogen [8].Production of hydrogen will participate in grid balance , it offers the path to a sustainable, carbon neutral or even carbon-free age of mobility in both the short- and long-term [9],and also it reduces emissions from industry, transportation, and heating by up to 72% by 2050 [10].Power-to-gas (PtG): Generation of combustible gas (for example hydrogen) by electrolysis of water splitting water molecules into hydrogen (H2) and oxygen, which can help with grid balancing and lower overall energy supply costs in a power system ,see Figure 3. Electrolysers are often discussed to transform power into gas because of excess power from intermittent RES. When the power generation from solar and wind generators exceeds the demand or cannot be transported to the consumers due to grid congestions, these power plants need to be curtailed. [11] [12] [13].

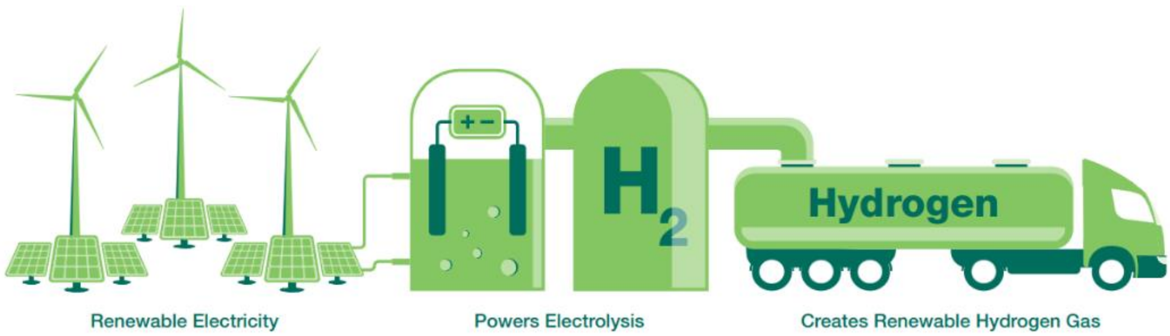


Figure 3:Production of hydrogen from RES *[14]*

1.1 Introduction KEROSyN100

As part of the transport sector, civil aviation is responsible for a significant share of greenhouse gas emissions, gas emissions with an expected growth rate for the next years [15] . One of the sources of greenhouse gas emissions with the quickest rate of growth is aviation [16].

KEROSyN100 is a research project intending to make the production of synthetic kerosene mass-market ready at an industrial process scale. In cooperation with various experts from research and industry, e.g. University of Bremen and Refinery Heide, a process layout is developed for large-scale plant in Heide, Schleswig-Holstein. In order to achieve these ambitions, the cooperation intends to develop a process layout to then build a Power-to-Liquid plant in Schleswig-Holstein [17] [18] [19].

1.2 Thesis objective

This thesis is conducted in cooperation with the German Aerospace Center (DLR) and is dedicated to the impact of future scenarios of the energy systems as well as storage technologies on the power grid operation. The following questions are investigated to answer the overarching question:

Q1) What are the impacts of extension RES on power grid in 2020,2030,2040 and 2050?

[**see chapter 5.3 Result and Analysis**]

Q2) How do storage affect grid utilization when integrating a power-to-fuel?

[**see chapter 5.1 Scenarios including hydrogen sector - see chapter 5.3.2 Storages Units and Congestions**]

Q4) Can we recommend actions to handle future grid congestions?

[**see chapter 5.2 Grid Congestion**]

This work is split into the following chapters:

- Hydrogen
- Electrolyser Technologies
- Energy Storage Technologies
- Scenarios
- Resume and outlook: evaluation of the results of the various methods.

2. Hydrogen

The Federal Government adopted the National Hydrogen Strategy on 10 June 2020 with the goal of quickly establishing green hydrogen and its derivatives as a key enabling technology for the energy transition and significantly advancing the achievement of the climate targets, a special focus has been placed on the industrial and transport sectors [20].

Hydrogen energy is very flexible, as it can be used as a gas or a liquid, converted into electricity or fuel, and produced in a number of different ways. Hydrogen gas was first produced artificially back in the 16th century, while the first fuel cells and electrolysers were made in the 19th century. The first reference we have found to the term green or renewable hydrogen was mentioned by National Renewable Energy Laboratory in 1995, who used the term renewable hydrogen (hydrogen produced from renewables) as a synonym for green. Challenges Facing Hydrogen are divided into three areas: hydrogen production, storage, and end use. Because no pure hydrogen on Earth, so it is produced by Industries.Since hydrogen is a very light gas, so is easily lost into the atmosphere and its storage is an essential obstacle to overcome due to low volumetric energy density [21].In 2018,the global production of hydrogen reached a total of 60 million metric tons [22]. The Germany's Government expects that around 90 to 110 TWh of hydrogen will be needed by 2030. In order to cover part of this demand, Germany plans to establish up to 5 GW of generation capacity including the offshore and onshore energy generation facilities needed for this. This corresponds to 14 TWh2 of green hydrogen production and will require 20 TWh of renewables-based electricity [23].

Hydrogen can be produced by the energetic splitting of water. The only byproduct is oxygen. For a process without greenhouse gas emissions the energy required must come from renewable sources (green hydrogen, It can be supplied either by electricity (electrolysis), high-temperature heat (solar) thermal, thermolysis) or by direct use of solar radiation (photolysis) can be provided. If the current electricity mix in Germany is used for the electrolysis of hydrogen (so-called grey hydrogen), greenhouse gas emissions are generated during the provision of electricity. in the provision of the electricity [24] [25] [26] ,and the types of hydrogen depend on the source of production [27].

2.1 Types of hydrogen

There are various production or extraction methods. As a colorless gas, but there are around nine colour codes see Figure 4 to identify hydrogen. The colors codes of hydrogen refer to the source or the process used to make hydrogen [28].

Figure 4:Hydrogen Colors *[28]*

Black hydrogen is hydrogen that is produced using coal, usually by the gasification method. **Brown hydrogen** is produced from lignite. Hydrogen produced from natural gas by the steam reforming process, is commonly known as **grey hydrogen**. Because of the existing and supposedly inexpensive nature of this industrialized process for producing hydrogen, the idea of combining it with CCS technologies is becoming increasingly popular. In the German hydrogen strategy, this combination is referred to as **blue hydrogen**.
Blue hydrogen will play an important role for the transition to a 100% green hydrogen scenario, as it is currently not possible to replace the entire demand with renewably produced hydrogen. However, blue hydrogen can only be evaluated as low-carbon and not, as mentioned in the German hydrogen strategy, as carbon-neutral. Since CCS technologies still release greenhouse gases into the atmosphere. In addition, the environmental consequences of its storage are unknown and further requires further research into storage. Therefore, blue hydrogen cannot be considered a sustainable solution in the long term. Further investment in the fossil fuel industry will also increase the lock-in effect. It is important to keep in mind the risk of a developing dependence on blue hydrogen, as this may slow down the energy transition.
Turquoise hydrogen is another type of hydrogen that the German government explicitly mentions in its hydrogen strategy. This hydrogen color is produced by the methane pyrolysis process. In this process, methane is split into hydrogen and solid carbon, which can be stored in old tunnels.

Orange hydrogen is hydrogen produced from bioenergy. Bioenergy is carbon neutral energy derived from organic matter and can be in various forms such as biomass, biofuel, biogas and biomethane. Unlike renewable energies, such as solar and wind energy, whose sources are unlimited, bioenergy is based on organic materials. These are usually derived from waste and residual materials from agriculture, forestry, households, and industry.

According to BASF, hydrogen produced with nuclear energy is called **red hydrogen.** Nuclear energy can be used in two ways: first, by harnessing electricity through electrolysis, and second, by using its high-temperature wastewater via the TWS process. In its power generation process, nuclear energy does not produce CO_2 emissions. It can also provide a stable energy supply. Therefore, red hydrogen is not considered sustainable.

White hydrogen refers to hydrogen that occurs in natural environments, it can be extracted by fracking similar to fracking for fossil fuel exploitation and is highly controversial. The environmental impact, exploration methods, and production potential are still unknown.

Green hydrogen is the only sustainable hydrogen option in the long term, as it must be produced from renewable sources. By using renewable resources, such as solar and wind, the direct carbon emissions of production for hydrogen production can be reduced to zero emissions. The most promising method is the use of renewable electricity as an energy source to produce hydrogen via electrolysers [29] [30] [31] [32]. There are a few barriers to be knocked down before the commercial aspect of green hydrogen is advanced; the costs of renewable energies need to be viable themselves, the storage of electricity generated is still too inefficient, the storage of hydrogen too volatile, the costs of desalination remain significant and important, there is a lack of industrial demand for hydrogen (especially green hydrogen) [33]

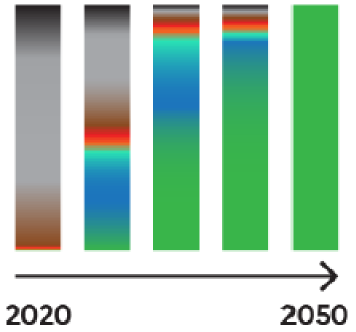


Figure 5:Development of the hydrogen colors [29]

3. Electrolyser Technologies

Electrolysers are a chemical process to split water into hydrogen and oxygen [34], see Figure 6 and rather flexible and may contribute to demand-side management [35].

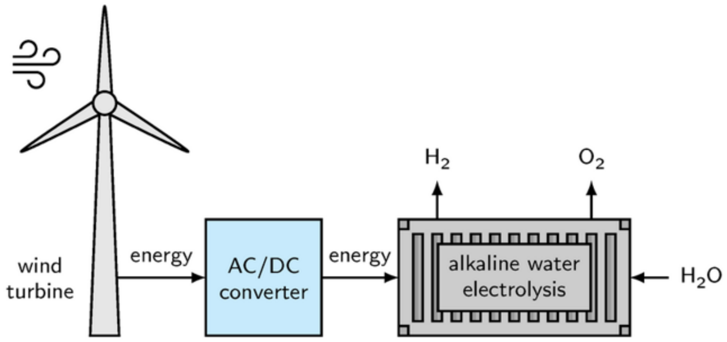


Figure 6: Schematic of alkaline water electrolysis powered by wind energy *[141]*

There are three basic types of electrolysis: Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM) and Solid Oxide Electrolysis Cell (SOEC) see Figure 7 .

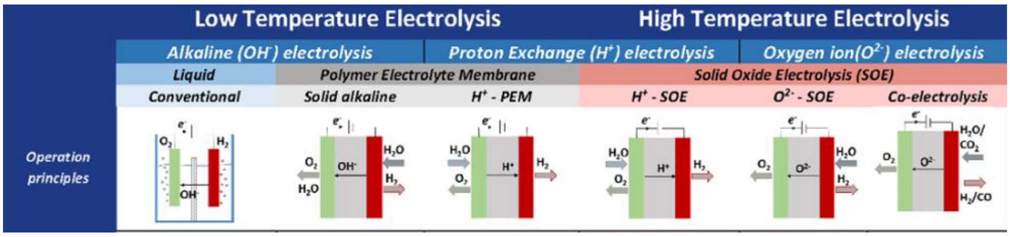


Figure 7:The typical characteristics of the main electrolyser technologies [79]

While the low-temperature technologies, AE, and PEM, both provide high technology readiness levels, the high-temperature SOEC technology is still in the development stage [36].Concentrated lye is used in AE as the electrolyte, and a gas-impermeable separator is needed to keep the resultant gases from mixing. The electrodes are made of non-elegant metals like nickel and have an electrocatalytic coating. The electrolyte used in PEMEL is a humidified polymer membrane, and the electrocatalysts are noble metals like platinum and iridium oxide. Both systems can operate at pressures of up to 30 bar and between 50°and 80 ° technologies nominal stack efficiency hovers around 70% [37] [38]. SOEL is referred to as high-temperature (HTEL) where steam electrolysis at temperature between 700°C and 900 °C leads to the division of hydrogen and oxygen. Due to favorable thermodynamic effects on power usage at higher temperatures, stack efficiencies close to 100% are theoretically feasible. SOEL provides only small stack capacities below 10 kW, compared to 6MW for AEL and 2MW for PEMEL. Therefore, the choice between AEL and PEMEL for the best system design for a large-scale application depends on the investment costs and lifetime. AEL's investment expenses currently range from 600 to 800 €KW, while PEMEL's investment more expensive than it. AE also has a longer lifespan than PEMEL systems and require less maintenance each year [38].

3.1 Alkaline electrolysis (AE)

In AE, two electrodes are immersed in an aqueous KOH solution with a concentration of 20-30%. These two electrodes are separated by a membrane which has the task to prevent the mixing of both product gases and thus to increase the efficiency of the cell increase the efficiency of the cell. At the same time this membrane must be permeable for hydroxide ions and water molecules see Figure *8*.

AE has three main problems:

(1) The membrane is not absolutely impermeable. This leads to the mixing of oxygen and hydrogen at both outlets, oxygen and hydrogen at both outlets. This occurs mainly at lower loads, which makes this type of electrolyte unusable for low loads.
(2) Due to high ohmic losses, only low current densities are achievable.
(3) AE can only be operated at low pressures

The reactions at anode and cathode are [39]:

Anode: $4OH^{-} \rightarrow O2 + 2H2O$

Cathode: $2H2O + 2e^{-} \rightarrow H2 + 2OH^{-}$

AE is technically mature and reliable. Today, they are built in large scales from several 10MW up to more than 100MW. Although this type of electrolysis shows a relatively dynamic behavior, it is not quickly possible to start up or shut down the electrolyser.However, a ramp-up or ramp-down into or out of the quiescent current range is problematic. Diffusion processes in the stand-by state cause mixing of the product gases. This may require costly coiling of the cells with inert gas, which in turn results in a reduction of the energy efficiency during frequent start-up and shutdown processes [40] [41] [42].

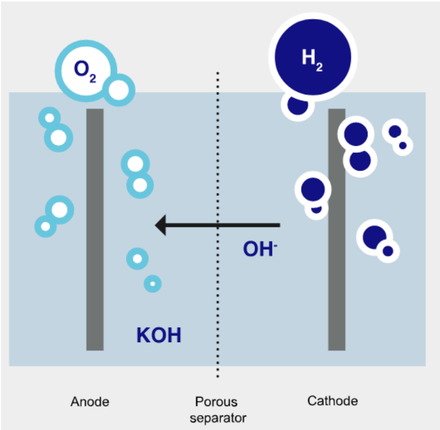


Figure 8:Alkaline Electrolyser *[39]*

3.2 Proton Exchange Membrane (PEM)

In PEM electrolysis, there is a polymer membrane between the electrodes that acts as an electrolyte. This membrane has the task of conducting protons from the anode to the cathode, but at the same time preventing the two product gases from mixing (see Figure 9). For this reason, this type of electrolyte is called a PEM. Materials used are, for example, Nafion ®or FumapemR in a thickness of 20 - 300µm, which enables a very compact design. PEMEL allow much higher current densities than AE and can be used in a much wider range due to the low gas exchange through the membrane.

Due to the low gas exchange through the membrane, PEMELs can be operated in a much wider load range of 10-100% of rated power. In addition, they can be operated under very high operating pressures. This has the advantage that the generated gases can already be at a storable pressure level, so that no further compression is necessary. However, very high operating pressures require thicker diaphragms membranes. Another disadvantage is the acidic, corrosive effect of the diaphragm. This makes the use of high-quality materials in PEMEL.

The reactions at the anode and cathode are

Anode: $2H2O \rightarrow O2 + 4H+ + 4e^-$

Cathode: $4H+ + 4e^- \rightarrow 2H2$

A significant advantage of the PEMEL is its high dynamic range. It can follow changing input powers practically without distortion. The peripheral devices also exhibit a higher dynamic than AE. In addition, PEMELs reach their operating temperatures faster after a start. However, some problems occur in the stand-by state, e.g., such as diffusion processes through the membrane, which lead to a contamination of the product gases. as well as subsequent recombination's, which cause a pressure decrease, which leads to mechanical stress due to different velocities on both sides of the membrane. In addition, frequent ramping up and down can and shutdown can lead to a reduction of the lifetime of the membrane [43] [44] [45].

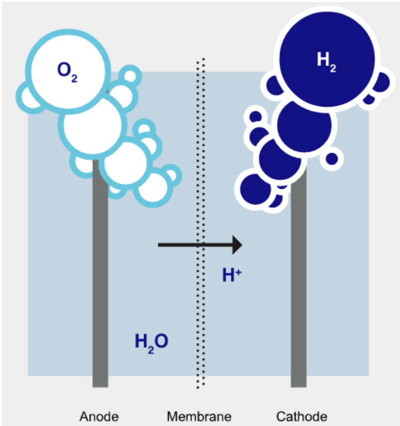


Figure 9: Protonen-Austausch-Membran-Elektrolyse (PEMEL)

3.3 High temperature electrolysis cell (SOEC)

The high temperature electrolytic cell has a solid electrolyte or a membrane which acts as an electrolyte Membrane. In contrast to the PEMEL, H+ ions are not transported through this membrane. H+ ions from the anode to the cathode, but O2- ions from the cathode to the anode see Figure 10 and Figure 11. These electrolysers are operated at very high temperatures of 800-1000 ◦C, hence the name "high-temperature electrolytic cell". The great advantage of this electrolysis is the high efficiency. Due to the high temperatures, the decomposition voltage is strongly reduced to values around 1.0V. A energy for the decomposition of the water comes from the heat energy to thermal energy. This makes the SOEC particularly suitable for use in processes with large amounts of waste heat.

One example is the combination of hydrogen production in a SOEC with geothermal energy, solar thermal energy or thermal power plants

Anode: O + O → O2

Cathode: H2O + 2e⁻→ H2 + O2⁻

SOECs are currently still under development, and there are currently few to no commercial plants. Problems with this type of electrolyte are, firstly, the lifetime, which is strongly determined by the degradation rate of the solid electrolyte. On the other hand, the SOEC is very sensitive to power fluctuations. This is due to the fact that changes in the input power led to changes in the Joule heat loss. This results in temperature changes, which in turn cause mechanical stresses. Also, start-up and shut-down processes have to be performed very slowly to keep these stresses low [46].

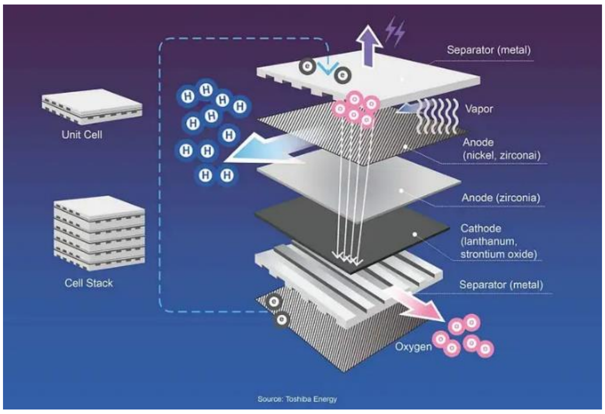


Figure 10:High temperature electrolysis cell (SOEC)

Figure 11:A typical schematic of SOEC *[142]*

4. Energy Storage Technologies

Nowadays, there are more RES, and consequently more production so Storages are necessary to temporal balance a mismatch of supply and demand. This mismatch occurs due to more supplied power than required or vice versa. Additionally, grid restrictions may prevent power transmission and lead to a mismatch. Grid operators often solve those grid-related mismatches with the curtailment of renewables and, hence, decrease the power supply [47].There are several energy storage systems currently being developed and in use or integrated into the distribution and transmission grid, each with their strengths and weaknesses. Preferably for technic storage solutions to ensure that sufficient storage capacity to meet both generation and grid needs, but also a long lifetime and the ability to resist a significant number of charge/discharge cycles [48] [49]. With the development of energy storage technology, the main energy storage technology can be divided into the following categories, according to the classification of technology see Figure 12 .

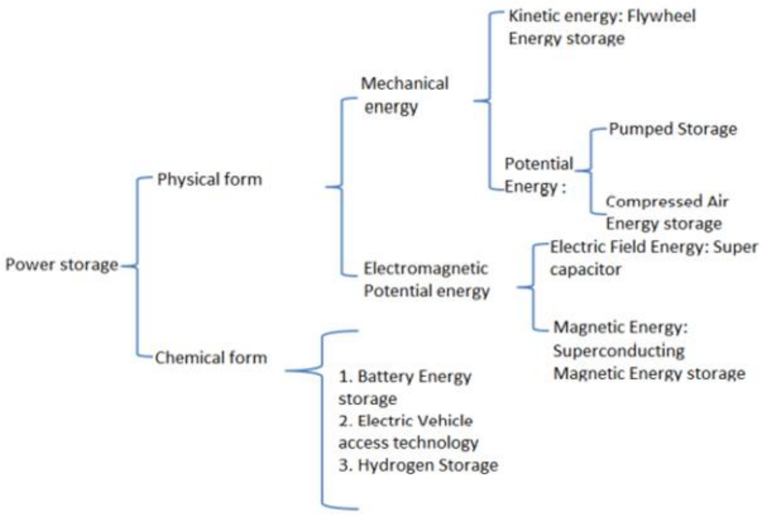


Figure 12 : Classification of Energy Storage Technologies [25]

At my thesis, I will focus to explain in detail some of energy storage technologies as Compressed air reservoir, Pumped Storage power plants, Lead-acid batteries, Lithium-ion batteries, and Redox flow batteries. These technologies are most economist and has good efficiency between other energy storages.

4.1 Compressed air reservoir

Compressed air energy storage (CAES) is a modification of the basic gas turbine (GT) technology, in which off-peak electricity is used for storing compressed air in an underground cavern [50] [51],it is available storage with a big capacity, but it has fewer geographical limits than Pumped hydro storage (PHS) [52] ,see Figure 13.The need for electricity storage technologies, such as CAES plants, increases along with the share of fluctuating renewable energy sources and other units with production restrictions, like e.g. combined heat and power production (CHP) [50] [53, 52, 54].

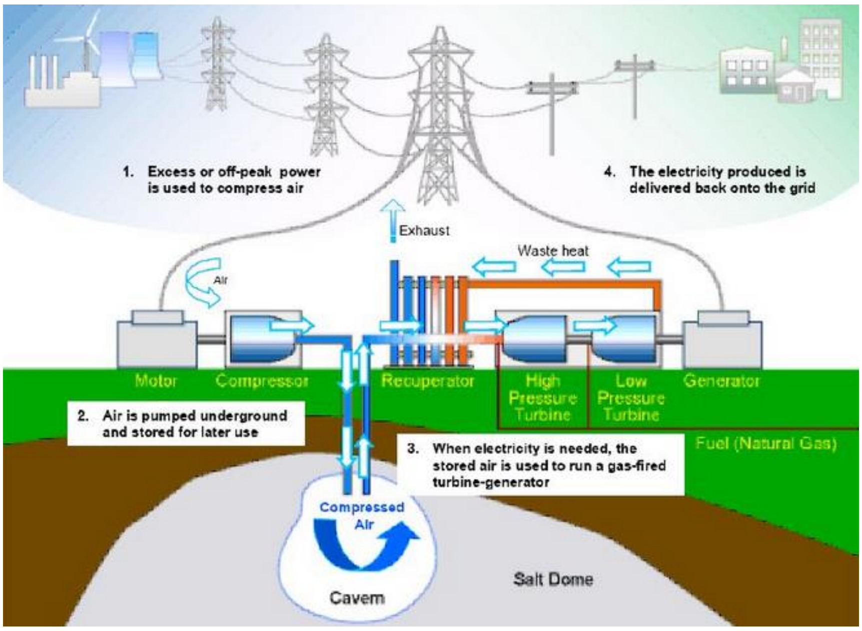


Figure 13:Working scheme of CAES *[53, 52, 54]*

Air can be stored in a CAES system in three ways: diabatic, adiabatic, and isothermal. Diabatic CAES is a system in which air is compressed and stored in a reservoir when electricity is in excess, and air is heated with natural gas and expanded through a turbine when energy is required , see Figure 14 . There are two diabatic CAES plants in operation around the world: the Huntorf plant in Germany (290 MW) and the McIntosh facility in Alabama (110 MW) [55] [56].

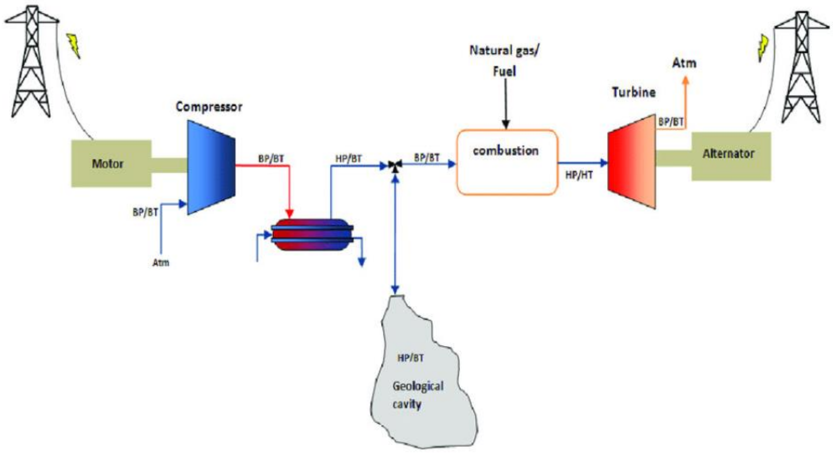


Figure 14:Diabatic compressed air energy storage (CAES) [57]

Adiabatic CAES is a system that uses a thermal energy storage device to absorb the heat produced by compressing air. When power is required, the stored heat is released into the air before being expanded by the turbine (see Figure 15). Unlike the diabatic approach, this method does not necessitate the use of premium fuels to heat the compressed air prior to expansion. The ADELE system in Saxony-Anhalt, Germany, is the world's first adiabatic

CAES system, with a storage capacity of 360 MWh and an electric output of 90 MW, aiming for a 70 percent cycle efficiency [58].

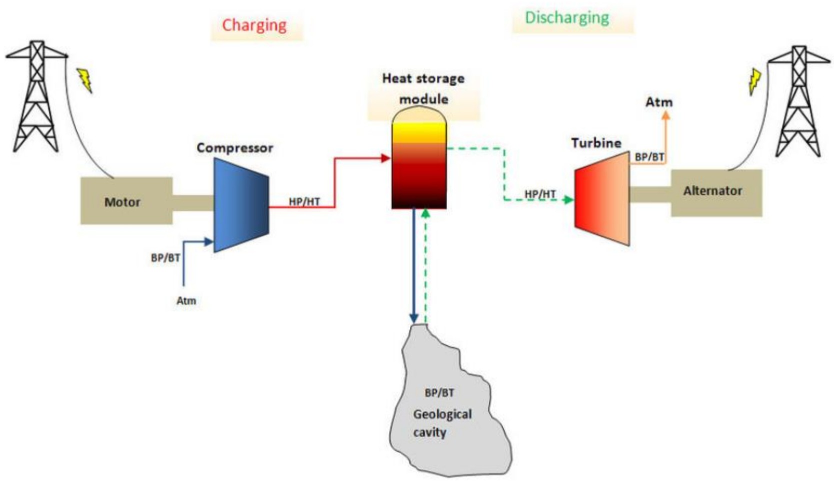


Figure 15::adiabatic compressed air energy storage (A CAES) [57]

Isothermal CAES is an evolving technology that attempts to overcome some of the limitations of conventional CAES (diabatic or adiabatic). For example, current CAES systems use turbomachinery to compress the air to about 70 bar prior to storage. Without intercooling, the air heats up to about 900 K, making it impossible to process and store. Isothermal CAES is a technological challenge because heat must be continuously removed from the air during the compression cycle and heat must be continuously added during expansion to ensure an isothermal process (see Figure 16). Currently, there are no isothermal CAES plants in the world, but several possible solutions based on reciprocating engines with 70-80% efficiency have been proposed [59] [54] [60] .

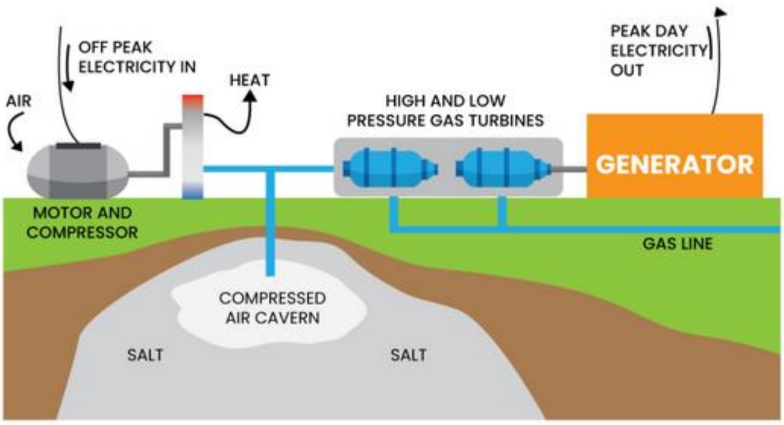


Figure 16:Isothermal Compressed Air Energy Storage *[61]*

4.2 Pumped storage power plants (PHS)

Hydropower is energy obtained from falling or swiftly flowing water that can be harnessed for useful purposes. PHS stores more than four-fifths of the world’s renewable electricity [53]. Because of its associated challenges in terms of development, PHS is not commonly used as residential storage. PHS is a technology for indirectly storing electric energy, according to the concept of electric energy conversion. The pump, which moves water from the lower reservoir to the upper reservoir for storage, is powered by the power system's surplus capacity and electricity at midnight low load. When the load on the power system grows, the water is discharged to the lower reservoir, where its kinetic and gravitational potential energy is utilized to generate electricity via the turbine. is a device that uses water to transform energy into electricity through the turbine [62] ,see Figure 17 .At the end of 2018, pumped storage has a global installed capacity of roughly 170.7 GW in China, Japan, and the United States [62] [63].

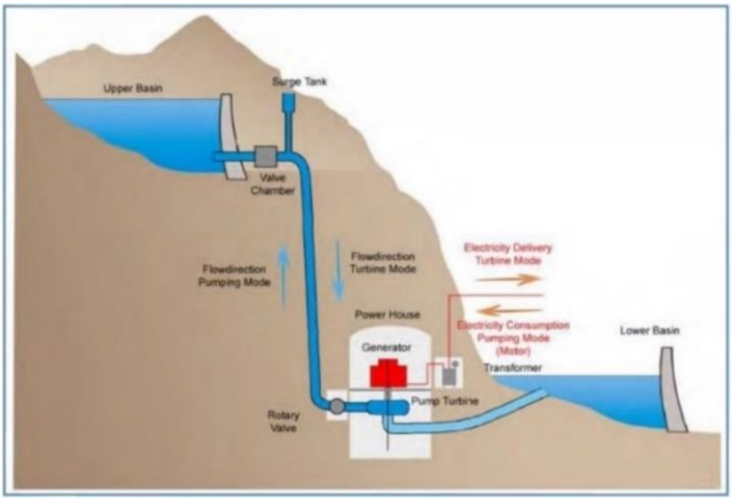


Figure 17:Pumped storage power plants [60]

4.3 Batteries

Batteries enable the chemical storage of energy, which can then be converted to electricity and used as a source of power when needed [64]. Battery storage technologies will become more and more essential for responding to electricity demand and supplying green energy. Battery storages are technologies that allow energy from renewable sources, such as solar and wind, to be stored and then released when customers need power [65].There are several battery technologies under consideration for energy storage, the main being: 1) Lead acid 2) Nickel Cadmium 3) Nickel metal-hydride 4) Sodium Sulphur 5) Lithium ion 6) Redox-Flow Batteries are a type of energy storage device that works by absorbing and releasing energy on demand. Some types of battery technologies will be explained in detail at next sub chapters. [66] Lead-acid and lithium-ion batteries have been the two main battery types in recent years(see Figure 18. Since 2017, lithium-ion technologies (notably NMC and LFP) have dominated the market share of about 100%. The success of lithium-ion batteries is attributed to their lower specific system costs, higher energy efficiency, and longer lifespans in cyclic applications than lead-acid batteries [67]. A major part of the storage capacity is lithium-ion battery storage (about 431 MWh, including second-life systems), followed by lead-acid batteries (about 55 MWh). Hybrid, redox-flow and sodium-sulfur projects add up to less than 70 MWh [68].

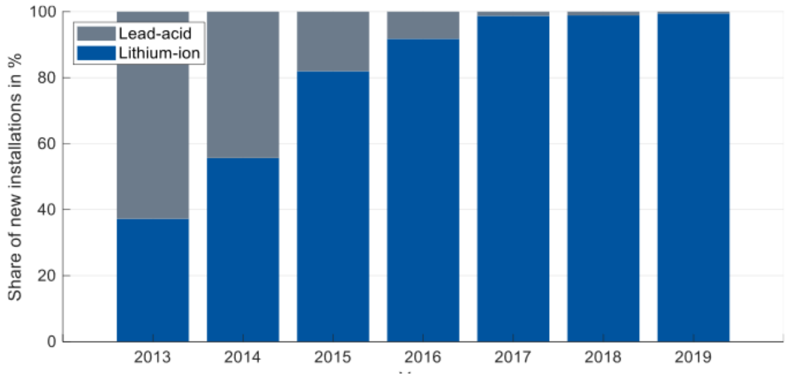


Figure 18:Market shares of battery technology (Lead-acid -Lithium-ion)

4.3.1 Lead-acid Batteries

One of the first battery technologies employed in energy storage was lead-acid batteries (PbAc) and it is the most common type of battery. However, because of their poor energy density and limited cycle and calendar life, they are not widely used for grid storage. The battery is made up of cells, each of which is made up of plates immersed in a dilute sulfuric acid electrolyte [69] .The construction of PbAc see Figure 19 .

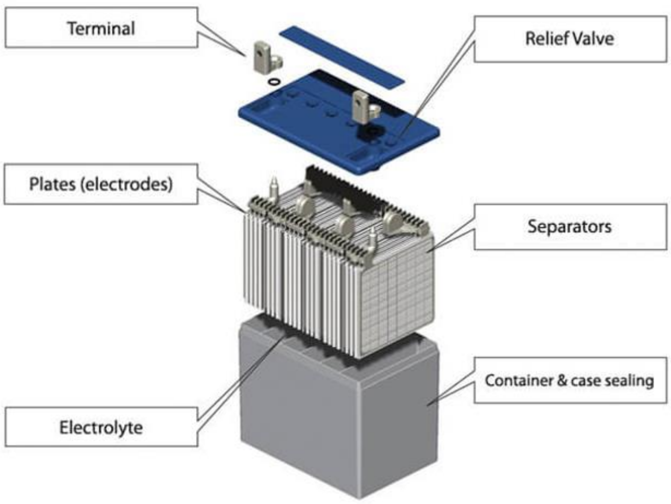


Figure 19 : Sealed Lead Acid Battery Construction

The most popular and least expensive form of deep-cycle battery is lead-acid. Unfortunately, **PbAc** technology hasn't improved much over time, and they still have several severe flaws. it has internal plates, make it heavy and the sulfuric acid must be monitored. Furthermore, depleting lead-acid batteries below 50% capacity harms them and reduces their life span [70].

These lead-acid battery constraints are unwelcome and have hindered the development of renewable energy. Additionally, A lead-acid battery's life cycle is usually between 2 and 5 years. This means you'll have to replace your batteries every few years and dispose of the ones you don't use [71].

4.3.2 Lithium-ion:

The most popular battery chemistry for storing electricity is lithium-ion (*Li-ion*). Instead of lead plates and sulfuric acid, lithium-ion batteries employ lithium salt to initiate a chemical reaction to store energy. **Li-ion** batteries are lighter, safer, more efficient, and easier to maintain, more cost-Effective, safer long-life span, Environmentally Friendly than their lead-acid equivalents due to their construction and chemistry [72]. The construction of a lithium battery is made up of four main parts. It has a cathode, which controls the battery's capacity and voltage and is the source of lithium ions. The anode allows electric current to flow through an external circuit, and lithium ions are stored in the anode when the battery is charged [69] ,see Figure 20.

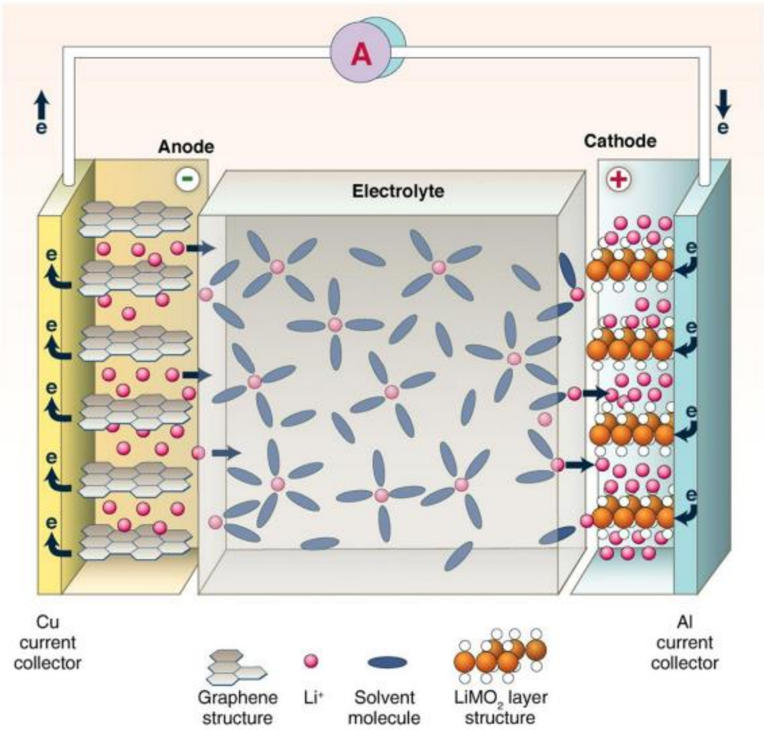


Figure 20:Schematic diagram describing the design of a LIB

Energy storage. Lithium has a high electrochemical potential and can store a lot of energy, despite being one of the smallest elements in the periodic table. Only one barrier has kept lithium batteries from becoming the mainstream storage option for renewable energy, despite its ideal low weight and excellent efficiency: their expensive price. However, it appears that the situation seems to be changing [73] .According to a recent Bloomberg NEF (BNEF) analysis, the cost of lithium-ion batteries will drop dramatically in the future years, surpassing the 85 percent drop between 2010 and 2018 [74].By 2030, BNEF expects 50 percent reduction in the cost of **Li-ion** batteries per kW/h, as demand grows [75] [76] [77].

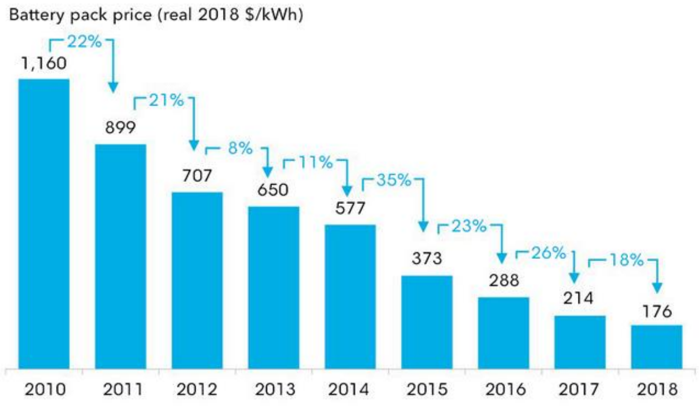


Figure 21:Global Cumulative Energy Storage Installations *[74]*

4.3.3 Redox flow

Redox flow batteries (RFBs) are one of the most modern electrochemical systems and a highly promising option for stationary energy storage in terms of operational powers and discharge times [78],see Figure 22. Redox flow batteries fulfill a set of requirements to become the leading stationary energy storage technology with seamless integration in the electrical grid and incorporation of renewable energy sources [79].

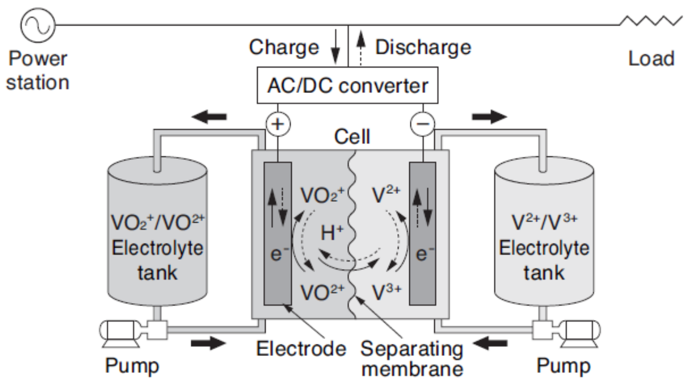


Figure 22:Principle and Configuration of an RF Battery *[80]*

There are two types of redox flow batteries **true redox flow batteries and hybrid redox flow batteries.** Scalability and flexibility, independent power and energy sizing, high round-trip efficiency, high DOD, long durability, fast responsiveness, and decreased environmental impact are the most enticing advantages of this technology [80] [81].These characteristics allow for a wide range of operational powers and discharge times, making them excellent for supporting renewable energy generation.

The following chart shows the characteristics of a range of energy storage systems and their suitability and shows the power handling capacity of each these systems and the duration for which this power can be sustained see Figure 23 .

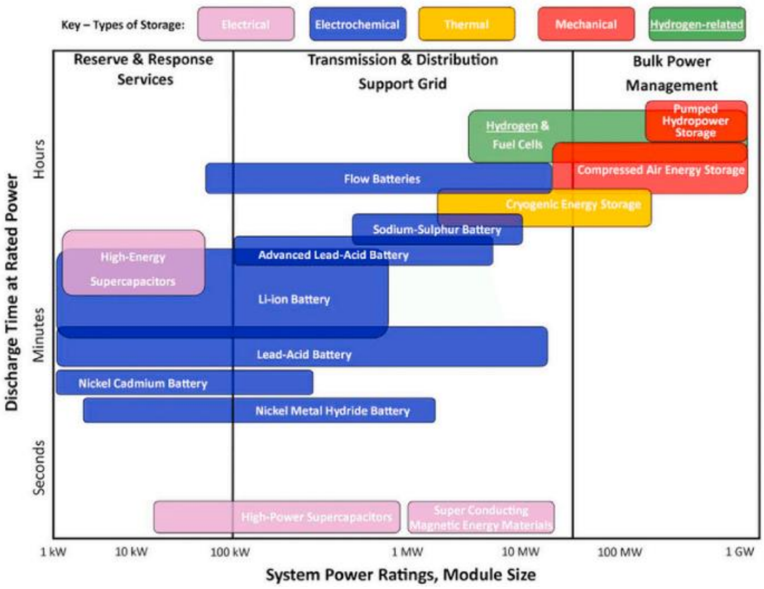


Figure 23: Comparison of power rating and discharge timescale of electrical storage systems *[82]*

Battery storage is not always the most cost-effective option for integrating renewable energy, as short-term storages balancing high frequent pattern as solar and PHS and so as long-term storages balancing low frequent pattern as wind [83].

4.4 Methods of hydrogen storage

Hydrogen is the only gas that can be stored in four different ways, resulting in a wide variety of applications. When discussing the possibilities for storing hydrogen, it should be remembered that one goal should always be to increase the density and thus the energy density [84] [85] [86].

4.4.1 Physical Storage

Physical storage systems are storage systems that can directly store hydrogen in liquid or gas form under high pressure. To store hydrogen volume-efficiently, the gas can be compressed, liquefied or chemically stored in a carrier medium. Compression of hydrogen increases the calorific value stored per volume, the most common physical storage systems, with respect to the density of hydrogen as a function of temperature and pressure see Figure 24 and Figure 25. Here it is mainly about storage systems that can be used as mobile as e.g. hydrogen tanks in motor vehicles. Additionally, even if physical storage systems are detailed, their goal is to store as much as possible (e.g. salt cavern storage) [85].

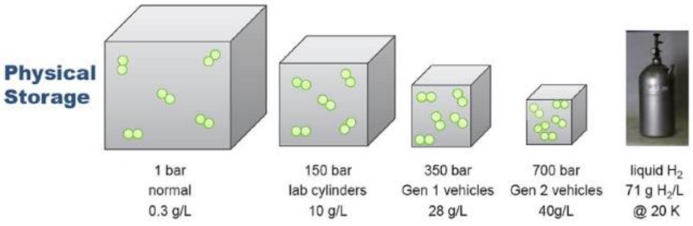


Figure 24:Physical H2 Storage *[85]*

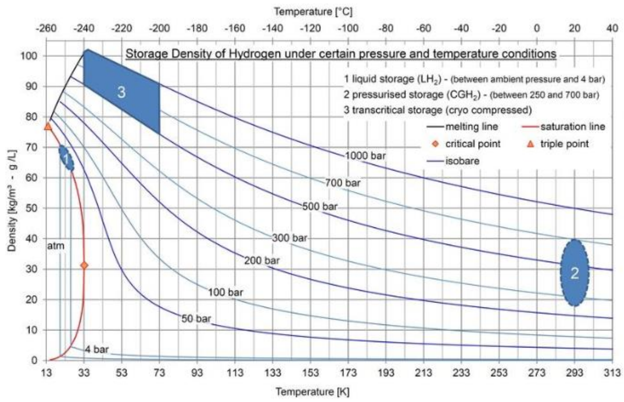


Figure 25: Comparison of the volumetric energy density of physaical hydrogen storage [2]

4.4.2 Pressurized storage

Gaseous storage of hydrogen at high pressures is the most common storage method and is already used in many areas of industry and also in mobile applications. All currently available hydrogen-powered vehicles use pressure tanks to store hydrogen.

Pressure tanks are usually cylindrical with spherical caps, these offer a good compromise between package and safety due to the round shape. The tanks consist of a liner, which is usually made of metal and prevents the hydrogen from leaking. The liner is wrapped with carbon fibers, which ensure the stability of the tank and protect it from external damage.

Cylinders are the most common pressure vessels; however composite vessels can also be polymorph or toroidal [87] [88] [89] [90].

Pressure tanks are divided into 4 types , see Figure 26 and Table 1

Type I: a typical steel bottle that is completely metal and is used in industrial procedures to store liquids and gases, cheap to manufacture but heavy and H2 is kept at pressures between 150 and 300 bar as an industrial gas (usually 200 bar). Today, these high-pressure vessels are the most popular and affordable options.

Type II: pressure vessel with a fiber-resin composite wrapped around a thick metallic liner hoop and when only greater pressures are needed, which is usually for fixed applications, type II tanks are preferable.

Type III: pressure vessel with a full-wrapped metallic liner consisting of a fiber-resin composite and vessels are designed for portable applications where weight reduction is critical.

Type IV: pressure vessel made of a fiber-resin composite with a fully wrapped polymeric lining.
Metal port that is constructed into the structure (boss) and vessels are designed for portable applications where weight reduction is critical.

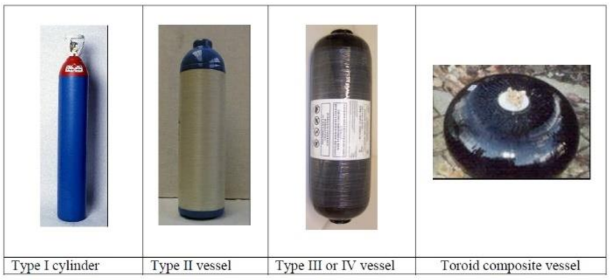


Figure 26:The four types of high-pressure tanks are compared and represented schematically.

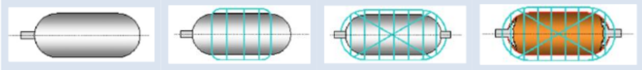
Typ I	Typ II	Typ III	Typ IV
			
Ganzmetall Zylinder	Metall mit Verstärkung im Mittelteil durch Glasfaser-Ummantelung	Metall mit Verstärkung durch Glasfaser-Ummantelung im gesamten Bereich	Polymerer (Kunststoff-) Behälter mit Verstärkung durch Glasfaser-Ummantelung und metallisch-integrierter Öffnung
Drücke bis 300 bar möglich	Drücke von mehr als 350 bar möglich	Drücke von 350 bis 700 bar möglich	Drücke von 350 bis 700 bar möglich
Preis-Leistungsverhältnis: ++	Preis-Leistungsverhältnis: +	Preis-Leistungsverhältnis: -	Preis-Leistungsverhältnis: -
Gewicht-Leistungsverhältnis: -	Gewicht-Leistungsverhältnis: 0	Gewicht-Leistungsverhältnis: +	Gewicht-Leistungsverhältnis: ++

Table 1:The four types of high-pressure tanks are compared and represented schematically [86]

4.4.3 Liquid Storage

As early as 1898, the Scottish researcher James Dewar succeeded in liquefying hydrogen by cooling it with liquid air. He determined the boiling temperature of hydrogen to be **-253.15 °C** at a pressure of 1 bar, in enclosed tanks to maintain the low temperature and reduce evaporation.

Liquid hydrogen is colorless, odorless, tasteless, and highly combustible and it is technically challenging and very costly. It is an attractive storage medium to store hydrogen, It is more dense in volume than it is in gas form, which results in superior storage capacity and It is not necessary to have a high tank pressure and lower total mass. The maximum useable volume is attained in cylindrical-shaped tanks . The operational pressure range for hydrogen liquid storage is 0.1 MPa to 0.35 MPa. The energy density is still far higher than compressed gas tanks even at these pressures. Liquid hydrogen has an energy density of 8.4 MJ/l as opposed to compressed gas's 4.4 MJ/l. The hydrogen transportation trailers are one example of increased density. It is demonstrated that trailers with liquid hydrogen storage tanks can transport six times as much hydrogen as those with compressed gas tanks [86],see Figure 27.

Figure 27:Hydrogen liquefier. (Courtesy of Linde Kryotechnik AG, Switzerland)

4.5 Underground storage

In recent years the role of hydrogen in future energy scenarios has moved somewhat into the background. Storing hydrogen underground is a solution to the problem of supplying hydrogen to users during times of peak seasonal demand. One of four approaches can be used to store hydrogen in underground caves or geological formations as Salt caverns, Depleted gas and oil reservoirs, Aquifer and Rock Caverns) ,see Figure 28.
Underground storage offers several benefits for the environment, safety, with high efficiency and low losses CAPEX (for high storage capacity), OPEX [91].

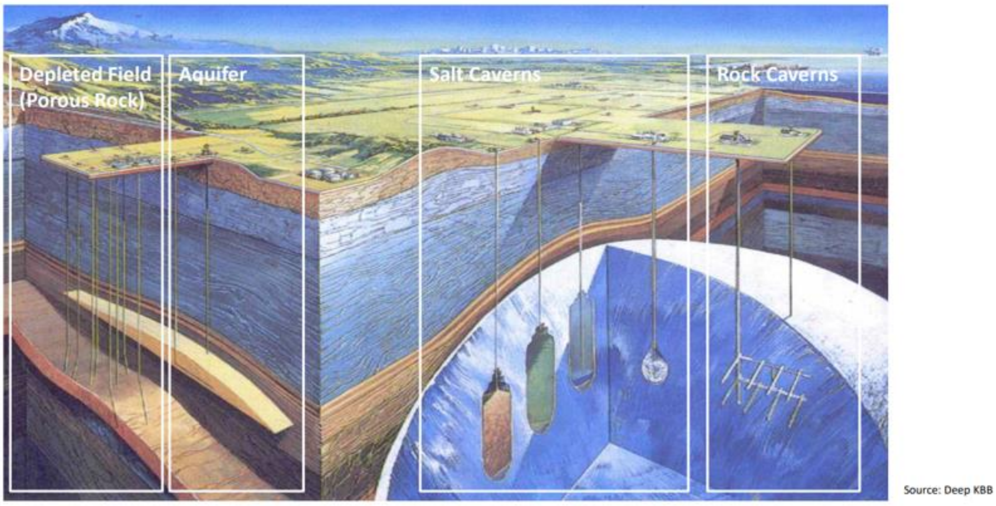


Figure 28:Different techniques for storing hydrogen underground [91]

The method for selecting an underground location for storing pure hydrogen is still being developed,to store a mixture of natural gas and hydrogen, it would be necessary to modify the selection procedures used for underground natural gas storage (UGS) and knowledge gained from studies of natural gas storage field conversion.
Additionally, new standards must also be created to take into consideration the underlying fundamental processes that are specific to hydrogen in the subsurface, such as fluid movement, diffusion geochemistry, and microbial activity) [92].

4.5.1 Salt Caverns

Around the world, there are more than 1,900 salt caverns. By injecting fresh or salt water into a deep well, a process known as solution mining, salt caverns are produced. The infusion of eight to ten volumes of water is necessary to create one volume. The process of "leaching" is another name for solution mining. In direct leaching, fresh water is introduced through a central tubing and saturated brine is removed through the annular area. The process of reverse leaching involves introducing fresh water into the annular gap and pulling out saturated brine through the central tubing. By situating the tubing, modifying the water flow rate, and choosing between direct and reverse leaching, one may regulate the shape of the cavern.
The size of the cavern should be customized to the owner's needs and the salinity level's features. But salt caverns are unable to match reservoir capacity, they cannot be used to supply base load requirements.

The depth of the cavern affects the operating pressure. The working pressure can surpass 200 bar if the cavern is deep enough, say more than 1,000 m deep, a minimum pressure is needed to avoid salt damage and cavern closure due to excessive visco-plastic behavior (also known as "salt creep") see Figure 29.

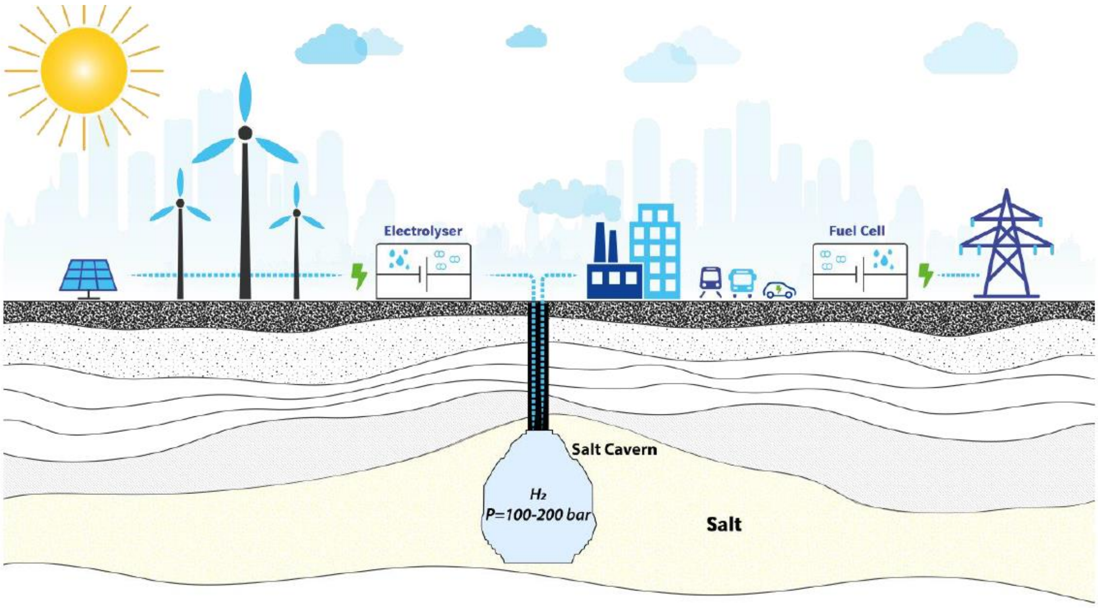


Figure 29:Hydrogen storage in salt cavern [76]

Six salt caverns have been constructed for the storage of hydrogen, five in the USA (Moss Bluff , Clemens Dome , Spindletop) and in the UK (Teeside) see Table 2 and also in Etzel Location, they are working to turn gas or oil salt cavern storage into huge hydrogen stores ,the final expansion sage should be 99 caverns ,to store 22.5 TWh of hydrogen [93] [94] [95] [96].

Localisation	Clemens Dome (US)	Moss Bluff (US)	Spindletop (US)	Teeside (UK)	Etzel
Operator	Conoco Pholips	Praxair	Air Liquide	Sabic	STORAG ETZEL
Start	1983	2007	2014	1972	2021
Volume (1000 m^3)	580	566	>580	3*70	70*500
Pressure (bar)	70-135	55-152	Confidential	45	N-a
Energy (GWh)	92	120	>120	25	22500 Final Expansion stage

Table 2: sites include Salt Caverns of Hydrogen Storage at the world

4.5.2 Depleted Field (Porous Rock)

Natural gas has been stored in depleted gas and oil reservoirs thousands of feet underground, where the majority of the recoverable commodity has been taken.
Cushion gas must make up 50% of the reservoir volume in order to maintain reservoir pressure and adequate extraction rates, when it used to keep the correct pressure levels, so cushion gas represents a capital loss for reservoirs. In addition to being lost as cushion gas, the most likely means for gas to escape is through leaky wells see Figure 30 . Other, most

likely insignificant gas losses could occur through the caprock, as well as by diffusion into the local groundwater and contamination from previously present hydrocarbons [97].

Pure hydrogen has not yet been stored in depleted gas fields. But In theory, natural gas reserves, which have proven to be capable of storing gas for millions of years, should be able to serve as hydrogen storage as well. It is being examined at various levels by a number of storage operators. a pilot project called the underground Sun storage, run by RAG Austria from 2014 to 2021, has already begun testing storage of a mixture of 10% hydrogen and 90% methane in a depleted gas well and has encountered no containment problems. The higher compressibility factor, lower diffusivity, and lower viscosity of hydrogen compared to natural gas may make it more challenging to contain for hydrogen storage in depleted gas fields.

Computer simulations have demonstrated that hydrogen diffusion through the cap rock is minimal, and the most likely pathway for escape, there should be through the wells, as is the case with all underground gas storage methods. but this needs to be verified experimentally case-by-case before using a depleted gas field to store hydrogen. [91]

Methane and hydrogen mixes can be stored safely and extracted later to separate them and get pure methane and pure hydrogen.

More research is necessary to find which infrastructure required and how done it economically.
However, if it is feasible, this could be a helpful solution in the short term when the demand for hydrogen is insufficient to warrant the storage of pure hydrogen in a whole gas field.

Depleted gas fields have the advantages of being greater in volume than salt caverns and having well-understood geology from being used for natural gas.
They already have a natural gas well infrastructure, some of which may be converted or reused for hydrogen, as opposed to the creation of new salt caverns. In addition, there are more gas fields than salt caverns [98].

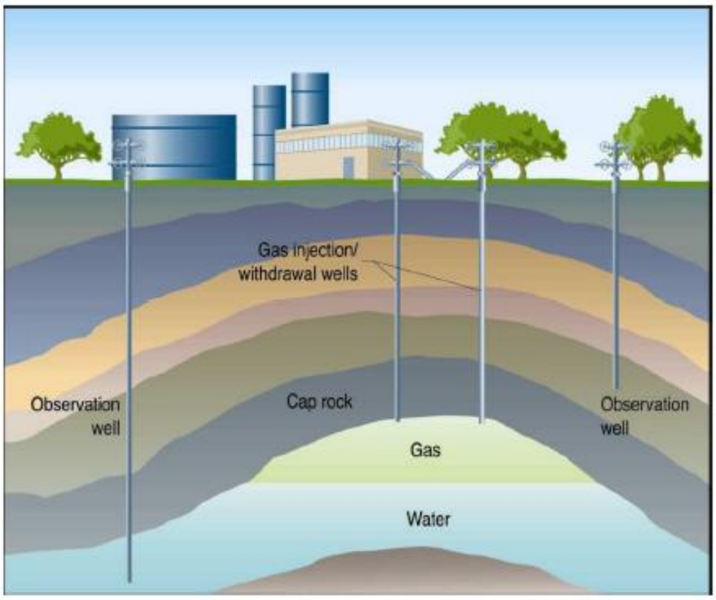


Figure 30: Depleted Oil/Gas Reservoirs [99]

4.5.3 Aquifer

In areas where there are no depleted reservoirs, and there are Water-bearing porous rocks that called aquifers., like sandstone, that are often found hundreds of feet below the surface, see Figure 31. The geology of an appropriate aquifer for storage will resemble that of depleted gas reserves. Aquifers are porous sedimentary rock formations, like natural gas reservoirs, except instead of holding natural gas, they hold water in comparison to depleted reservoirs, aquifers require more cushion gas. It’s possible that up to 80% of the reservoir's entire volume will need to be filled with cushion gas Aquifers do not already have enough naturally occurring gas to meet current gas requirements, unlike depleted reservoirs. This changes according on the geological structure, where the wells are located, and the operating requirements. Aquifers in Europe have operational pressures between 30 and 315 bar and depths between 400 and 2,300m .Aquifer development normally takes about as long as depleted field development, plus extra time for geological investigations when adding fresh storage in an aquifer. Due to their unclear geology and lack of infrastructure, Aquifer development is more costly. Aquifers are frequently used to store natural gas, and they account for 13% of the capacity now available in Europe.

Unlike depleted gas fields, which are known to be tight because they were formerly occupied with gas, aquifers may not be tight on all sides, before they can be used as storage, comprehensive geological studies are needed to ascertain whether there are routes for the gas to escape.

These studies often take two years to complete. By using methane to pump them, which forces the water within their pores to the side. Depending on the construction of the aquifer and the position of the well, the displaced water may occasionally be used in place of cushion gas, filling the pores when the methane is exhausted. This is called an active water drive. The extent to which this process may be used is determined by how rapidly water diffuses into the pores when gas is drawn out. Cushion gas is usually preferred in its place.

Hydrogen store in Aquifiers, there have not been any testing regarding to it yet. But the Lacq Hydrogen Project intends to store hydrogen in one of Teréga's aquifers. By 2026, the project should be up and running [91]. Enagás is also investigating the feasibility of storing hydrogen in its aquifers. Given that both aquifers and depleted fields are porous rock formations, the successful demonstration of hydrogen storage in depleted fields demonstrates that it is also achievable in aquifers.

Water is a typical contaminant in gas stored in aquifers, hence gas drying infrastructure is an important aspect of the gas treatment process. Due to structural similarities, it is possible to convert natural gas-storage aquifers into hydrogen storage areas. A little amount of the methane cushion gas may occasionally be progressively purged using water in situations when there are active water drives.

It is anticipated that this method will be too sluggish in the majority of situations to be economically efficient. In addition to the hydrogen extracted from the aquifer, methane will also need to be slowly withdrawn from the aquifer over a period of years in modest volumes [91] [100].

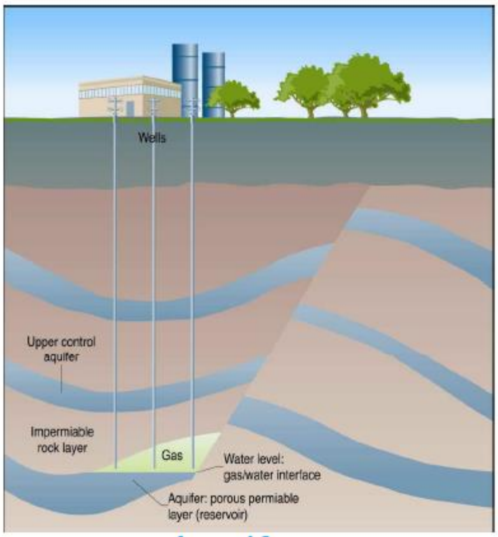


Figure 31:Aquifers [83]

4.5.4 Rock Caverns

The newest of four main underground storage types are hard rock caverns, made of caverns carved out of metamorphic or igneous rock, similar to salt caverns.
The cave walls are lined with steel or plastic after being first coated with concrete to make them smooth. In comparison to other constructions, hard rock caves may be operated at higher pressures. Due to their meticulous construction and lining, which eliminates the chance of contaminants. They may also go through a number of injection and withdrawal cycles annually, which makes them a good choice for peaking. Additionally, they use very less cushion gas.
at Svartöberget in Luleå, Sweden, SSAB, LKAB, and Vattenfall are opening the HYBRIT trial plant for fossil-free hydrogen gas storage. The storage facility in the rock cavern is the first of its sort in the world. The two-year test phase will begin with the inauguration ceremony and last until 2024. The "Hybrit" facility, measuring 100 cubic meters, will be constructed around 30 meters underground [101].

Hard rock caverns are probably ideal for storing hydrogen, but as they are expensive to create, they will probably only be used for peaking facilities in areas where there are no other storage choices.
Long-term hydrogen exposure to steel can result in hydrogen embrittlement, which is a possible problem for steel-lined caverns, so may be required to use different type of steel in high quality.The Figure 32 taken from first hard rock cavern at the world to store hydrogen [102] [103].

Figure 32: Rock cavern [80]

4.5.5 Storage in metal hydrides

Metal hydrides are composed of metal alloys that, like a sponge, absorb gaseous hydrogen. Under hydrogen pressure, solid metal hydrogen compounds are formed, and heat is produced as a result of a chemical process. When heat is added to the materials, such as when the tank is heated and the pressure is lowered, hydrogen is released. The surface absorbs the hydrogen molecule, which is subsequently broken down into individual, securely bonded hydrogen bonds. Alloying the metals reduces system weight while raising the temperature at which hydrogen may be recovered. When hydrogen is needed, it is extracted from the hydride at a certain temperature and pressure. This method can be performed indefinitely with no loss of storage capacity [104] .In principle, storing hydrogen in solid materials is a large-volume, safe (the release of hydrogen is exothermic thus, heat is necessary), and efficient storage method. The ease with which hydrogen may be recovered is critical, and this is represented in the material's dissociation pressure, which is temperature dependent.
However, the mechanics and thermodynamics of hydride formation from gaseous hydrogen must be better understood. Managing hydride kinetics and performance has proven to be a demanding issue, especially when these materials must demonstrate high hydrogen capacities and reversibility at temperatures ranging from 270 to 360 K and pressures ranging from 1 to 10 bar [105] [106], see Figure 33.
Metal hydrides are classed as follows: Interstitial metal hydrides have a poor reversible hydrogen absorption, with a storage capacity of 1.8wt% (percentage of hydrogen by weight) at 60–70oC [107] [108] or as high as 3wt% for quasi-crystalline Zr–Ti–Ni alloys. In the lab, activated magnesium-rich powders can reach up to 6 percent by weight at 260-280oC (at 1 bar), but their kinetics need to be improved using reasonably priced procedures. [109]
Complex light-metal hydrides (alanates and their isostructure counterparts) take up between 5 and 8 percent of their weight in hydrogen and release it gradually. Catalyzed hydride complexes are the hydride compounds with the best prospects (with Ti or Zr catalyst). Since they can achieve 5 weight percent at 180 C and 1 bar, lab-scale alanates are promising materials for hydrogen storage tanks, although lattice distortion can still be used to optimize the kinetics of hydrogen absorption and release [110] [111].

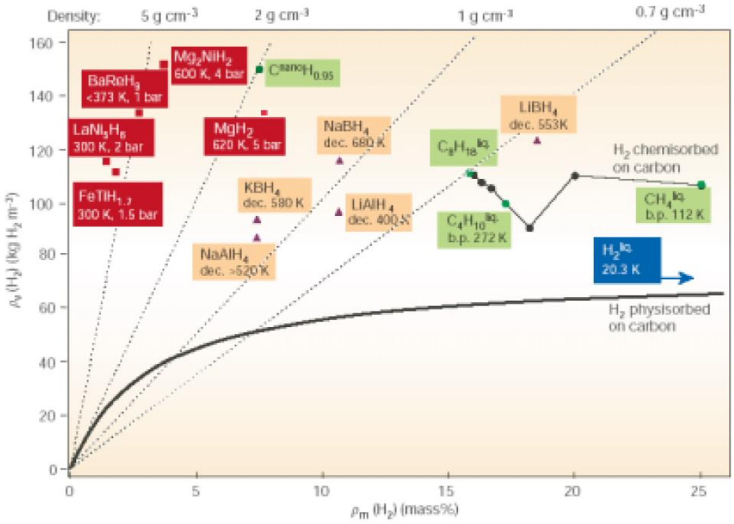


Figure 33:Hydrogen storage capacity (considering mass and volume) for metal hydrides, carbon nanotubes, petrol and other hydrocarbons[83]

Hydrogen storage capacity (in terms of mass and volume) for metal hydrides, carbon nanotubes, gasoline, and other hydrocarbons. It contains around 2400 hydrides that produce metals and alloys.
At this time, the studies indicate that systems based on reversible intermediate or low temperature compounds are promising [112] .However, inadequate hydrogenation/dehydrogenation rates, cyclic instability, and the requirement to operate at pressures of 60 to 150 bar and rather high temperatures exceeding 1500 °C continue to limit their performance [113] [114].

The important performance parameters of different energy storage technologies as PbAc , Li-ion , RFBs, CAES and PHS are efficiency, Capex and Opex see Table 3 for Compressed Air energy Storage .

Compressed Air Energy Storage
2020 & 2030 Cost & Performance Estimates

	Parameter	Units	100 MW				1,000 MW				10,000 MW			
			4 hr		10 hr		4 hr		10 hr		4 hr		10 hr	
			2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030
ESS Cost	Capital Cost Related to Turbine, Compressor, BOP, and EPC Mangement	$/kW	[1038 - 1268] 1153		[1038 - 1268] 1153		[955 - 1167] 1061		[955 - 1167] 1061		[878 - 1073] 976		[878 - 1073] 976	
ESS Cost	Cavern Capital Cost	$/kWh	[2 - 10] 3.66	[2 - 10] 3.09	[2 - 10] 3.66	[2 - 10] 3.09	[2 - 9] 3.37	[2 - 9] 2.85	[2 - 9] 3.37	[2 - 9] 2.85	[1 - 7] 3.10	[1 - 7] 2.62	[1 - 7] 3.10	[1 - 7] 3.00
	Total ESS Installed Cost*	$/kW	[1046 - 1308] $1,168	[1044 - 1302] $1,165	[1058 - 1368] $1,190	[1055 - 1353] $1,184	[962 - 1204] $1,074	[961 - 1198] $1,072	[973 - 1259] $1,094	[970 - 1245] $1,089	[885 - 1107] $988	[884 - 1102] $986	[895 - 1158] $1,007	[893 - 1145] $1,002
	Total ESS Installed Cost*	$/kWh	[261 - 327] $292	[261 - 326] $291	[106 - 137] $119	[105 - 135] $118	[241 - 301] $269	[240 - 299] $268	[97 - 126] $109	[97 - 124] $109	[221 - 277] $247	[221 - 276] $247	[90 - 116] $101	[89 - 115] $100
Operating Costs	Fixed O&M	$/kW-yr	[14.51 - 17.73] 16.12				[8.84 - 10.8] 9.82				[7.87 - 9.61] 8.74			
Operating Costs	Variable O&M	$/MWh	0.5125				0.5125				0.5125			
Operating Costs	System RTE Losses	$/kWh	0.0005				0.0005				0.0005			
Performance Metrics	Round Trip Efficiency	%	52%				52%				52%			
Performance Metrics	Response Time	sec												

Scenario	Response Time
Cold start to full generation	10 min
Online to full power	5 min
Full speed (no load) to full load	3.33 min
Offline to full load	4 min

	Parameter	Units	100 MW	1,000 MW	10,000 MW
Performance Metrics	Cycle Life	#	10,403	10,403	10,403
Performance Metrics	Calendar Life	yrs	30	30	30
Performance Metrics	Duration Corresponding to Cycle Life**	yrs	30	30	30

* Does not include decommissioning costs
** Assumes 80% depth of discharge, one cycle/day, and 5% downtime

Table 3:Compressed Air Energy Parameters [43]

5 Scenarios

one part of the KEROSyN100 project is the analysis of power grid and the duration of congestions is one parameter to assess the impact of a PtF plant on the power grid.

My work focuses on studying the electrolyser facilities and storage units on power grids with increasing RES within Schleswig-Holstein by using Linear power flow optimizations (LOPF), and study the effect on the grid to find suitable method to reduce the number of grid congestions occurs during transmission the electricity from RES to the load demands , At some locations high number of grid congestions happened .The modelling tool called Python for power system analysis (PyPSA) is using for analysis the whole network, first scenario without electrolyser and get result for different years in 2020,2030,2040 and 2050 and second scenario by adding electrolyser in the network to produce hydrogen ,then study the effect of it on the network and there are other scenarios by adding storages in the network as new battery or underground storage hydrogen. Finally, compare between results to find the suitable method to reduce number of grid congestions happens in the network. All of these scenarios have implemented in my project, and they will be introduced in next chapters.

The source of network data is electricity grid optimization (eGo), **eGo** is a tool designed and implemented as controlling, integrating, and evaluating software and an interface between the calculations of eDisGo and eTraGo [115] .**eDisGo**, a toolbox capable of assessing distribution grids for grid problems and evaluating strategies to address them [116].**eTraGo** uses an open data network model for the technical and economical optimization of transmission network and storages expansion in Germany at the extra-high voltage (EHV) and high voltage (HV) levels (380, 220, and 110 kV levels) [117]. **PyPSA** tool is used by the eTraGo tool for optimizing network and storage expansion at the extra-high and high-voltage levels. In this case, linear power flow optimization (LOPF), The pypsa Network is an overall container for all network components, The bus is the fundamental node to which all loads, generators, storage units, lines, transformers and links attach. Their mathematical responsibility is to ensure that energy conservation is always followed on the bus (essentially Kirchhoff's Current Law). A bus's power balance is determined by the connections between its loads, generators, storage containers, stores, and shunt impedances, the power of loads is constant [118] .

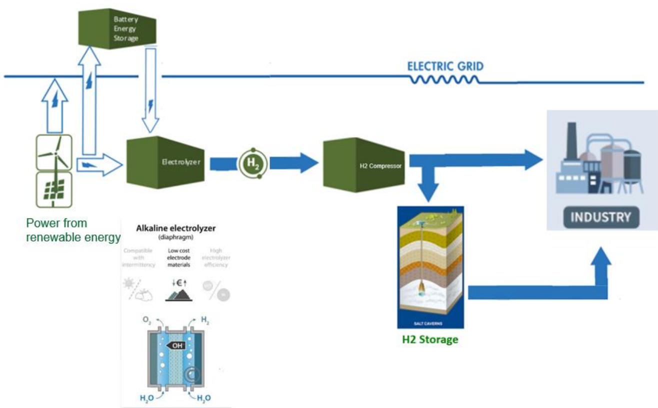


Figure 34:process of converting elec. to hydrogen (PtH) *[119]*

The process of converting electricity to store energy or use it in industries has become so popular in recent years. As shown as in Figure 34 , RES generate power and it is possibility to store some of power in Batteries to use it later (when the electricity source is not available) and it connects also directly to electrolyser and the electrolyser uses that energy to split water into oxygen and hydrogen , because of the hydrogen output of alkaline electrolysis has low pressure around (20 bar - 30 bar) [120],so it is necessary to use compressor it to be able to store at Underground storage called **salt cavern** [69] [121].The majority of caves in Northern Germany are 500 - 2500 m deep, with widths of 50 to 100 m and heights of 100 to 500 m. It is important to note that approximately one-third of the total volume is required as a buffer gas to maintain the cavern's integrity, while the other two-thirds are working hydrogen gas for storage operations [122] . we achieve the hydrogen demand for industries in accordance with Germany's overall target (188 tonnes hourly in 2020, 308.5-378 tonnes hourly in 2030, 380-1030 tonnes hourly in 2040, 1371 tonnes hourly in 2050) [123], my project focuses only on Schleswig Holstein grid, since no concrete data available, so i have assumed that industries in Schleswig Holstein use 0.01 % share of total hydrogen demand in Germany.

The georeferenced grid is from 2016. The other data (supply/demand/cost) are from 2018 and, hence, are quite up-to-data. This data should not be big difference between 2018 and 2020 so we use the same data for our Model at year 2020, according to different years at Future Germany’s target, RES will increase, so the power capacity is forecast to rise. This optimization is running for one single year over 8760 hours [86].Table 4 includes the parameters of my project for each scenario depends on what are the requirements for each scenario.

All my calculations depend on annual full load hours on renewable energy sources, so renewable energy sources operate 5000 hours per year ,because they need maintenance and sometimes require shutting them down, so also other equipment as electrolyser and compressor operate 5000 hours per year that require to convert electricity to hydrogen then store the hydrogen in underground storage as salt cavern or use it in industries.

Parameters	
Grid Data	eGo Data
Battery	Lithium- ion Battery
	Life time = 10 years
	Efficiency = 80 %
Electrolyzer	Alkaline Water Electrolyzer
	Capacity :100 MW
	Life time = 60000 Hours = 7 years
	Efficiency = 75 %
Compressor	Reciprocating Compressor
	Life time = 12 years
	Efficiency = 75 %
H2 Storage	Salt Cavern
	Capacity: 50 tpd-H2
	Depth : 800 m
	Volume : 80000 m3
	Life time : 30 years
H2 Demand	2020 : 188 tonnes hourly 2030 : 308.5 -378 tonnes hourly 2040 : 380 - 1030 tonnes hourly 2050: 1371 tonnes hourly– 2742.5 tonnes hourly

Table 4:Parameters of my Project

At my work, PyPSA tool will be used and it is the main tool that uses for modelling the input eGo data, the aim of modelling by PyPSA to minimize the total system costs which include CAPEX and OPEX of generation, storage, and transmission, given technical and physical constraints [118].eGo data is the electrical grid consists of generation, transformers, transmission and distribution lines and storage units [124] and PyPSA tool uses to read the component data in network from csv files, each components has specific parameters that required to run modelling.These parameters could be modified depend on our requirements [118].it is possibility to add new components and set parameters for them as example for eGo data has no values of generators, so I have done lots of research to get the actual cost of each generator at 2020,2030,2040,2050 and also I have increased the power nominal of renewable energy sources in eGo data regarding to each year and for different Scenarios ,to convert electricity to hydrogen require to add new component as electrolyser , also for storing electricity at the location of project require to add extra new lithium-ion battery and also for storing hydrogen require to add compressor and underground storage hydrogen, each of them needs to specify the parameters depend on the requirement of the project and my research to find suitable parameters for them .

PyPSA uses a LOPF module to optimize the distribution of generation and storage as well as the capacities of the infrastructure for generation, storage, and transmission. It is assumed that the load is inelastic and needs to be satisfied at every snapshot [118].Final results obtained by Gurobi solver.

As the target of Germany in context of the energy transition is the increase of RES in the system, I investigated four target years with appropriate RES share (see Table 5), and also regarding to IRENA Research that Germany’s target in 2020 to use 35 percentage share of renewable energy , in 2030 to use 55 percentage share of renewable energy , in 2040 to use 65 percentage share of renewable energy and in 2050 to use 80 percentage share of renewable energy [125].

	2011	2012	2013	2014	2020	2030	2030	2040	2050
	Achievements				German target		REmap results	German target	
Greenhouse gas emissions									
Greenhouse gas emissions (base year = 1990)	-25.6%	-24.7%	-24.1%	-27.0%	min. -40%	min. -55%	-55%[1]	min. -70%	min. -80-95%
Renewable energy									
Share of renewable electricity	20.4%	23.7%	25.4%	27.4%	min. 35%	min. 55%	65%	min. 65%	min. 80%
Share of renewable energy in gross final energy	11.8%	12.8%	13.1%	13.5%	18%	30%	37%	45%	60%
Energy efficiency									
Primary energy demand (base year = 2008)	-5.4%	-6.5%	-7.3%	-8.6%	-20%		-30%[2]		-50%
Power demand (base year = 2008)	-1.8%	-1.8%	-2.4%	-4.6%	-10%		-[3]		-25%
Electricity share from CHP	17.7%	18.0%	17.8%	17.3%	25%		21%		
Energy productivity improvement rate	1.7%	1.2%	1.4%	1.6%	2.1%		2.5%		
Time frame	2008-2011	2008-2012	2008-2013	2008-2014	2008-2050		2010-2030		

Table 5:Short-, medium- and long-term targets of Germany Energiewende, and REmap results [119]

The increasing of RES and consequent injection of fluctuating power to the grid and also with increasing total hydrogen demand from industry is expected to expand over 500 TWh a year by 2050 [126],and probably number of grid congestions occurs will be increased so it is necessary to study first the causes of grid congestions to get the suitable method to reduce it .

According to the Statistics Office North, in 2018, 22.6 million megawatt hours (MWh) of electricity were generated from renewable energies in Schleswig-Holstein. There is 60.3 percentage of the total electricity production. Mathematically, the power consumption in Schleswig-Holstein (around 14.7 million MWh) [127] ,and also regarding to the input data from eGo project at year 2018 in Schleswig Holstein includes 73.57 percentage share of renewable energy and 26.43 percentage share of conventional energy, after run optimization of eGo data, it reaches more than 90 percentage share of renewable energy starts from 2030 till 2050 ,see Figure 35 and Figure 36 .

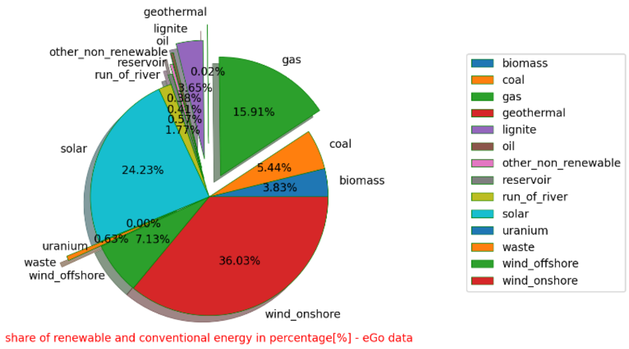


Figure 35 : share of renewable and conventional energy in percentage (%) -eGo data

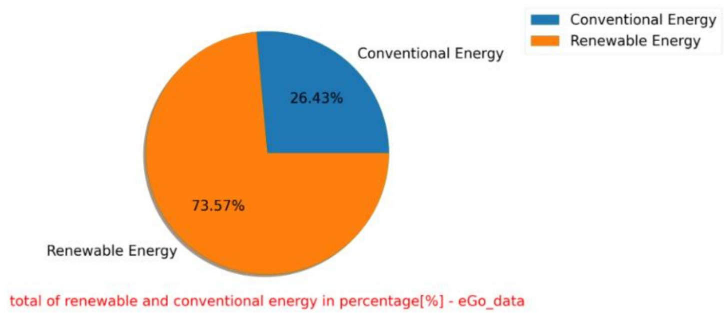


Figure 36:total of renewable and conventional energy in percentage (%)-eGo data

Regarding to IRENA Research at Table 5 that Germany's target in 2020 to use 35 percentage share of renewable energy , in 2030 to use 55 percentage share of renewable energy , in 2040 to use 65 percentage share of renewable energy and in 2050 to use 80 percentage share of renewable energy [125],and in Real Grid, RES generate around 60 percentage share of renewable energies, after considering losses will decrease to 35 till 40 as IRENA Research as shown at Table 5 ,so at my work the constraints are used to increase RES until the desired amount to guarantee minimal share of renewables as IRENA Research.

According to PyPSA's documentation, before running optimization of the model, it is necessary to use load shedding, it means to add generators with a prohibitively high marginal cost to simulate load shedding and avoid problem infeasibilities, that happens due to the demand cannot be met at certain times ,so the original data of generators includes currently extra load shedding with high marginal costs, my model is able to use loadshedding ,in case has no other generator sources to achieve the load demand [128] [129].

As increasing RES, my work focuses on modelling the grid to use more RES and less conventional energy. There are challenging between different RES especially wind onshore and solar because sun and wind are free, both has big advantage to use. After optimization at year 2020, most power capacities are divided into 61.12 percentage of RES and 38.88 percentage of conventional energy as shown as in Figure 37 .Then after optimization at year

2030 , power capacities of RES increase up to 90 percentage as shown as in Figure 39 and Figure 40 ,because solar has the lowest capital and marginal cost in generators data so it uses more than others generators .My expectation after optimization that both of solar and wind will share of RES between of them but the result of modelling show that most of share RES is solar but wind has a few share of RES because wind has high capital and marginal cost more than solar so the modelling prefers to use only solar , and at the period that no sun ,that solar does not produce energy ,so it is possibility that storage has enough energy to fulfill the load demand . It is important to mention also, that the weather data does not include in my modelling, but I have provided the modelling with data that include the max. generating power at hourly during the whole year for all generators, as example when no sunshine, power maximum at this period of time equal zero for solar generator.

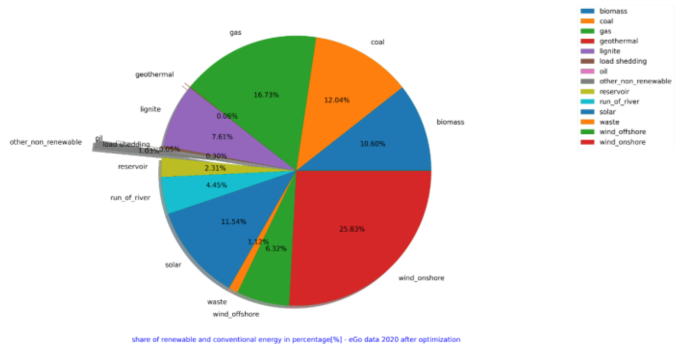


Figure 38:share of renewable and conventional energy in percentage (%) -eGo data 2020 after optimization

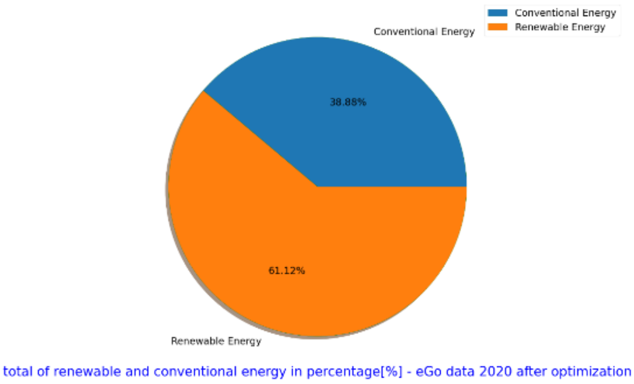


Figure 37:total share of renewable and conventional energy in percentage (%) -eGo data 2020 after optimization

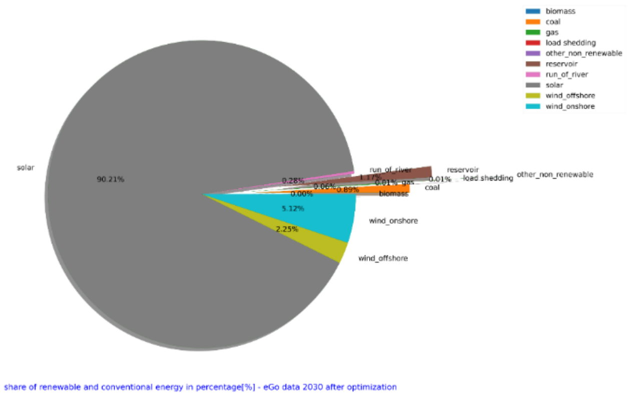


Figure 40:share of renewable and conventional energy in percentage (%) -eGo data 2030 after optimization

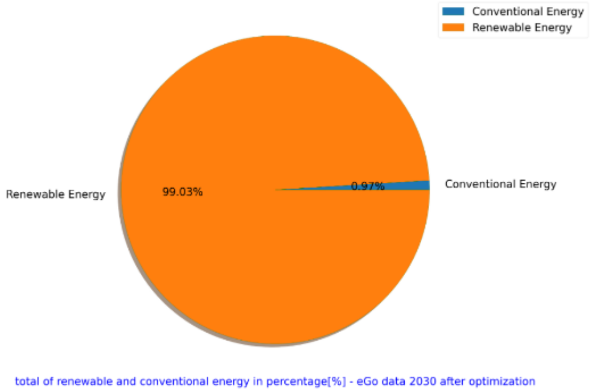


Figure 39:total share of renewable and conventional energy in percentage (%) -eGo data 2030 after optimization

the output in year 2040 - 2050 as shown as in Figure 41 , Figure 42, Figure 43 and Figure 44, these Figures show that high share of RES is solar and it reaches till 93 percentage because that solar has lower capital and marginal cost, so my model prefers to use solar more than any other generators and at the period that no sun, that solar does not produce energy ,so it is possibility storage has enough energy to fulfill the load demand .

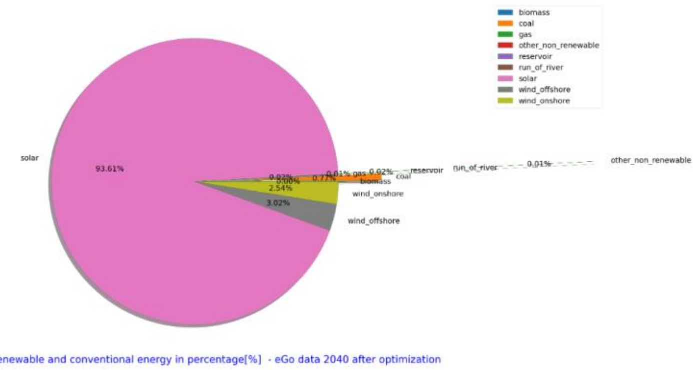


Figure 41:share of renewable and conventional energy in percentage (%) -eGo data 2040 after optimization

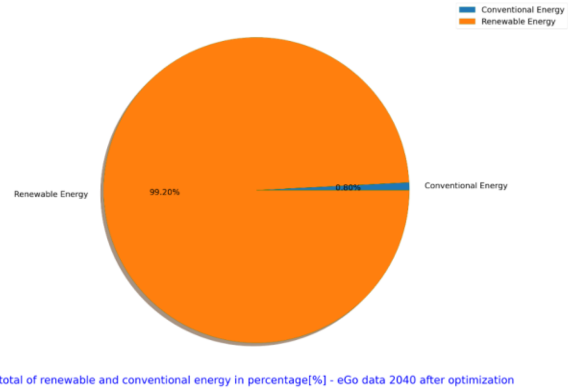


Figure 42:total share of renewable and conventional energy in percentage (%) -eGo data 2040 after optimization

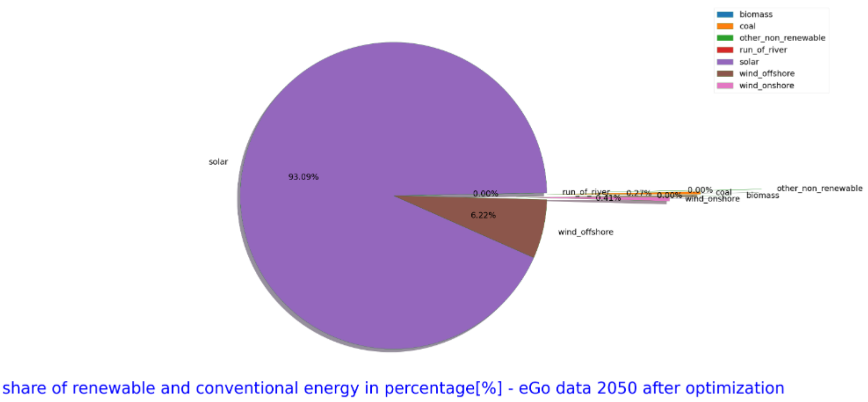


Figure 43:share of renewable and conventional energy in percentage (%) -eGo data 2050 after optimization

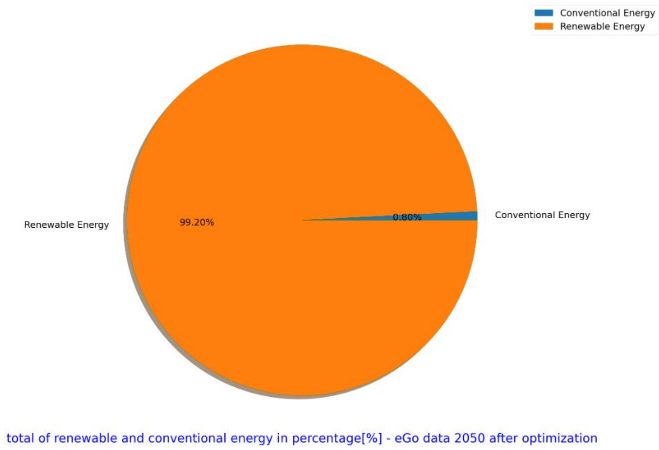


Figure 44:total share of renewable and conventional energy in percentage(%) -eGo data 2050 after optimization

5.1 Scenarios including hydrogen sector

Modeling sector coupling focuses on how it affects the electrical grid, so we design four scenarios with extension of renewable energies to study the effect on the power grid, especially number of Grid congestion and compare between each scenario.

- First Scenario: The Grid model couples to electrolyser and both storages (Underground hydrogen storage – Battery storage) to supply hydrogen industry demand.
- Second Scenario: The Grid model couples to electrolyser and battery storage to supply hydrogen industry demand.
- Third Scenario: The Grid model couples to electrolyser and Underground Hydrogen storage to supply hydrogen industry demand.
- Fourth Scenario: The Grid model couples to electrolyser to supply hydrogen industry demand.

I have assumed that the target of green hydrogen in Schleswig Holstein is 0.01 % of the total green hydrogen demand in Germany, because the modelling by PyPSA has not found any solution when i considered more demand of green hydrogen. I believe, because that the production of renewable energy were not enough to fulfil the load demand.

5.2 Grid Congestion

The rising amount of power generated from RES is challenging how electrical grid work. While Conventional power plants used to be near to major demand centers, a large portion of the RES capacity developed in recent years is situated distant from areas of strong demand. With a strong growth of RES leads to grid congestion that affects both the transmission and distribution levels see Figure 45,it shows that based on certain forecasts at specific moments in time there is no capacity, so it is necessary that grid operators keep the network within operating limits while increasing the share of RES [131].

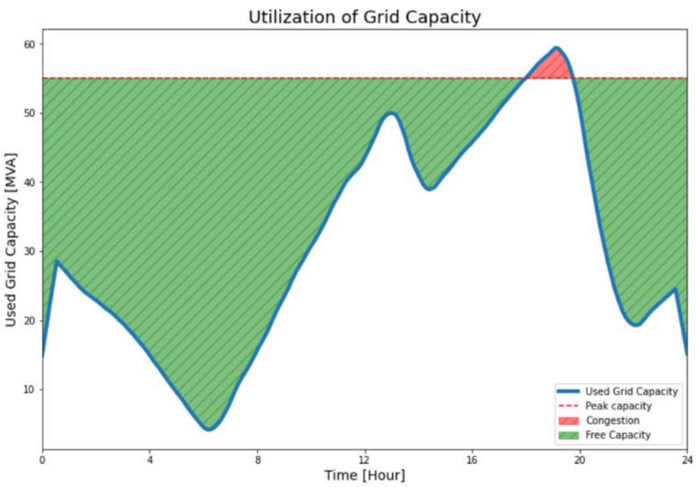


Figure 45:Congestions in the electricity grid [131]

Grid congestion happens when the demand for transmission more than the capability for transmitting power. Excessive grid loads can lead to grid infrastructure failure or damage, which would restrict generating units from feeding in or supplying consumers [130] [131]. Grid congestions forces curtailment since it is not possible for the grid to grow as quickly as the capacity for distributed renewable energy, and network congestion needs to measure to avoid overloading network assets. The curtailment due to Grid Congestion increased recently in Schleswig Holstein see Figure 46, and curtailment refers to where the output of RES is reduced to a level below its maximum generation capacity [132] .

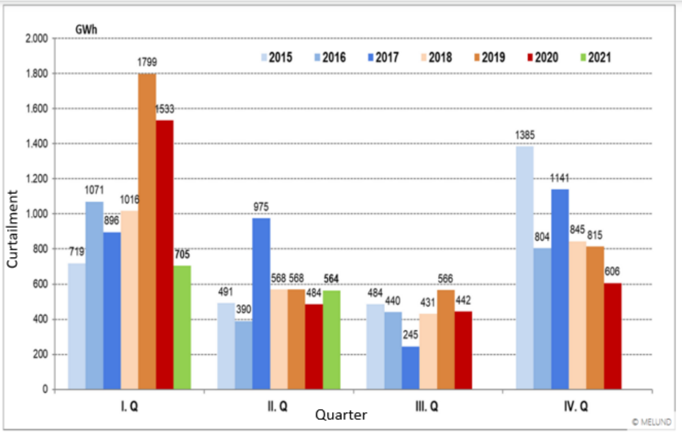


Figure 46:Curtailment of renewable electricity in Schleswig-Holstein (quarterly values) Q1-2 20121 37% [149]. Q1: 1 January – 31 March Q2: 1 April – 30 June

so, we need to use Energy storage that enables excess electricity causing congestion to be stored during periods of strong RES output. Later, when the overloaded network situation relaxed, the power that has been stored can be released and transmit to the load demands [133] [134].

The goal of my work to analysis the grid congestion and find the best solution to reduce the grid congestion by applying different scenarios and I will declare the methods in detail at next Sub-chapter.

5.3 Results and Analysis

The aim of my project to find the suitable method to decrease number of congestions and prevent overloading of lines by implementing each scenario and discuss the result in detail.

As results of my modeling for different scenarios that describe the changes of no. grid congestions due to fluctuation of the power production and storage units and load demand during 24 hours at one day, due to many research the grid congestion occurs in two situations ,the first situation when there are lots of power production and low demand and the second situation when high load demand and low power production to meet the load .

5.3.1 Curtailment and Congestions

As according of many research that grid congestion causes curtailment [90] [135], most of curtailment are wasted so it is necessary to calculate the curtailment of the actual data, and find the best method to reduce grid congestion and consequently reduce curtailment.

RES as solar and wind have no marginal costs due to the fact that they generate when their cost-less fuel source , the sun and wind is available. [136] So, it is necessary to mention that the marginal cost of wind generators is a little higher to have wind curtailed before solar, according to PyPSA documentation .

The next function that I have used for calculating the curtailment of power generation of grid in Schleswig Holstein:

curtailment = (network. generators_t.p_max_pu* network.generators.p_nom_opt) - network.generators_t.p

As shown as in Figure 47 , Figure 48 , Figure 49 and Figure 50 that the output of reference scenario with extension of renewable energies 35 percentage and 55 percentage shows the changes of curtailment during the whole year (starting from January 2018 till end of December 2018) on x-axis with histogram to visualize the distribution of the curtailment, and these Figures show that there are lots of Curtailment at the beginning of year till the middle of year and it is happened due to high RES production and also because of increasing no. of Grid Congestions till the middle of year as expected.

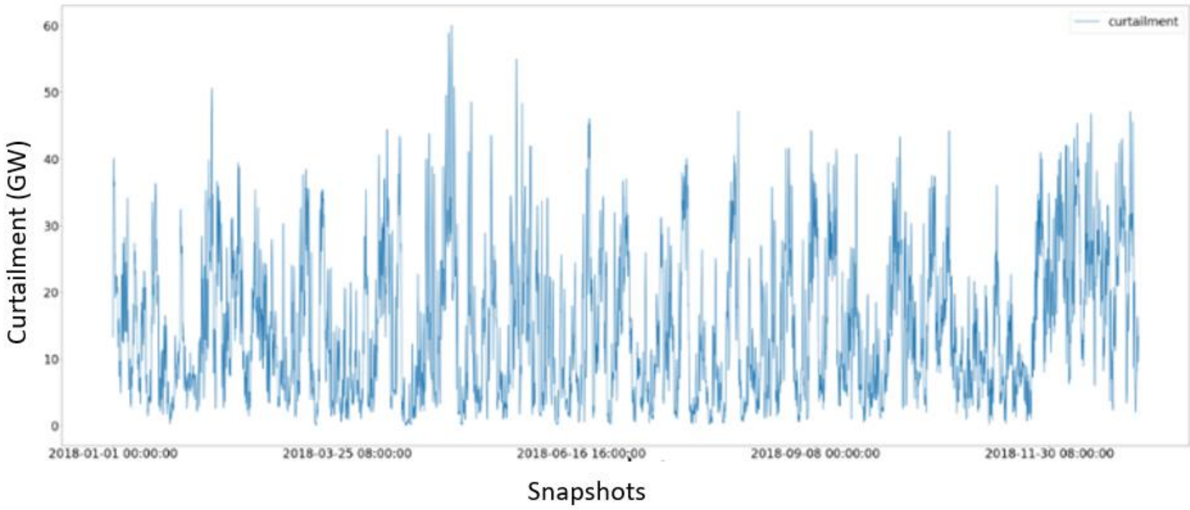


Figure 47:Curtailment when renewable energy 35% of total renewable energy

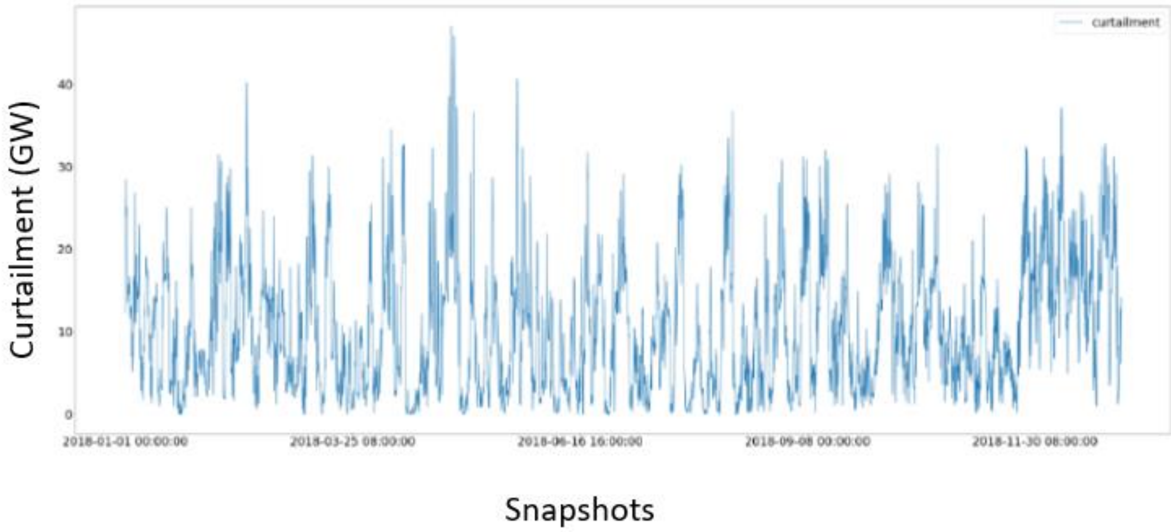


Figure 48:Curtailment when renewable energy 55% of total renewable energy

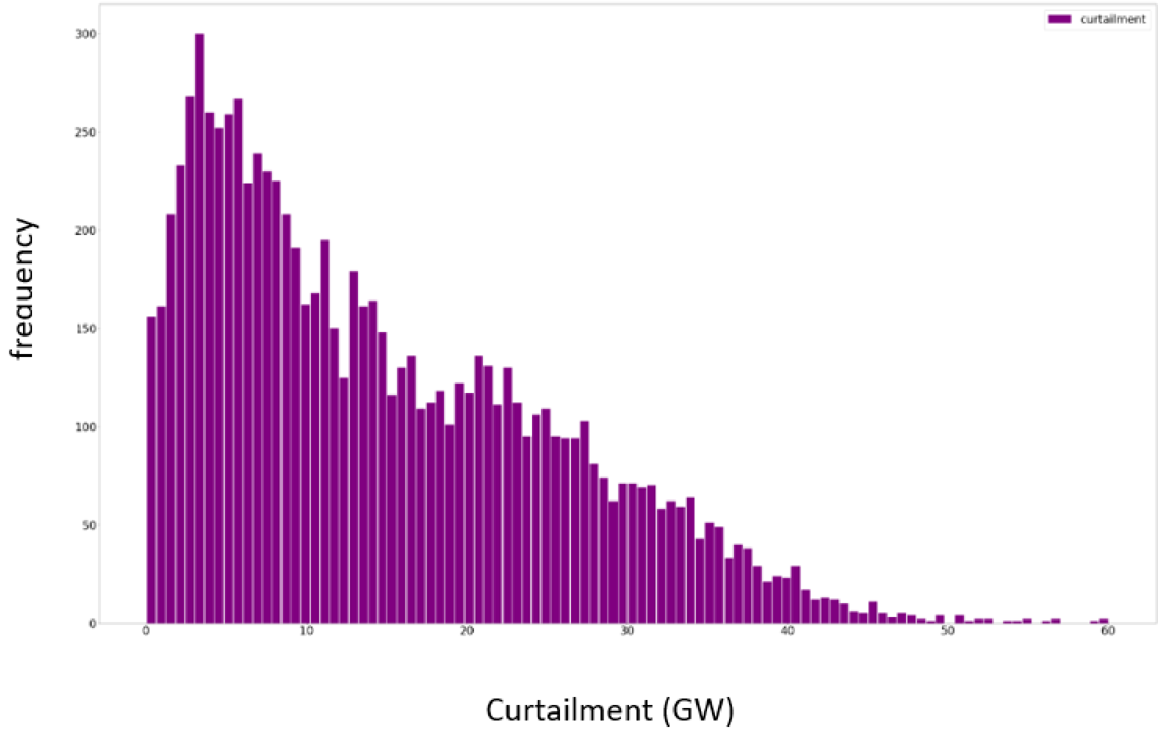


Figure 49:Curtailment when renewable energy 35% of total renewable energy (Histogram)

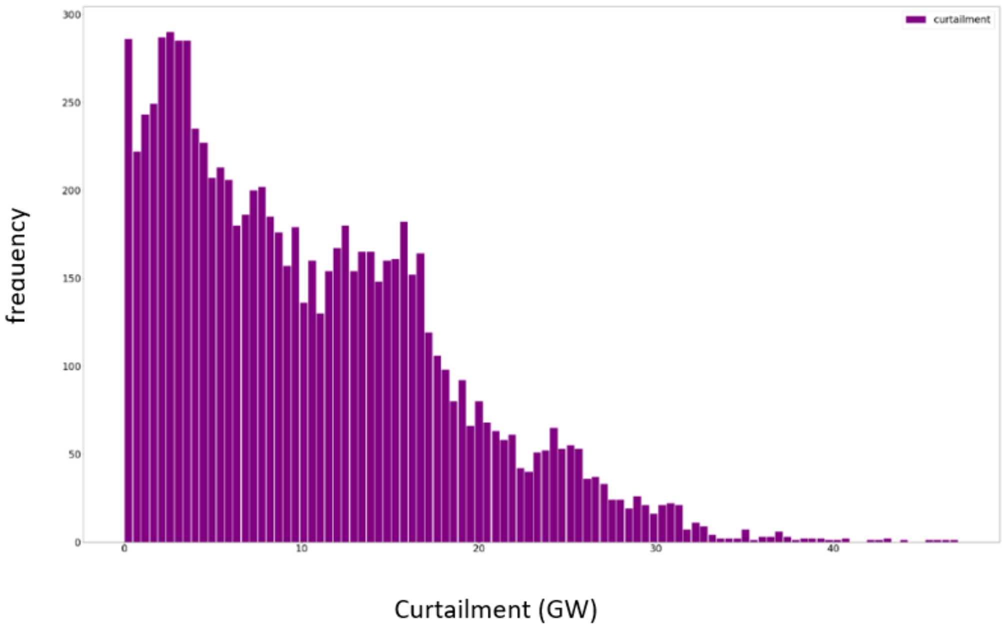


Figure 50:Curtailment when renewable energy 55% of total renewable energy (Histogram)

as shown as in Figure 51, Figure 52, Figure 53 and Figure 54 that the output of ref. scenario with extension of renewable energies 65 percentage and 80 percentage shows the changes of curtailment during the whole year (starting from January 2018 till end of December 2018) with histogram to visualize the distribution of the curtailment , and these Figures show that there are lots of Curtailment at the beginning of year till the middle of year and it is happened due to high RES production and also because of increasing no. of Grid Congestions till the middle of year as expected.

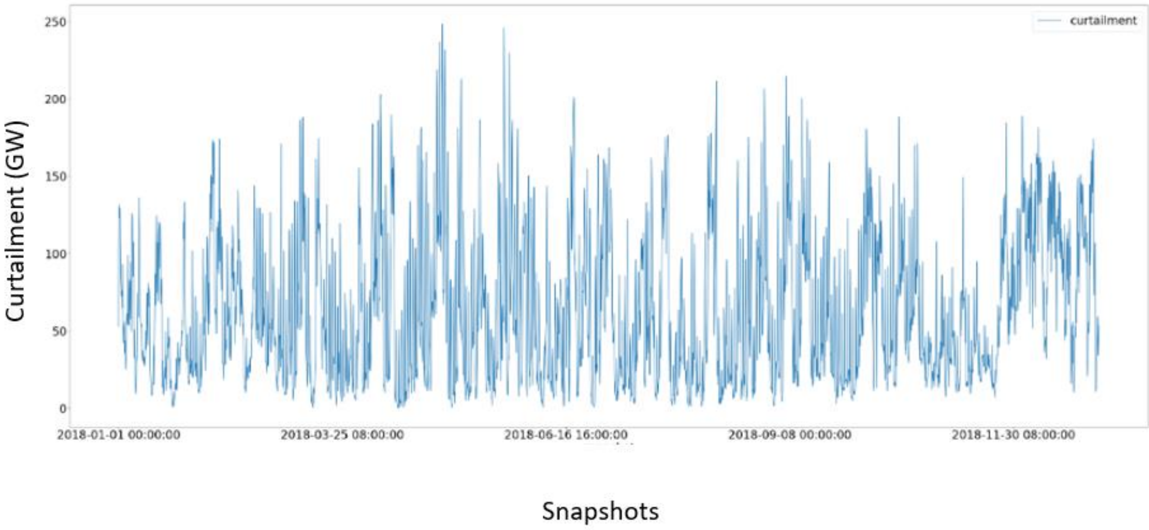


Figure 51:Curtailment when renewable energy 65% of total renewable energy

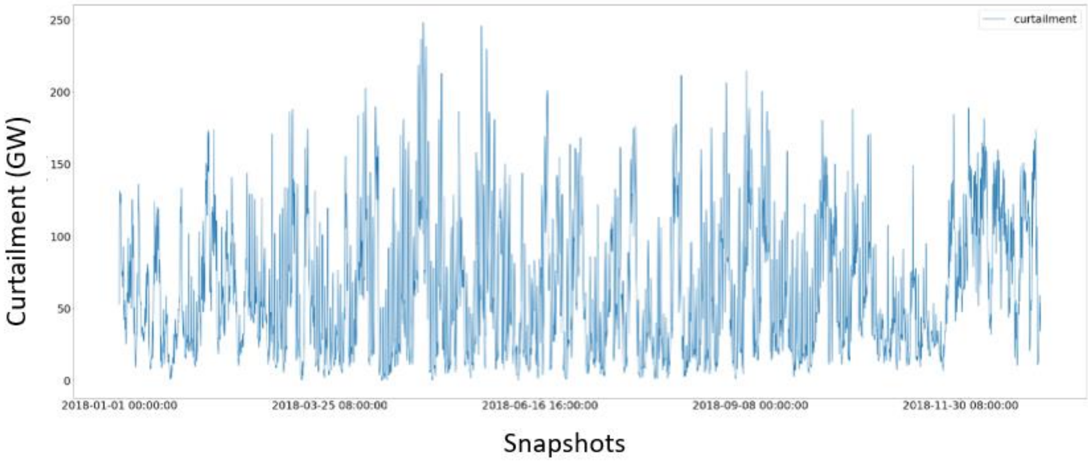


Figure 52:Curtailment when renewable energy 80% of total renewable energy

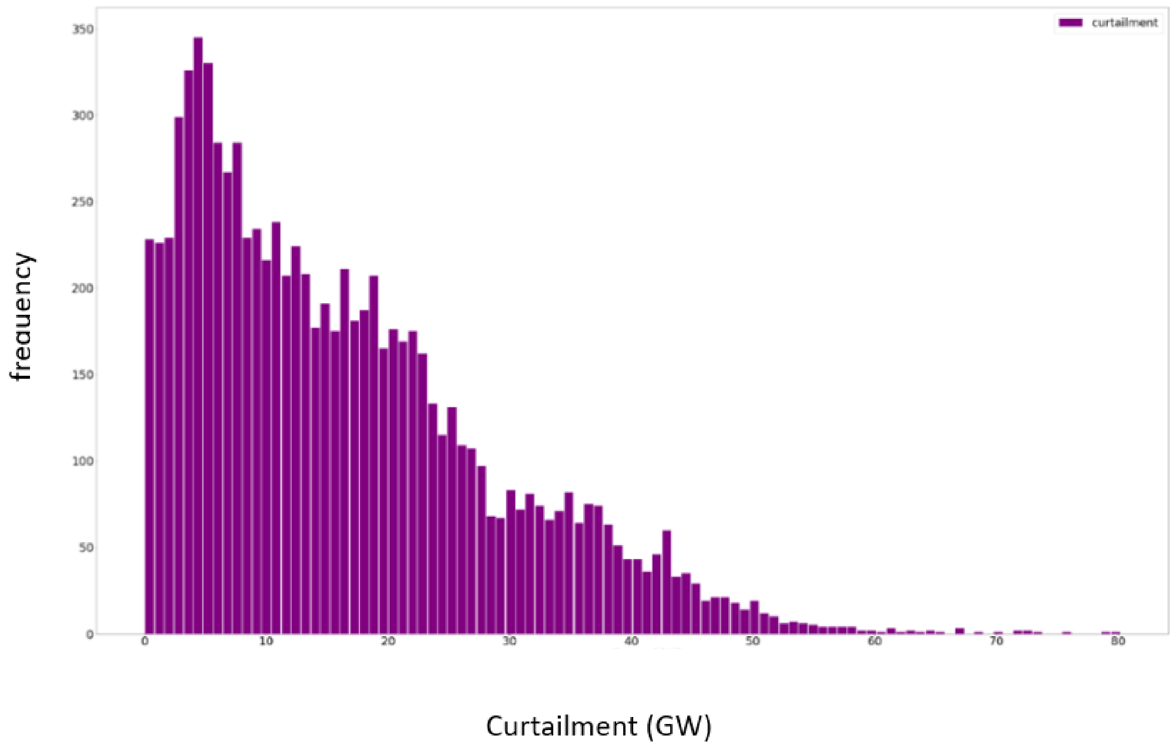


Figure 53:Curtailment when renewable energy 65% of total renewable energy (Histogram)

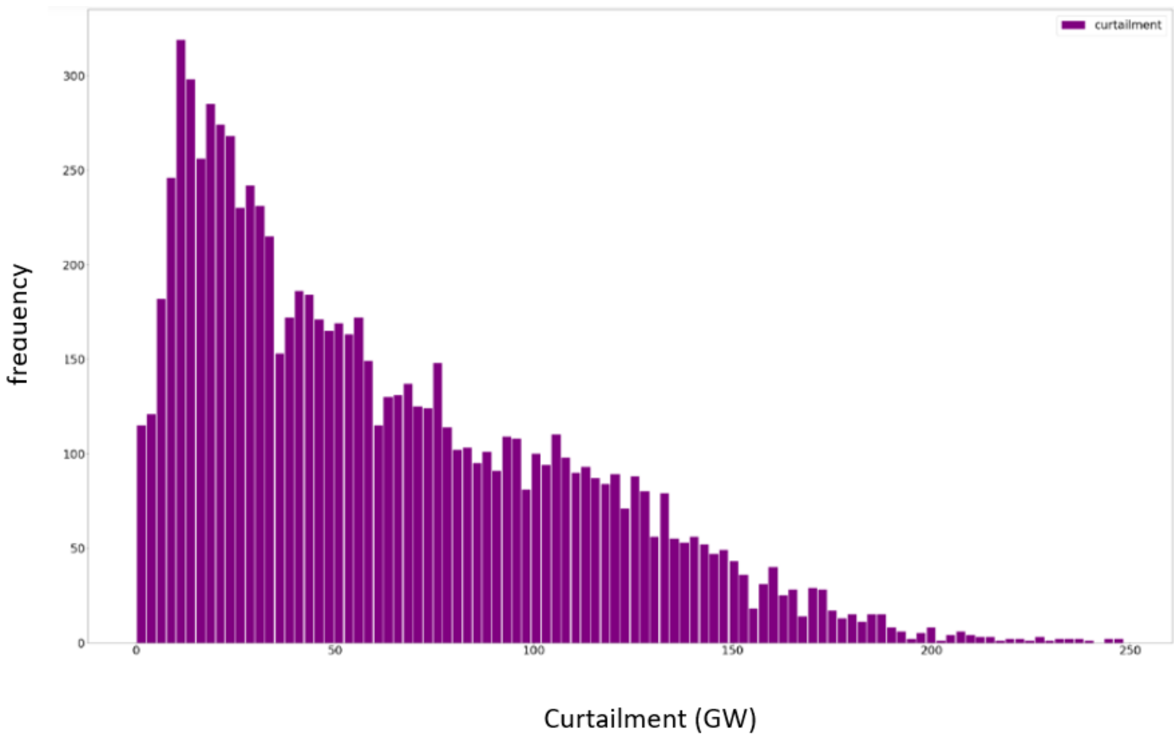


Figure 54:Curtailment when renewable energy 80% of total renewable energy

For reference scenario, by summing all curtailed data during the whole year, so the result will be 0.12 865 GW, and the total power production of renewable energy and conventional energy is 0.28015 G W, so the curtailment of electricity is 0.459 %, around half of total production of energy sources. I ha ve found in other scenarios almost has similar the same amount of curtailment as mentioned above ar ound the half of total production of RES and in fact, one of main factor causes curtailment is the grid congestion, so my work focuses to find a suitable solution for grid congestion, by applying different s cenarios to prevent overloading of transmission and distribution lines and consequently reducing the curtailment of energy sources.

Grid congestion of reference scenario over the whole year are plotted with extensions of renewable energies (35 percentage and also 55 percentage), as shown in Figure 55, Figure 56 , Figure 57 and Figure 58.These Figures show that there no. of congestions happened during the whole year and for a certain period of time has high no. of congestions caused curtailment and my work to decrease occurring grid congestion .

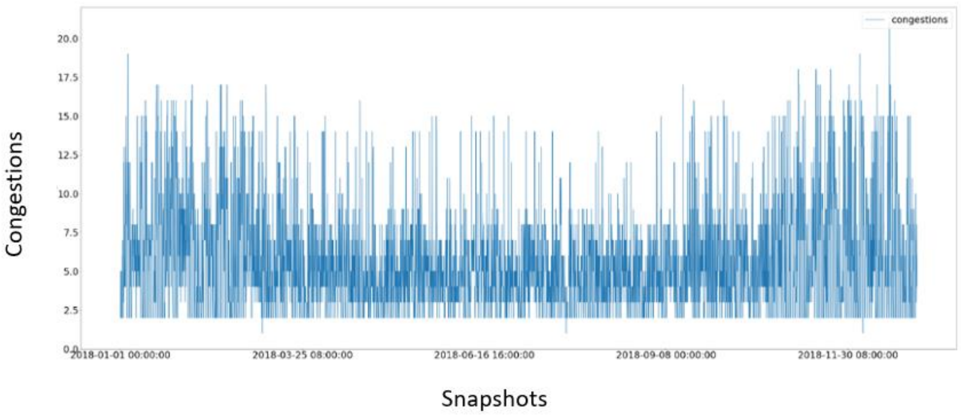


Figure 55:congestion when renewable energy 35% of total renewable energy

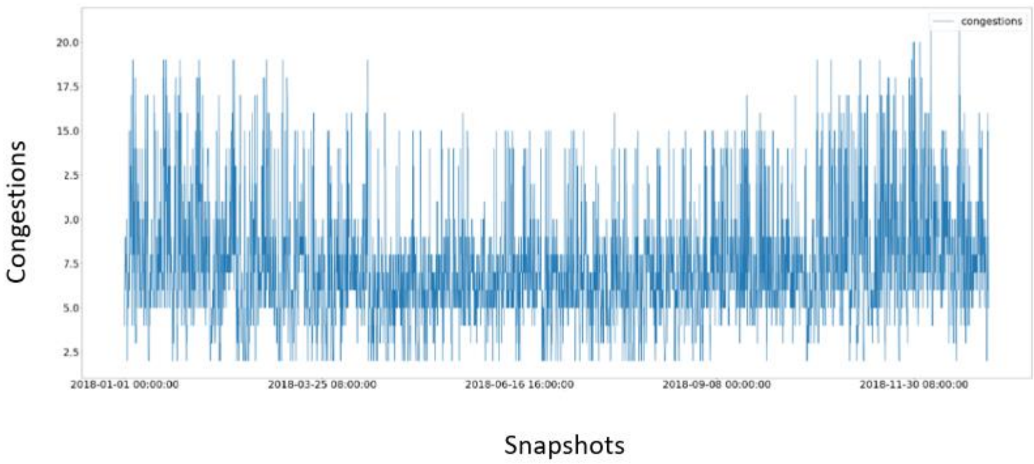


Figure 56:congestion when renewable energy 55% of total renewable energy

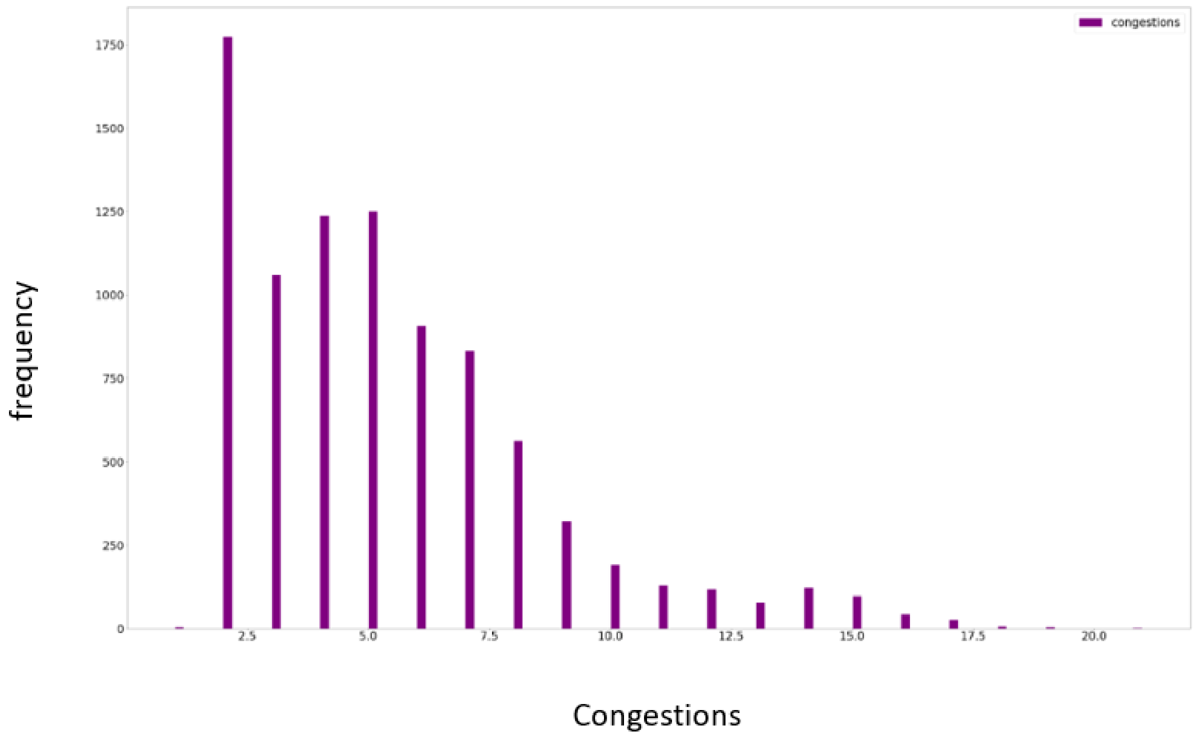


Figure 57:congestion when renewable energy 35% of total renewable energy (Histogram)

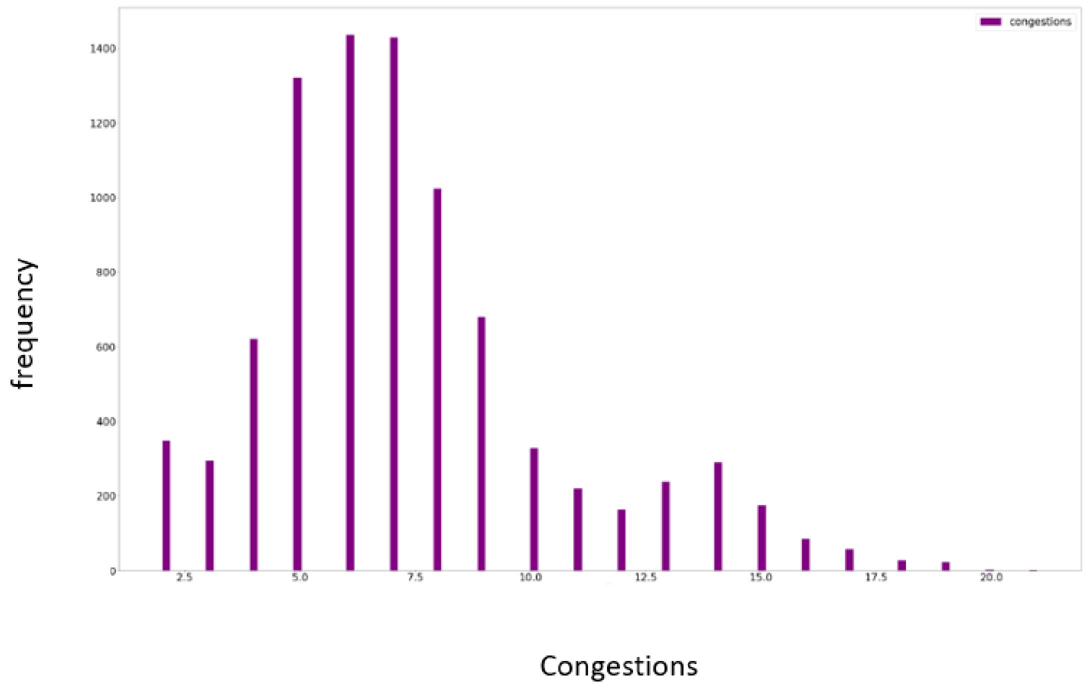


Figure 58:congestion when renewable energy 55% of total renewable energy (Histogram)

Grid congestion of reference scenario over the whole year are plotted with extensions of renewable energies (65 percentage and also 80 percentage), as shown below in Figure 59, Figure 60 ,Figure 61 and Figure 62. These Figures show that there are no. of congestions happened during the whole year and for a certain period of time has high no. of congestions caused curtailment my work to decrease occurring grid congestion.

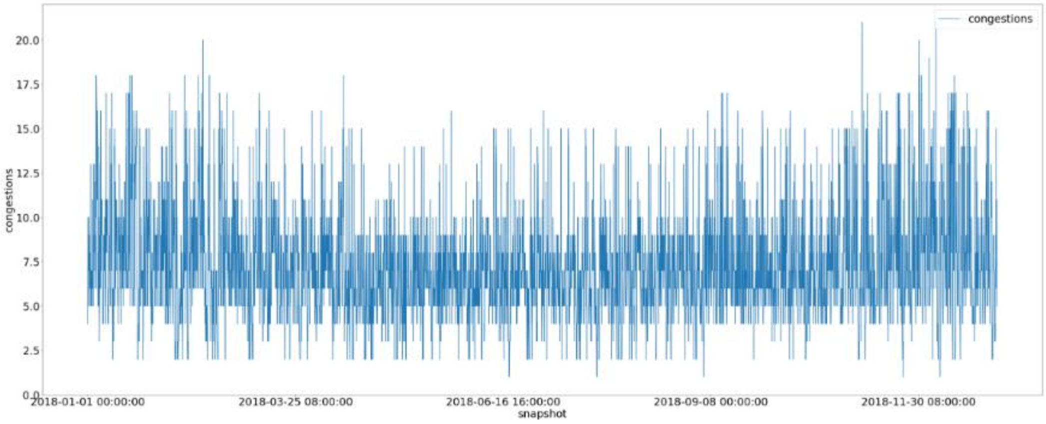


Figure 59: congestion when renewable energy 65% of total renewable energy

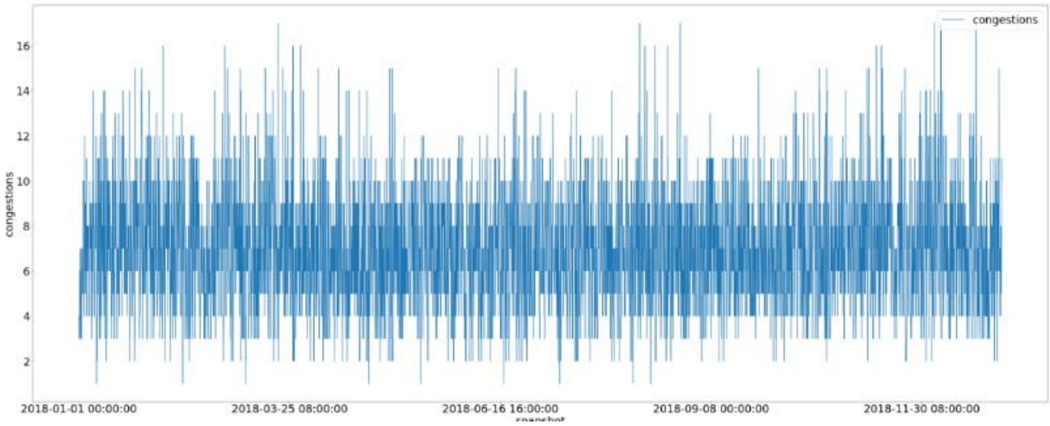


Figure 60: congestion when renewable energy 80% of total renewable energy

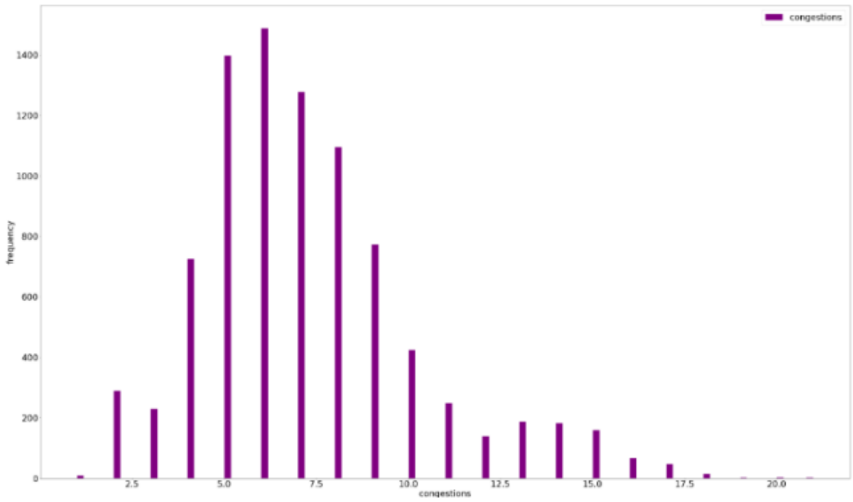


Figure 61: congestion when renewable energy 65% of total renewable energy (Histogram)

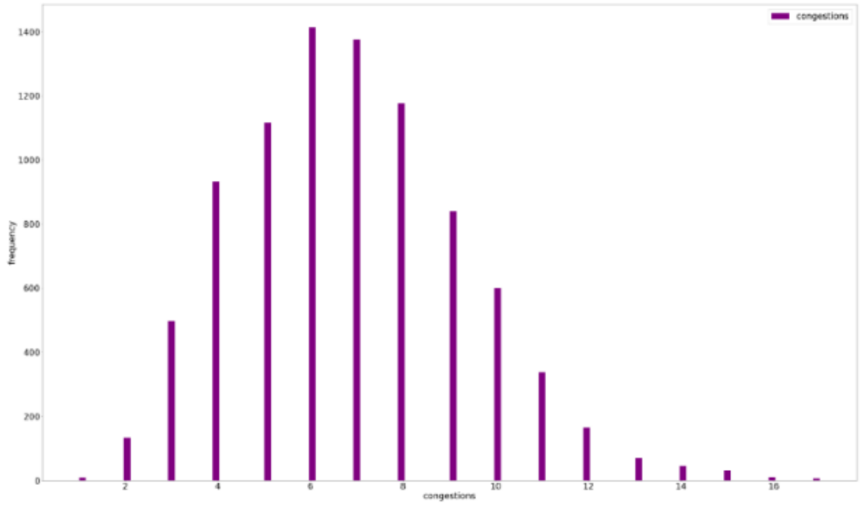


Figure 62: congestion when renewable energy 80% of total renewable energy (Histogram)

5.3.2 Storage Units and Congestions

As I have discussed before that there is eGo input data as a reference scenario and I have also applied four scenarios with extension of renewable energy to study the effect on the power grid, especially number of Grid congestion.

As many recent research that describe to reduce grid congestion by transmission lines expansions and also other method by adding renewable energy storage technologies [137] as

1. Battery storage 2. Thermal storage 3. Mechanical storage 4. Pumped hydro 5. Hydrogen

But because of expansion of transmission lines is costly so we will focus on finding a suitable solution by adding renewable energy storage technologies.

As the share of renewable energy increases, utilities are more concerned about its "intermittency" on the grid. In other words, weather variations mean that their supply is not always predictable. Energy storage helps to overcome this problem by storing surplus energy produced by renewable energy sources so that it may be used later and minimize its dependence on fossil fuels such as oil and coal [138] [139].

There are two methods of storing renewable energy in PyPSA model:

1. Storage units. 2.Stores.

Both are attaching to a Single Bus. Each storage unit has variables efficiency and a state of charge that changes over time. A fixed ratio max hour of the nominal power is used to represent the nominal energy, but to control and optimize the storage energy capacity independently from the storage power capacity, it should use the store component with two Link components, one for charging and one for discharging.

According to the requirements of my project, that I have to do modelling of reference scenario by using storages as input of storage units and no need to add any additional storage by the store components, so no controlling of storage of renewable energy sources.

But for other scenarios, I am using the same eGo storage units data and adding battery lithium-ion storage for storing electricity as at the second scenario or underground storage for storing hydrogen as the third scenario or both storages as the first scenario.

The battery added as extra storage in storage units without any controlling but with max_hours = 4 hours and nominal power = 48 MW at the same location of my project in Heide and the underground storage is added directly at the electrolyser location as store components for storing hydrogen with more capability for controlling and optimization.

it is important to discuss the effect of charging of storage units on no. of Congestions in different seasons as shown as in Figure 63, Figure 64, Figure 65 and Figure 66 that show the relation and effect of storage units on congestion in different months during the whole year for reference scenario .

As shown in Figure 63 , during the first two weeks in January that increasing charging of storage units then consequently decreasing occur no. of congestions but as shown in 15 January, in case of the charging of storage units is lower so no. of congestions are higher , and it agrees with the expectations regarding to lots of researches that charging storage units participate in grid balancing and also decrease no. of grid congestions [7] and the same expectations happened also at different season in April, August, December as shown as in Figure 64 , Figure 65 and Figure 66 . Storage units are responsible for balancing between supply and demand and also have impact on grid congestion so my observation from my result, since storage units are empty and unable to supply any more energy, so congestions increase then storage units have a big impact on grid congestions.

It is necessary to run the simulation in the absence of storage units to check the grid congestions. First simulation without storage units, Second simulation include storage units .The second simulation ,I have already done it and the result shown in Figure 63, Figure 64 , Figure 65 and Figure 66 but for First simulation because of the time limit of my master thesis ,I have not enough time to do it.

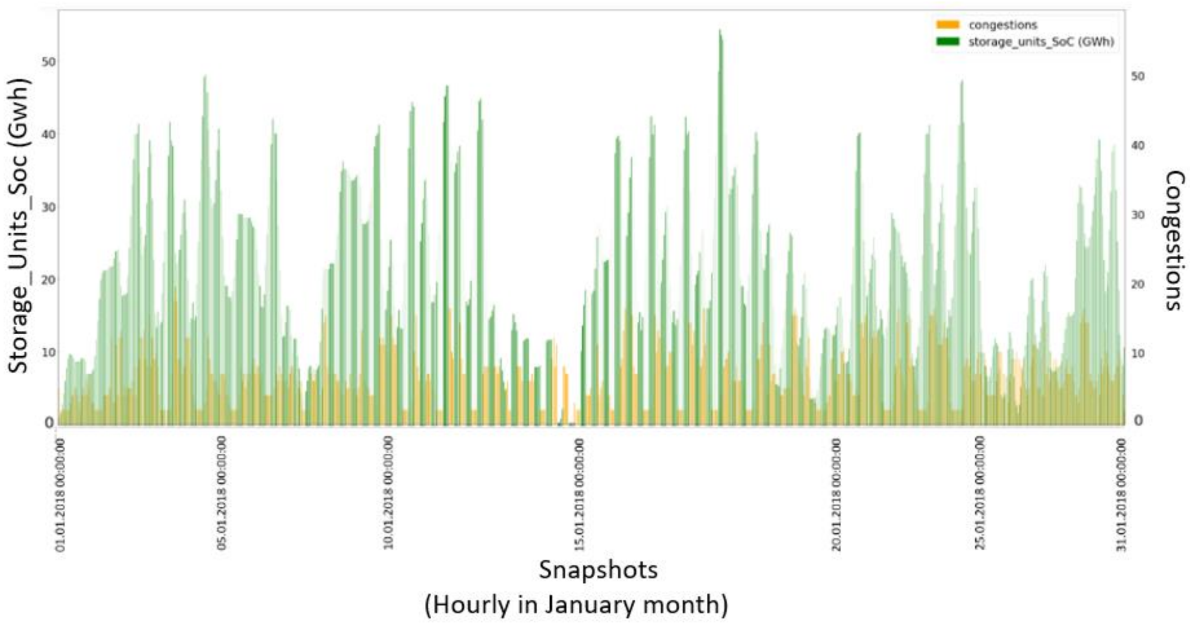


Figure 63:: effect of storage units on congestion, hourly in January for reference scenario

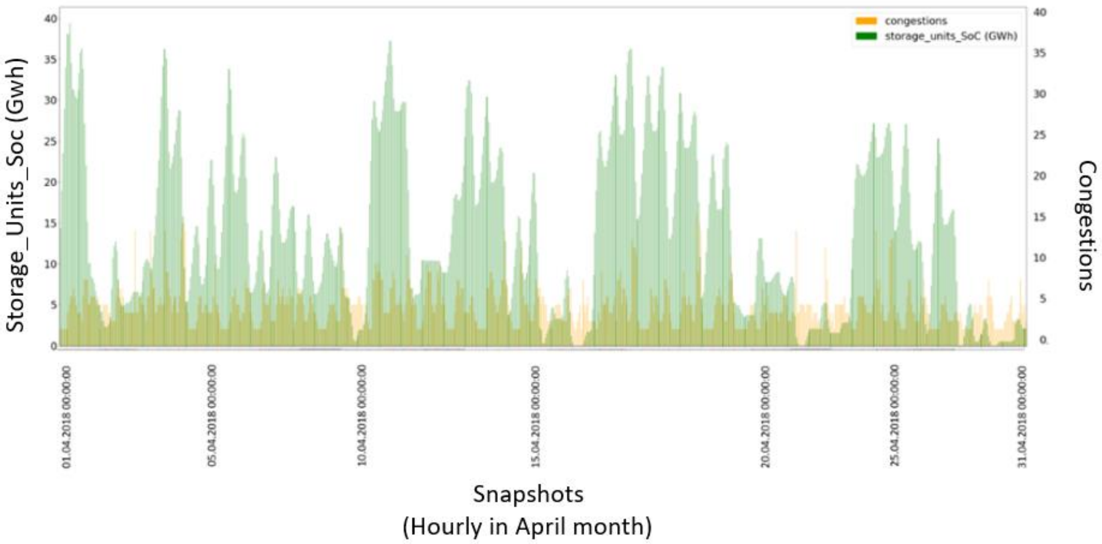


Figure 64:effect of storage units on congestion, hourly in April for reference scenario

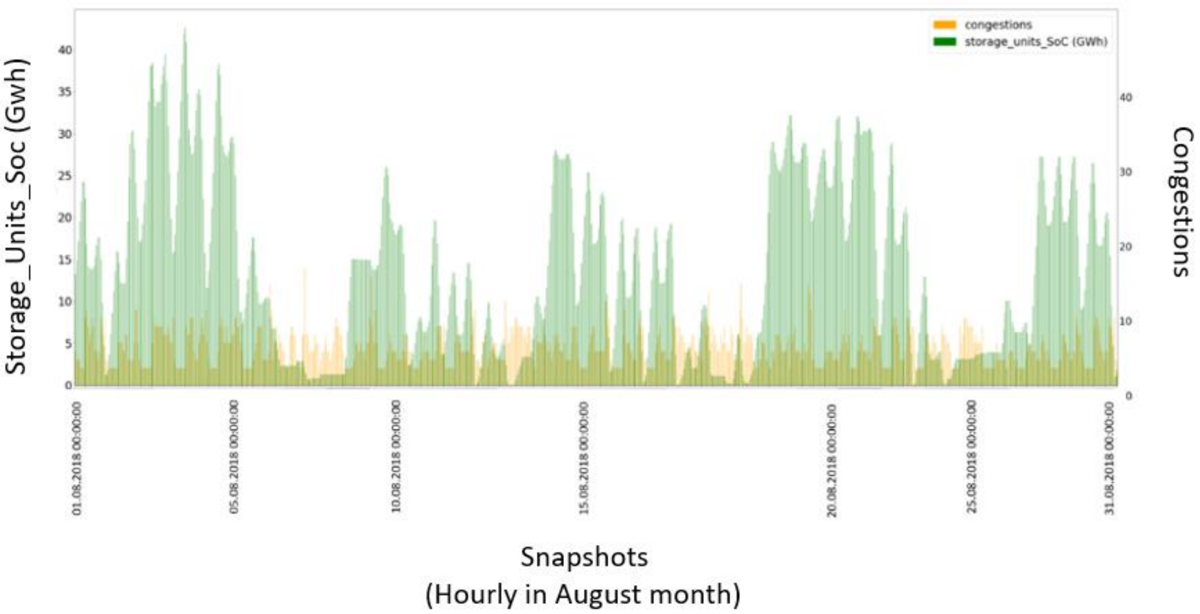


Figure 65:effect of storage units on congestion, hourly in August for reference scenario

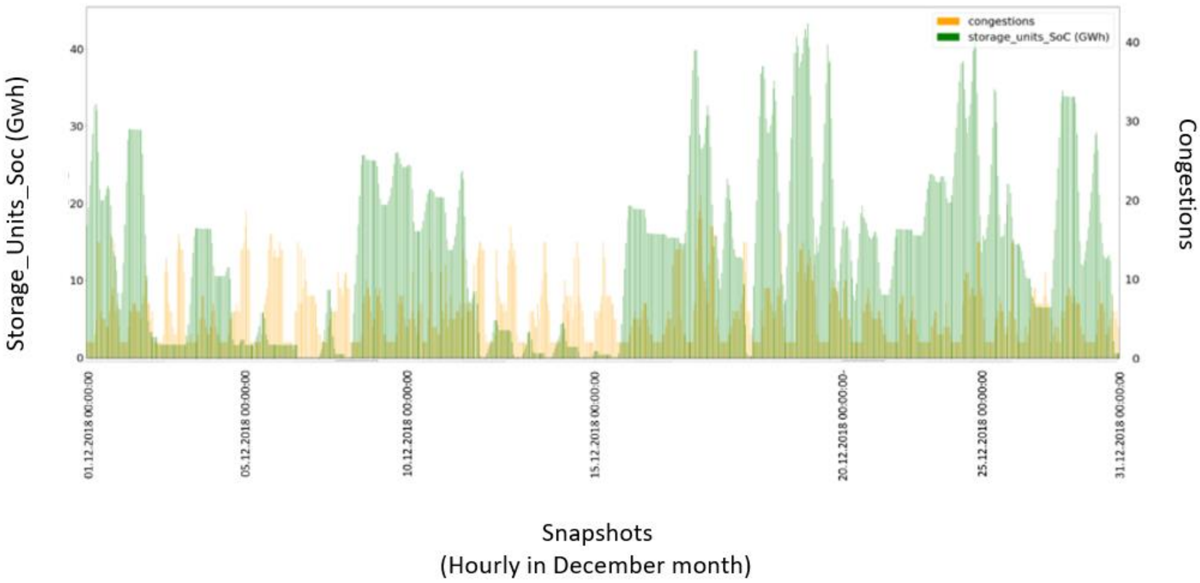


Figure 66:effect of storage units on congestion, hourly in December for reference scenario

5.3.3 Total number of Congestions for each Scenario

The result from my modelling that show the total number of congestions of each scenario with extension of renewable energy in Table 6 .

Extension of renewable energy	reference scenario	first scenario	second scenario	third scenario	fourth scenario
35%	46787	46140	47669	46888	46349
55%	64342	64536	60598	64203	64528
65%	63038	63467	62977	63349	60474
80%	60146	59341	63390	59633	60481

Table 6:total number of congestions over the whole year

From Table 6 ,it is observed that that the difference variation for no. of grid congestions between scenarios in each extension of RES approximately are very small , **at 35 percentage** shares of RES that **the first scenario** has the lowest no. of grid congestion , **at 55 percentage** shares of RES that **the second scenario** has the lowest no. of grid congestion , **at 65 percentage** shares of RES that **the fourth scenario** has the lowest no. of grid congestion and **at 80 percentage** shares of RES that **the first scenario** has the lowest no. of grid congestion.

My observation, with increasing RES, cheap and available for the whole time so storage units are used less , because RES are able to fulfill the load demand and also the Locations where each scenario's grid congestions occurred, some of which occurred in the same locations and others in different locations and as a result of the above Table 6 as mixture ,then it is hard to decide which scenario is the best,

From my view, it is better to make a comparison for grid congestions in each scenario in few specific locations where grid congestions occurred at reference scenario, then apply different scenarios and observe the effect from each scenario on these few locations, instead of comparing the total no. of grid congestion in each scenario during the whole year because some of grid congestions occur at different locations in each scenario.

From my For **Reference scenario**, I have chosen 35 percentage extension of renewable energy and plotted them in different seasons (during 24 hours at one day at February month , June month , October month, and December month).These Figures (Figure 67 - Figure 68 - Figure 69- Figure 72) describe the relation between power production and storages , load demand and affect them on number of congestions during 24 hours at one day , due to many research the grid congestion occurs in two situations ,the first situation when there are lots of power production and low demand and the second situation when high load demand and low power production to meet the load .

As example of the first situation from my figures, low consumption of power production at late night of each day and there is still excess energy, it means higher production of power more than load demand, and as result of that, the grid bottlenecks should happen and increase. but it is clear at the first 5 hours at late night from Figure 67 , Figure 68 , Figure 69 and Figure 70 that the number of congestions still low in my model ,even it should be higher .

The reason of that because most of storage units at my model locate close to the source of generators ,and this location of storage units has big benefit because when day is windy , so there are excess energy and we do not want the excess energy waste so the storage units store it to use later , to meet demand so storage units help to keep the grid balance ,and consequently decrease the number of congestions, so we could say that storages do great work at this situation and the result as our expect regarding to many research .

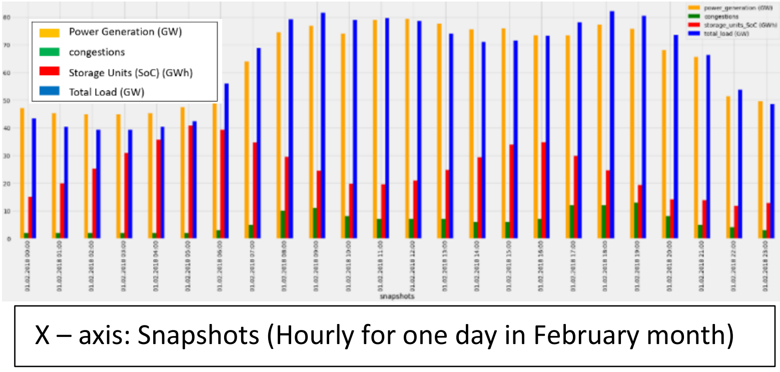


Figure 68:Relation of power generation – total load – storage units, one day in February month (ref. scenario 35%)

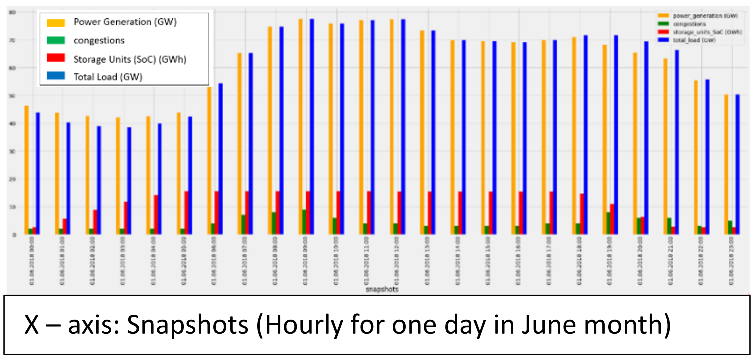


Figure 67:Relation of power generation – total load – storage units, one day in June month (ref. scenario 35%)

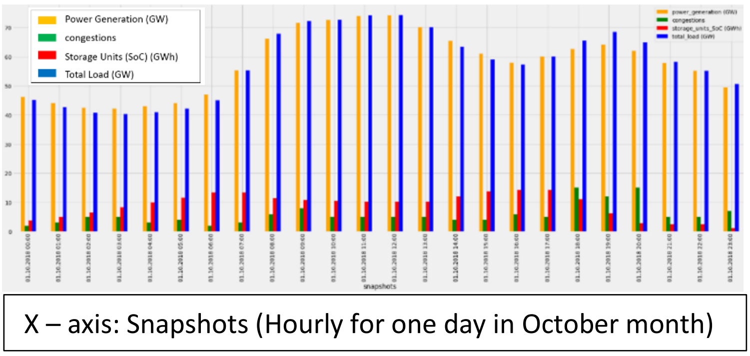


Figure 70:Relation of power generation – total load – storage units, one day in October month (ref. scenario 35%)

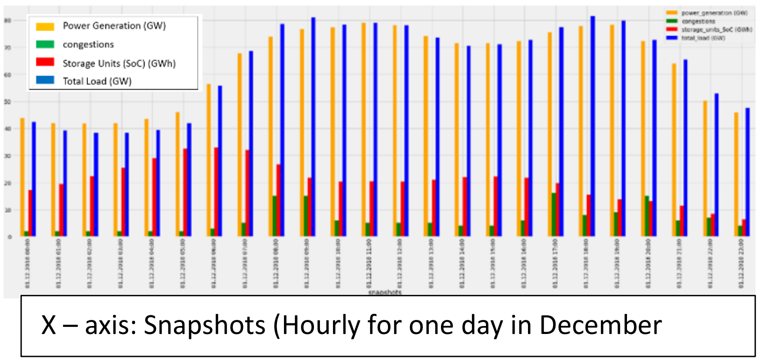


Figure 69:Relation of power generation – total load – storage units, one day in December month (ref. scenario 35%)

As example of the second situation from Figure 67 , Figure 68 , Figure 69 and Figure 70 that the bottleneck in the grid (Grid congestion) increase at the middle of the days when load demand is high and no available power of production to meet the load demand at this period ,that overload may be damage the grid ,so it is important to prevent overloading and also grid failure ,and this case happens exactly at my model and result of that the number of grid congestions increase , although there are storage units at our model but they have no effect on decreasing number of congestion ,the reason of that it is possibility that the charging capacity of storages was not enough to meet the load demand at this moment so no effect of storages ,and also other factors should we put in consideration which time period ,at which location happens the grid congestion ,and are storage units close to feed the grid quickly when grid congestions happens or are they locate far away of this grid failure and how many grid congestions happens at this moment ,so the effect of high load demand more than power production on no. of grid congestions happened as expectation of many researches .

Then by comparing the result of reference scenario with other scenarios.

For **first scenario** by adding extra battery to Storage units and Underground hydrogen storage to the model as mentioned before, adding extra battery has a little bit effect on the grid, no big difference if we add it or not, the reason of that is the capital cost play a big role in each component as generators, storages units, etc. According to eGo data that the capital cost of PHS in Storage Units is equal zero, this is done since PHS plants are already in the system and we don’t allow to build new ones! So, no cost increases due to the existing PHS plants, after modelling by PyPSA found that extra battery will not store a lot of energy, then consequently it has a little bit effect on the grid to participate in decreasing no. of congestions, because PyPSA prefer to use the lowest cost of Storages as PHS then use other storages, if needed. And also the effect of Underground hydrogen storage on the grid at this model is weak, because of the same reason that the capital cost of PHS is zero, so most of electricity production from RES go to PHS for storage at first even if they close or far away from energy sources and charge few days during the year other storages , so other storages even hydrogen underground will not have big impact on grid congestions .I have chosen 65 percentage extension of renewable energy during one day in different seasons to understand and discuss the relation and effect between power generation, total load, Storage units, H2 storage and no. of congestions .It is clear from Figure 71, Figure 72 , Figure 73 and Figure 74 that increasing charging of storage units in most cases ,cause to decrease no. of grid congestions and these figures show that store hydrogen is lower and consequently has few effect on grid congestions

and it is clear from Table 6 that no. of grid congestions is higher than reference scenario so this scenario has not advantage and big effect to decrease no. of grid congestions.

It is important to mention that at 35 percentage shares of RES, the underground storage hydrogen is empty because the production of RES is low, so no excess energy to store in underground storage of hydrogen. so, I have plotted the graphs for each scenario with 65 percentage shares of RES instead of 35 percentage, because underground storage started to fill with hydrogen in at this extension of RES as shown in Figures below.

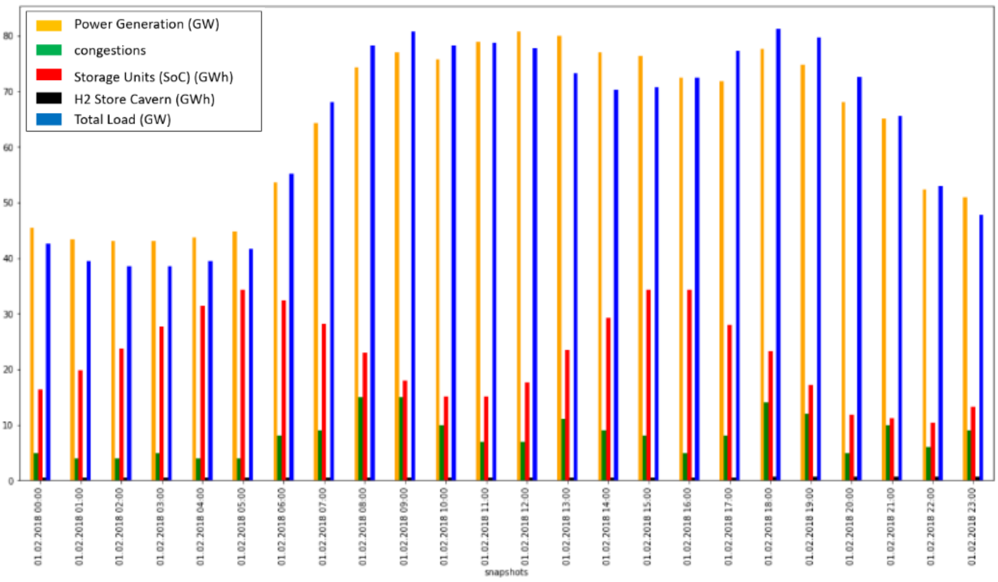


Figure 71:relation between power generation, total load, storage Units, H2 store cavern and congestions, one day in February month (First scenario 65%)

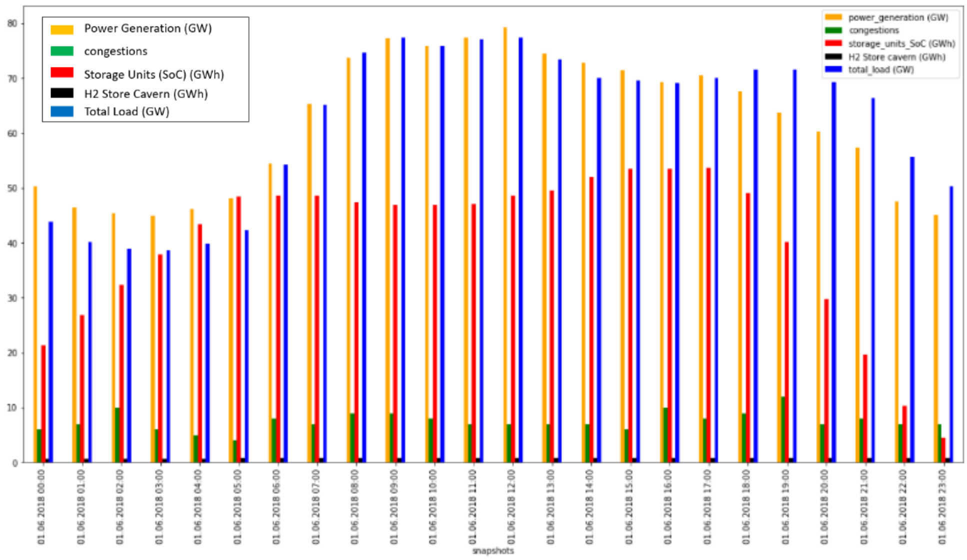


Figure 72:relation between power generation, total load, storage units ,H2 store cavern and congestions, one day in June month (First scenario 65%)

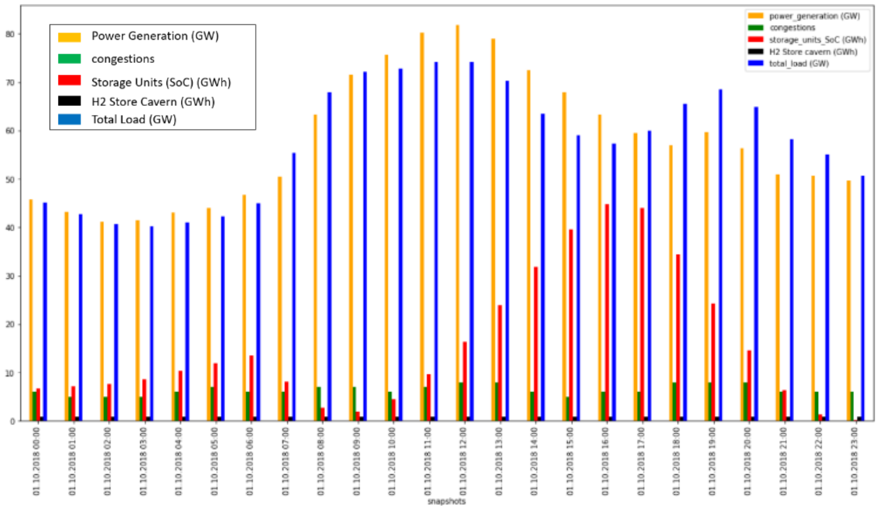


Figure 73:relation between power generation, total load, storage units, H2 store cavern and congestions, one day in October month (First scenario 65%)

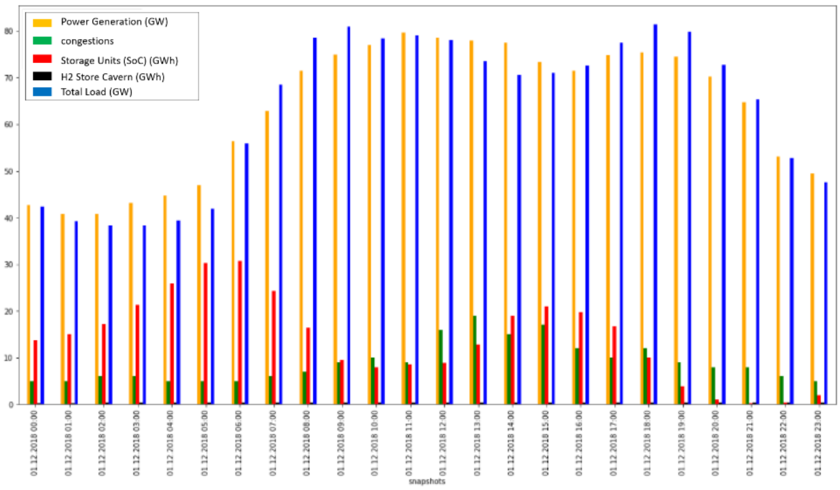


Figure 74:relation between power generation, total load, storage units, H2 store cavern and congestions, one day in December month (First scenario 65%)

Second scenario: i have chosen 65 percentage extension of renewable energy during one day in different seasons to understand and discuss the relation and effect between power generation, total load, Storage units, and no. of congestions .It is clear from Figure *75* , Figure *76* , Figure *77* and Figure *78* that increasing charging of storage units in most cases ,cause to decrease no. of grid congestions. and it shows that the no. of grid congestions at the second scenario is a little bit lower than both of first and reference scenario.

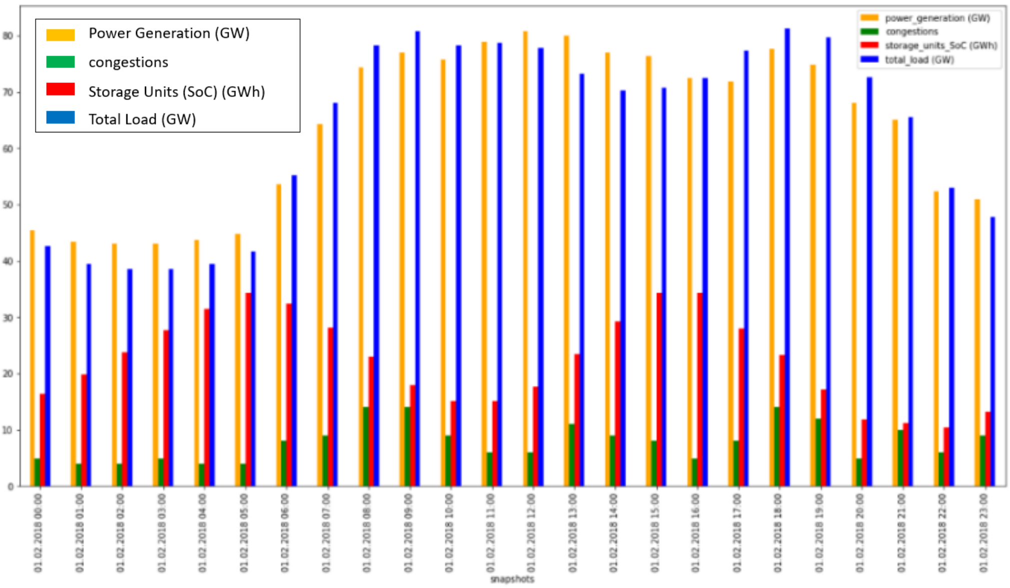


Figure 75:relation between power generation, total load, storage units, H2 store cavern and congestions, one day in February month (Second scenario 65%)

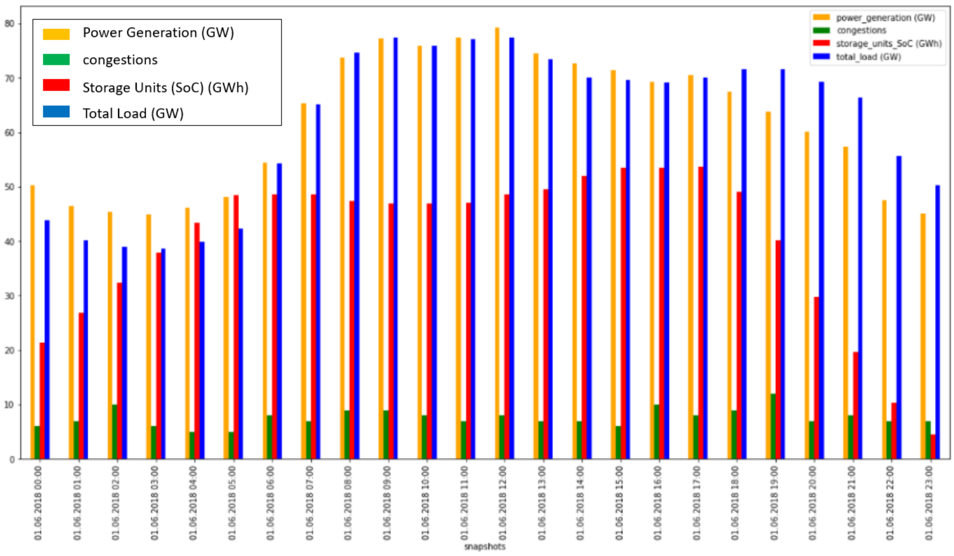


Figure 76:relation between power generation, total load, storage units, H2 store cavern and congestions, one day in June month (Second scenario 65%)

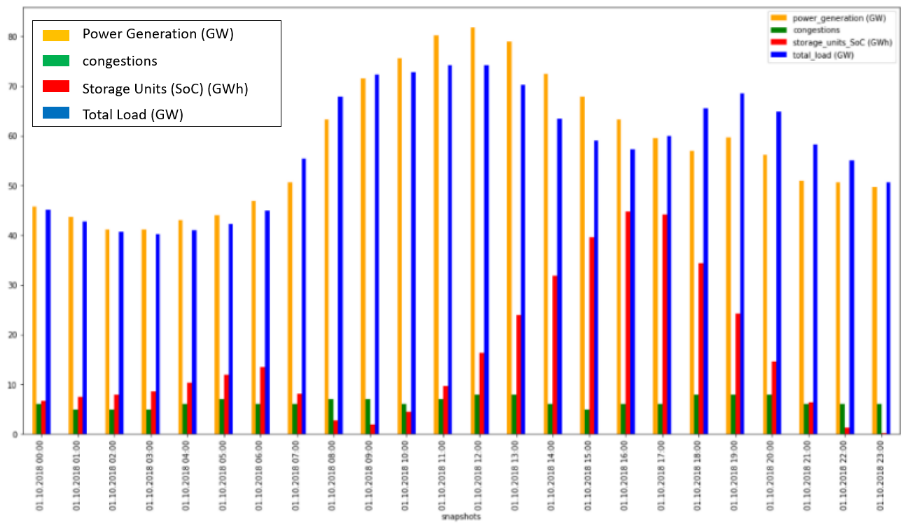


Figure 77:relation between power generation, total load, storage units ,H2 store cavern and congestions, one day in October month (Second scenario 65%)

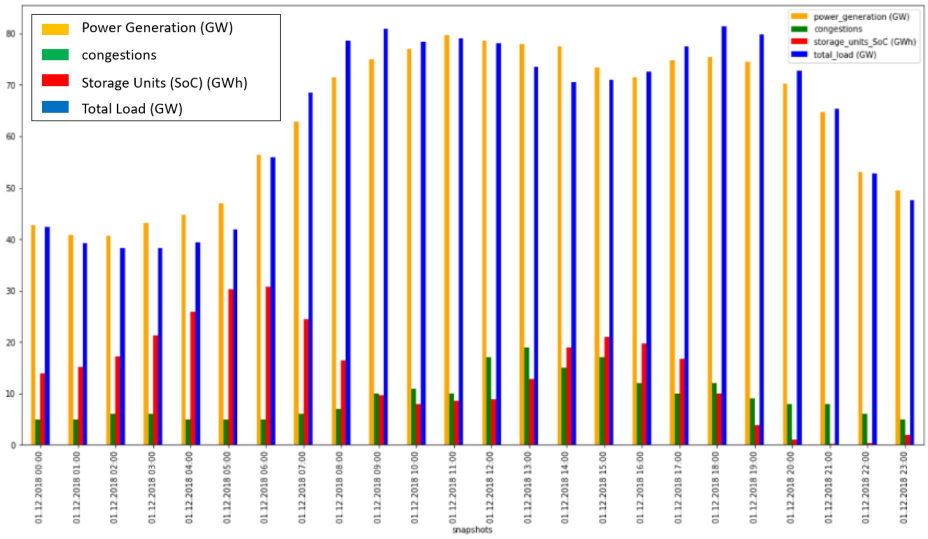


Figure 78:relation between power generation, total load, storage units, H2 store cavern and congestions, one day in December month (Second scenario 65%)

Third scenario: i have chosen 65 percentage extension of renewable energy during one day in different seasons to understand and discuss the relation and effect between power generation, total load, Storage units, and no. of congestions .It is clear from Figure *79* , Figure *80* , Figure *81* and Figure *82* that increasing charging of storage units in most cases ,cause to decrease no. of grid congestions. Because of hydrogen storage capacity is not high, so it has not big effect on no. of grid congestions, and the result of no. of grid congestions are highest than any scenario else.

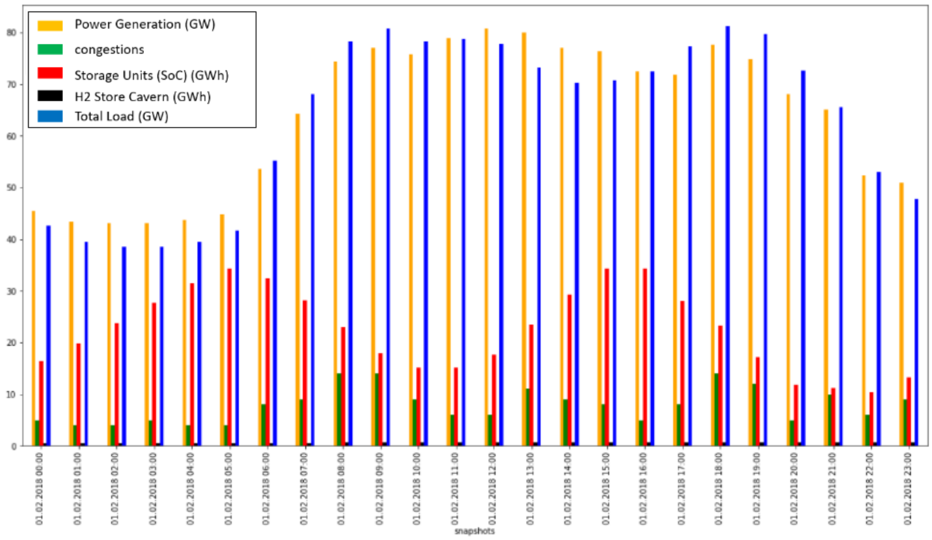


Figure 79:relation between power generation, total load, storage units ,H2 store cavern and congestions, one day in February month (Third scenario 65%)

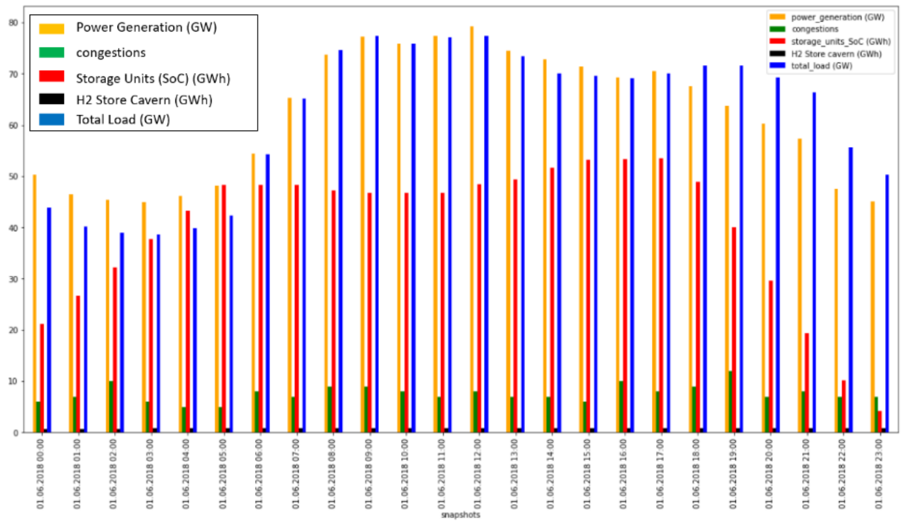


Figure 80:relation between power generation, total load, storage units, H2 store cavern and congestions, one day in June month (Third scenario 65%)

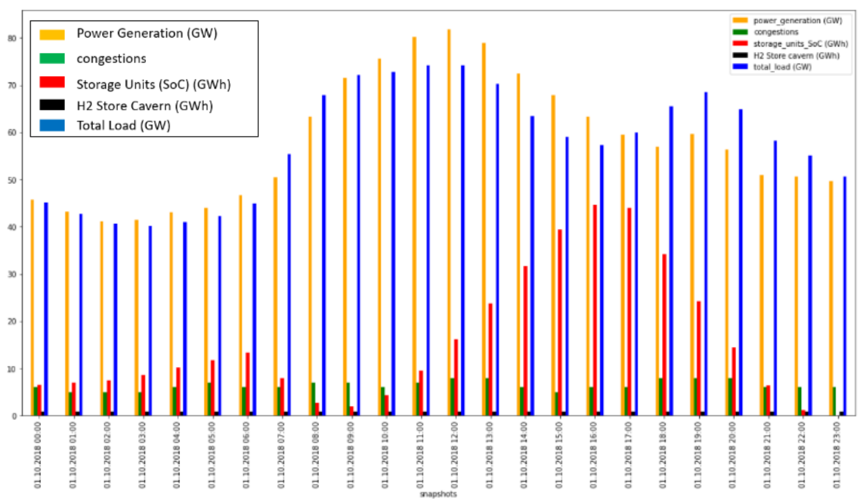


Figure 81:relation between power generation, total load, storage units ,H2 store cavern and congestions, one day in October month (Third scenario 65%)

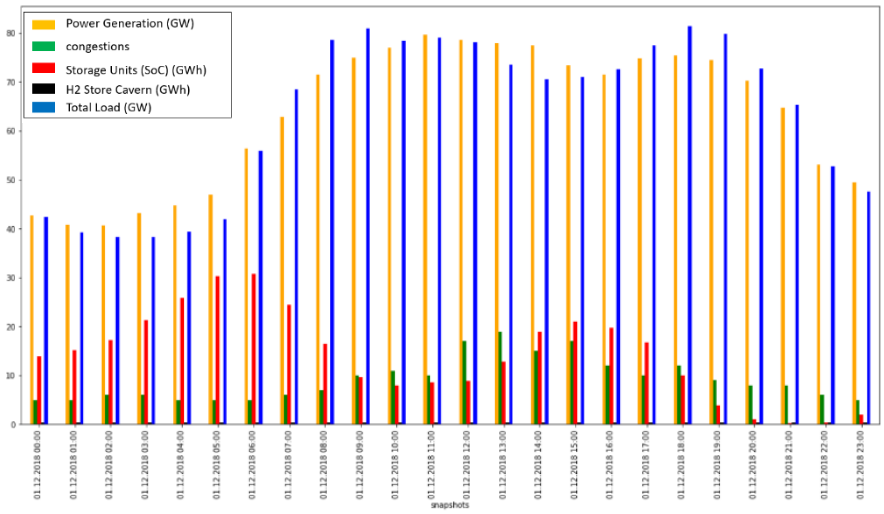


Figure 82:relation between power generation, total load, storage units ,H2 store cavern and congestions, one day in December month (Third scenario 65%)

Fourth scenario: i have chosen 65 percentage extension of renewable energy during one day in different seasons to understand and discuss the relation and effect between power generation, total load, Storage units, and no. of congestions .It is clear from Figure *83* , Figure *84* ,Figure *85* and Figure *86* that increasing charging of storage units in most cases ,cause to decrease no. of grid congestions. The result of the Fourth scenario has lowest no. of grid congestions comparing with reference and other scenarios.

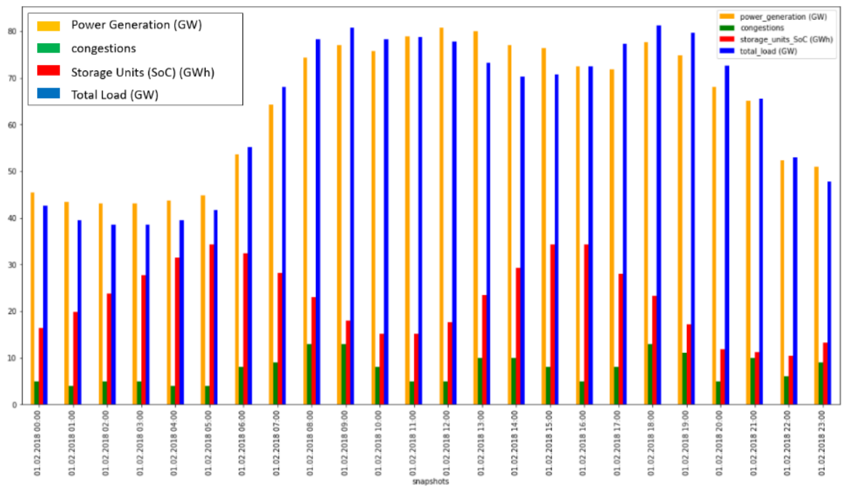


Figure 83:relation between power generation, total load, storage units and congestions, one day in February month (Fourth scenario 65%)

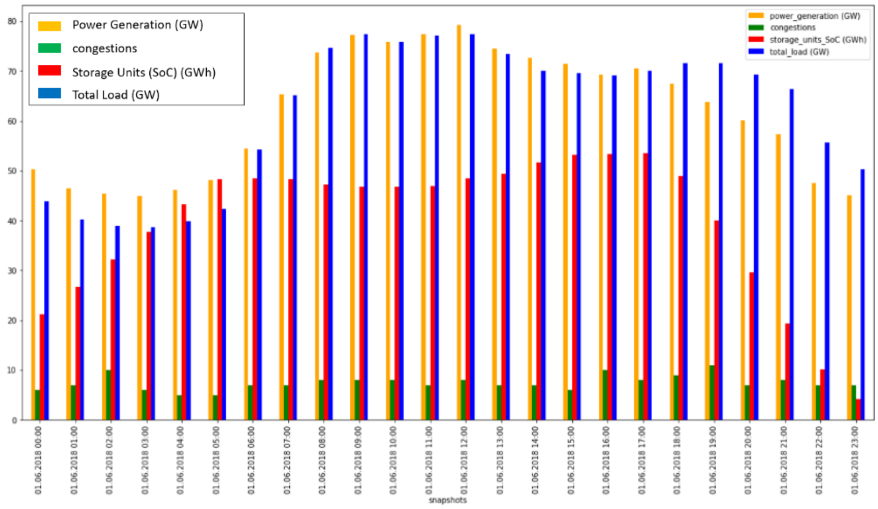


Figure 84:relation between power generation, total load, storage units, and congestions, one day in June month (Fourth scenario 65%)

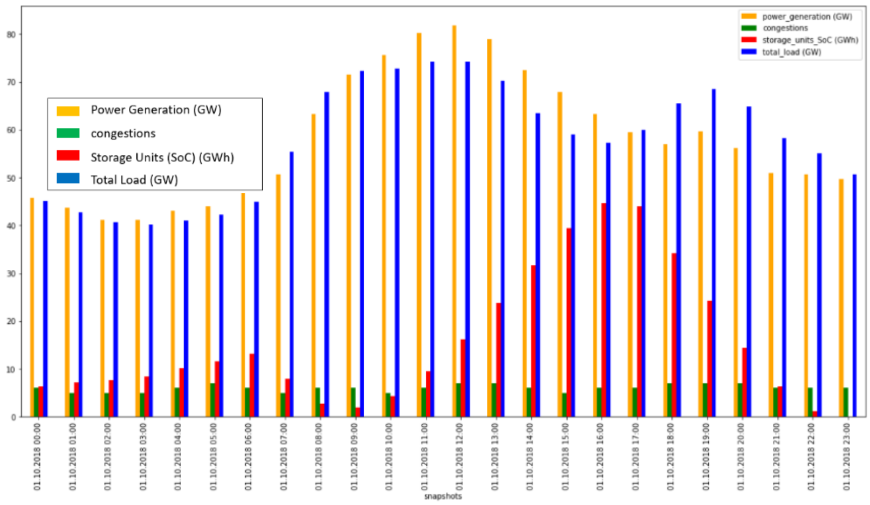


Figure 85:relation between power generation, total load, storage units, and congestions, one day in October month (Fourth scenario 65%)

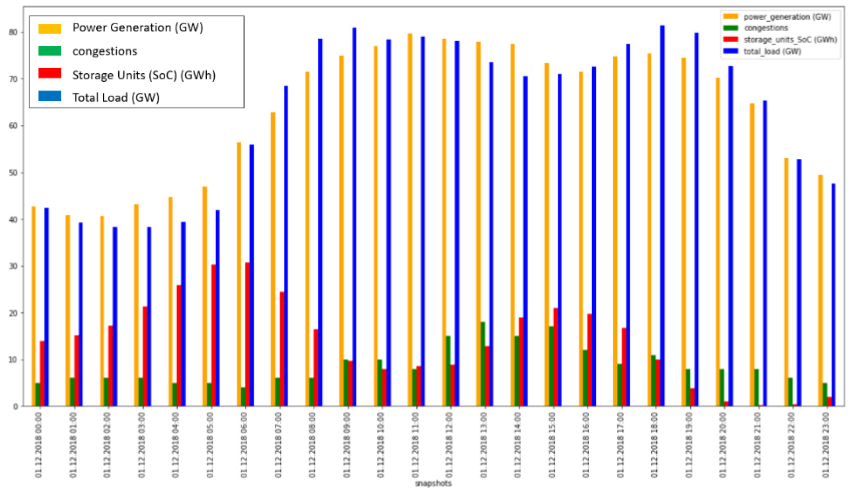


Figure 86:relation between power generation, total load, storage units, and congestions, one day in October month (Fourth scenario 65%)

6. Resume and outlook: evaluation of the results of the various methods. Discusses the results and provides an outlook on future scientific work

My work focuses on modelling the grid without electrolyzer and with electrolyzer in different scenarios to find the suitable method to decrease the no. of grid congestions because grid congestions is an obstacle of continue distribution the electricity production on the grid and sometimes cause to grid failures. Grid congestions occur when high production of RES more than Load demand or high demand and low production to meet this load demand, it is important to reduce no. of grid congestions as possible, so I have reference scenario introduced and also other four scenario with extension of RES to compare between them to find the suitable method to reduce no. of grid congestions.

My Scenarios:

- First Scenario: The Grid model couples to electrolyser and both storages (Underground hydrogen storage – Battery storage) to supply hydrogen industry demand.
- Second Scenario: The Grid model couples to electrolyser and battery storage to supply hydrogen industry demand.
- Third Scenario: The Grid model couples to electrolyser and Underground Hydrogen storage to supply hydrogen industry demand.
- Fourth Scenario: The Grid model couples to electrolyser to supply hydrogen industry demand.

Regarding to my results , it is hard to say which model is the best because at my model ,the grid congestions happen at locations far away from charging stations so the storages could not reach quickly with the grid to prevent the overloading .in addition to , the charging of most of storages are weak because the capital cost of pumped storage equal to zero ,so all electricity go to charge them at first even if they close or far away from energy sources then charge other storage for few days during the year , so other storages even hydrogen underground will not have enough capacity of hydrogen to be able to check the impact of it on grid congestions ,regarding to DLR institute that no need to control charging and discharging on the storages and I believe ,controlling is so necessary to keep the lifespan of batteries and other storages as maximum as can and also to control storages to store the excess energy when the day is windy or the sun is more shiny to use it later . by controlling, we will store curtailment when we have it so no waste energy and also it helps to grid balance. These are the factors that effect on the whole result of my model.

For Future work, it is necessary to run the whole grid system without any storages then we declare the places where the grid has capacity constraints, then install charging stations and also install charging stations at areas with a high share of variable renewable energy production and weak interconnections. It is important to install charge station close to the places that grid congestion happens so the storages has quickly effect on the grid and able prevent overloading and do balance grid. Control of all storage units in charging and discharging is important to implement and my opinion, it is necessary to add value for the capital cost of pumped storage in grid data instead of zero so the effect of other storages in the model will be possible to notice.

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Appendix

Pumped Storage Hydro
2020 & 2030 Cost & Performance Estimates

	Parameter	Units	100 MW		1,000 MW	
			4 hr	10 hr	4 hr	10 hr
			2020 / 2030	2020 / 2030	2020 / 2030	2020 / 2030
ESS Cost	Reservoir Construction & Infrastructure	$/kWh	[73 - 89] 81	[68 - 83] 76	[61 - 75] 68	[57 - 70] 64
ESS Cost	Powerhouse Construction & Infrastructure	$/kW	[321 - 817] 742	[321 - 817] 742	[270 - 686] 623	[270 - 686] 623
ESS Cost	Electro-mechanical	$/kW	[420 - 513] 467	[420 - 513] 467	[353 - 431] 392	[353 - 431] 392
	Total ESS Installed Cost*	$/kW	[1034 - 1688] $1,534	[1424 - 2164] $1,967	[868 - 1417] $1,288	[1195 - 1817] $1,651
		$/kWh	[259 - 422] $384	[142 - 216] $197	[217 - 354] $322	[120 - 182] $165
	Total ESS Installed Cost + Contingency Fee*	$/kW	[1301 - 2250] $2,046	[1792 - 2885] $2,623	[1093 - 1889] $1,717	[1504 - 2422] $2,202
		$/kWh	[325 - 563] $511	[179 - 289] $262	[273 - 472] $429	[150 - 242] $220
Operating Costs	Fixed O&M	$/kW-yr	[27.36 - 33.44] 30.40		[16.02 - 19.58] 17.80	
Operating Costs	Variable O&M	$/MWh	0.5125		0.5125	
Operating Costs	System RTE Losses	$/kWh	0.0075		0.0075	
Performance Metrics	Round Trip Efficiency	%	80%		80%	
Performance Metrics	Response Time(s)	sec	see below			
Performance Metrics	Cycle Life	#	13,870		13,870	
Performance Metrics	Calendar Life	yrs	40		40	
Performance Metrics	Duration Corresponding to Cycle Life**	yrs	40		40	

Response Time(s):

Scenario	Fixed Speed	Variable Speed	Ternary
Spinning-in-air to full-load generation	5-70	60	20-40
Shutdown to full generation	75-120	90	65-90
Spinning-in-air to full load	50-80	70	25-30
Shutdown to full load	160-360	230	80-85
Full load to full generation	90-220	280	25-60
Full generation to full load	240-500	470	25-45

* Does not include any additional transmission costs that may be required or decommissioning costs
** Assumes 80% depth of discharge, one cycle/day, and 5% downtime

Table 7:Pumped Storage Hydro parameters [43]

Lead Acid
2020 Cost & Performance Estimates

			1 MW					10 MW					100 MW				
	Parameter	Units	2hr	4hr	6hr	8hr	10hr	2hr	4hr	6hr	8hr	10hr	2hr	4hr	6hr	8hr	10hr
ESS Installed Cost / Energy Storage System / Storage System	Storage Block	$/kWh	[169 - 190] 180	[169 - 190] 180	[169 - 190] 180	[169 - 190] 180	[169 - 190] 180	[161 - 181] 171	[161 - 181] 171	[161 - 181] 171	[161 - 181] 171	[161 - 181] 171	[153 - 172] 162	[153 - 172] 162	[153 - 172] 162	[153 - 172] 162	[153 - 172] 162
ESS Installed Cost / Energy Storage System / Storage System	Storage Balance of System	$/kWh	[46 - 52] 49	[46 - 52] 49	[46 - 52] 49	[46 - 52] 49	[46 - 52] 49	[44 - 50] 47	[44 - 50] 47	[44 - 50] 47	[44 - 50] 47	[44 - 50] 47	[42 - 47] 45	[42 - 47] 45	[42 - 47] 45	[42 - 47] 45	[42 - 47] 45
ESS Installed Cost / Energy Storage System	Power Equipment	$/kW	[146 - 164] 155	[146 - 164] 155	[146 - 164] 155	[146 - 164] 155	[146 - 164] 155	[125 - 141] 133	[125 - 141] 133	[125 - 141] 133	[125 - 141] 133	[125 - 141] 133	[108 - 122] 115	[108 - 122] 115	[108 - 122] 115	[108 - 122] 115	[108 - 122] 115
ESS Installed Cost / Energy Storage System	Controls & Communication	$/kW	[38 - 42] 40	[38 - 42] 40	[38 - 42] 40	[38 - 42] 40	[38 - 42] 40	[7 - 8] 8	[7 - 8] 8	[7 - 8] 8	[7 - 8] 8	[7 - 8] 8	[1 - 2] 2	[1 - 2] 2	[1 - 2] 2	[1 - 2] 2	[1 - 2] 2
ESS Installed Cost / Energy Storage System	Systems Integration	$/kWh	[51 - 57] 54	[45 - 50] 47	[42 - 48] 45	[41 - 47] 44	[41 - 46] 43	[46 - 52] 49	[41 - 47] 44	[40 - 45] 42	[39 - 44] 41	[38 - 43] 41	[43 - 48] 46	[39 - 44] 41	[37 - 42] 40	[37 - 41] 39	[36 - 41] 39
ESS Installed Cost	Engineering, Procurement, and Construction	$/kWh	[57 - 64] 60	[49 - 55] 52	[47 - 52] 50	[45 - 51] 48	[45 - 50] 47	[53 - 59] 56	[46 - 52] 49	[44 - 50] 47	[43 - 48] 46	[42 - 48] 45	[49 - 55] 52	[43 - 49] 46	[41 - 47] 44	[41 - 46] 43	[40 - 45] 43
ESS Installed Cost	Project Development	$/kWh	[72 - 81] 76	[63 - 71] 67	[60 - 67] 64	[58 - 66] 62	[57 - 65] 61	[65 - 73] 69	[58 - 65] 62	[56 - 63] 59	[55 - 62] 58	[54 - 61] 57	[60 - 67] 64	[54 - 61] 58	[52 - 59] 56	[51 - 58] 55	[51 - 57] 54
ESS Installed Cost	Grid Integration	$/kW	[29 - 33] 31	[29 - 33] 31	[29 - 33] 31	[29 - 33] 31	[29 - 33] 31	[23 - 26] 25	[23 - 26] 25	[23 - 26] 25	[23 - 26] 25	[23 - 26] 25	[19 - 21] 20	[19 - 21] 20	[19 - 21] 20	[19 - 21] 20	[19 - 21] 20
	Total ESS Installed Cost*	$/kW	[975 - 1154] $1,065	[1658 - 1956] $1,808	[2341 - 2758] $2,552	[3024 - 3561] $3,296	[3707 - 4365] $4,040	[870 - 1028] $950	[1520 - 1792] $1,657	[2171 - 2557] $2,364	[2821 - 3322] $3,072	[3472 - 4086] $3,780	[801 - 946] $873	[1419 - 1672] $1,544	[2037 - 2398] $2,215	[2655 - 3125] $2,886	[3273 - 3852] $3,558
	Total ESS Installed Cost*	$/kWh	[488 - 577] $533	[414 - 489] $452	[390 - 460] $425	[378 - 445] $412	[371 - 436] $404	[435 - 514] $475	[380 - 448] $414	[362 - 426] $394	[353 - 415] $384	[347 - 409] $378	[401 - 473] $436	[355 - 418] $386	[339 - 400] $369	[332 - 391] $361	[327 - 385] $356
Operating Costs	Fixed O&M	$/kW-yr	[3.19 - 3.59] 3.39	[5.59 - 6.3] 5.9	[7.98 - 9] 8.5	[10.38 - 11.71] 11.0	[12.78 - 14.41] 13.6	[2.82 - 3.18] 3.00	[5.11 - 5.76] 5.43	[7.39 - 8.33] 7.86	[9.68 - 10.91] 10.29	[11.96 - 13.49] 12.72	[2.63 - 2.97] 2.80	[4.8 - 5.42] 5.11	[6.97 - 7.87] 7.42	[9.15 - 10.31] 9.73	[11.32 - 12.76] 12.04
Operating Costs	Variable O&M	$/MWh			0.5125					0.5125					0.5125		
Operating Costs	System RTE Losses	$/kWh	0.009	0.008	0.007	0.006	0.005	0.009	0.008	0.007	0.006	0.005	0.009	0.008	0.007	0.006	0.005
Performance Metrics	Round Trip Efficiency	%	77.0%	79.0%	82.0%	83.5%	85.0%	77.0%	79.0%	82.0%	83.5%	85.0%	77.0%	79.0%	82.0%	83.5%	85.0%
Performance Metrics	Response Time	sec			1-4					1-4					1-4		
Performance Metrics	Cycle Life	#	862	739	675	635	599	862	739	675	635	599	862	739	675	635	599
Performance Metrics	Calendar Life	yrs			12					12					12		
Performance Metrics	Duration Corresponding to Cycle Life**	yrs	2.49	2.13	1.95	1.83	1.73	2.49	2.13	1.95	1.83	1.73	2.49	2.13	1.95	1.83	1.73

* Does not include warranty, insurance, or decommissioning costs
** Assumes various depths of discharge, one cycle/day, and 5% downtime

Table 8:Lead Acid Battery parameters [43]

			Lithium-ion LFP						Lithium-ion NMC					
			1 MW / 4 hr		10 MW / 4 hr		100 MW / 4 hr		1 MW / 4 hr		10 MW / 4 hr		100 MW / 4 hr	
	Parameter	Units	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030
ESS Installed Cost / Energy Storage System / Storage System	Storage Block	$/kWh	[164 - 200] 182	[87 - 128] 109	[156 - 191] 174	[83 - 122] 104	[149 - 182] 165	[79 - 116] 99	[175 - 213] 194	[93 - 136] 116	[166 - 203] 185	[89 - 129] 111	[158 - 194] 176	[84 - 123] 106
ESS Installed Cost / Energy Storage System / Storage System	Storage Balance of System	$/kWh	[38 - 47] 42	[25 - 35] 30	[36 - 44] 40	[24 - 33] 28	[35 - 42] 38	[23 - 32] 27	[30 - 45] 37	[22 - 30] 26	[29 - 43] 35	[21 - 29] 25	[27 - 41] 34	[20 - 28] 24
ESS Installed Cost / Energy Storage System	Power Equipment	$/kW	[76 - 93] 85	[59 - 77] 73	[66 - 80] 73	[51 - 66] 63	[57 - 69] 63	[44 - 57] 54	[76 - 93] 85	[59 - 77] 73	[66 - 80] 73	[51 - 66] 63	[57 - 69] 63	[44 - 57] 54
ESS Installed Cost / Energy Storage System	Controls & Communication	$/kW	[36 - 44] 40	[24 - 33] 28	[7 - 9] 8	[5 - 6] 5	[1 - 2] 2	[1 - 1] 1	[36 - 44] 40	[24 - 33] 28	[7 - 9] 8	[5 - 6] 5	[1 - 2] 2	[1 - 1] 1
ESS Installed Cost / Energy Storage System	System Integration	$/kWh	[37 - 56] 50	[37 - 46] 36	[35 - 52] 47	[35 - 42] 33	[33 - 49] 44	[33 - 40] 31	[38 - 58] 51	[38 - 47] 42	[36 - 54] 48	[35 - 44] 39	[34 - 51] 45	[33 - 41] 37
ESS Installed Cost	Engineering, Procurement, and Construction	$/kWh	[48 - 74] 61	[45 - 56] 50	[44 - 68] 56	[42 - 51] 46	[42 - 64] 53	[39 - 48] 43	[49 - 77] 63	[46 - 57] 51	[45 - 71] 58	[43 - 52] 47	[42 - 67] 54	[40 - 49] 44
ESS Installed Cost	Project Development	$/kWh	[57 - 90] 73	[54 - 67] 60	[52 - 83] 67	[50 - 61] 55	[49 - 78] 63	[47 - 58] 52	[58 - 94] 75	[56 - 68] 62	[53 - 87] 69	[51 - 63] 57	[50 - 81] 65	[48 - 59] 53
ESS Installed Cost	Grid Integration	$/kW	[28 - 34] 31	[23 - 28] 25	[22 - 27] 25	[18 - 23] 20	[18 - 22] 20	[15 - 18] 16	[28 - 34] 31	[23 - 28] 25	[22 - 27] 25	[18 - 23] 20	[18 - 22] 20	[15 - 18] 16
	Total ESS Installed Cost*	$/kW	[1517 - 2040] $1,793	[1105 - 1460] $1,266	[1389 - 1868] $1,643	[1008 - 1334] $1,156	[1302 - 1752] $1,541	[944 - 1249] $1,081	[1537 - 2122] $1,838	[923 - 1239] $1,089	[1408 - 1947] $1,685	[1031 - 1365] $1,204	[1320 - 1827] $1,581	[965 - 1279] $1,128
	Total ESS Installed Cost*	$/kWh	[379 - 510] $448	[276 - 365] $317	[347 - 467] $411	[252 - 333] $289	[326 - 438] $385	[236 - 312] $270	[384 - 531] $459	[231 - 310] $272	[352 - 487] $421	[258 - 341] $301	[330 - 457] $395	[241 - 320] $282
Operating Costs	Fixed O&M	$/kW-yr	[3.96 - 4.84] 4.40	[3.26 - 4] 3.61	[3.63 - 4.43] 4.03	[2.98 - 3.67] 3.30	[3.41 - 4.16] 3.79	[2.8 - 3.44] 3.10	[4.06 - 4.96] 4.51	[3.34 - 4.1] 3.70	[3.72 - 4.55] 4.13	[3.06 - 3.76] 3.39	[3.5 - 4.27] 3.89	[2.88 - 3.54] 3.19
Operating Costs	Variable O&M	$/MWh	0.5125		0.5125		0.5125		0.5125		0.5125		0.5125	
Operating Costs	System RTE Losses ($/kWh)	$/kWh	0.005	0.004	0.005	0.004	0.005	0.004	0.005	0.004	0.005	0.004	0.005	0.004
Performance Metrics	Round Trip Efficiency	%	86%	88%	86%	88%	86%	88%	86%	88%	86%	88%	86%	88%
Performance Metrics	Response Time	sec	1-4		1-4		1-4		1-4		1-4		1-4	
Performance Metrics	Cycle Life	#	2,000	2,100	2,000	2,100	2,000	2,100	1,200	1,260	1,200	1,260	1,200	1,260
Performance Metrics	Calendar Life	yrs	10		10		10		10		10		10	
Performance Metrics	Duration Corresponding to Cycle Life**	yrs	5.77	6.06	5.77	6.06	5.77	6.06	3.46	3.63	3.46	3.63	3.46	3.63

* Does not include warranty, insurance, or decommissioning costs
** Assumes 80% depth of discharge, one cycle/day, and 5% downtime

Table 9:Lithium-ion Battery parameters [140]

Vanadium Redox Flow
2020 Cost & Performance Estimates

	Parameter	Units	1 MW					10 MW					100 MW				
			2hr	4hr	6hr	8hr	10hr	2hr	4hr	6hr	8hr	10hr	2hr	4hr	6hr	8hr	10hr
ESS Installed Cost / Energy Storage System / Storage System	Storage Block	$/kWh	[346 - 423] 384	[260 - 317] 289	[231 - 282] 257	[217 - 265] 241	[208 - 254] 231	[329 - 402] 366	[247 - 302] 275	[220 - 269] 245	[206 - 252] 229	[198 - 242] 220	[313 - 382] 348	[235 - 287] 261	[209 - 256] 232	[196 - 240] 218	[188 - 230] 209
ESS Installed Cost / Energy Storage System / Storage System	Storage Balance of System	$/kWh	[69 - 85] 77	[52 - 63] 58	[46 - 56] 51	[43 - 53] 48	[42 - 51] 46	[66 - 80] 73	[49 - 60] 55	[44 - 54] 49	[41 - 50] 46	[40 - 48] 44	[63 - 76] 70	[47 - 57] 52	[42 - 51] 46	[39 - 48] 44	[38 - 46] 42
ESS Installed Cost / Energy Storage System	Power Equipment	$/kW	[139 - 170] 155	[139 - 170] 155	[139 - 170] 155	[139 - 170] 155	[139 - 170] 155	[120 - 146] 133	[120 - 146] 133	[120 - 146] 133	[120 - 146] 133	[120 - 146] 133	[103 - 126] 115	[103 - 126] 115	[103 - 126] 115	[103 - 126] 115	[103 - 126] 115
ESS Installed Cost / Energy Storage System	Controls & Communication	$/kW	[36 - 44] 40	[36 - 44] 40	[36 - 44] 40	[36 - 44] 40	[36 - 44] 40	[7 - 9] 8	[7 - 9] 8	[7 - 9] 8	[7 - 9] 8	[7 - 9] 8	[1 - 2] 2	[1 - 2] 2	[1 - 2] 2	[1 - 2] 2	[1 - 2] 2
ESS Installed Cost / Energy Storage System	Systems Integration	$/kWh	[69 - 84] 76	[50 - 61] 55	[44 - 53] 48	[41 - 50] 45	[39 - 47] 43	[64 - 78] 71	[46 - 56] 51	[40 - 49] 45	[38 - 46] 42	[36 - 44] 40	[59 - 73] 66	[43 - 53] 48	[38 - 46] 42	[35 - 43] 39	[34 - 41] 38
ESS Installed Cost	Engineering, Procurement, and Construction	$/kWh	[78 - 96] 87	[57 - 69] 63	[50 - 61] 56	[47 - 57] 52	[45 - 55] 50	[73 - 89] 81	[53 - 64] 58	[46 - 57] 51	[43 - 53] 48	[42 - 51] 46	[68 - 83] 76	[49 - 60] 54	[43 - 53] 48	[40 - 49] 45	[39 - 47] 43
ESS Installed Cost	Project Development	$/kWh	[98 - 120] 109	[72 - 88] 80	[64 - 78] 71	[60 - 73] 66	[57 - 70] 64	[89 - 109] 99	[66 - 81] 73	[59 - 72] 65	[55 - 67] 61	[53 - 64] 59	[83 - 101] 92	[61 - 75] 68	[54 - 66] 60	[51 - 62] 57	[49 - 60] 54
ESS Installed Cost	Grid Integration	$/kW	[28 - 34] 31	[28 - 34] 31	[28 - 34] 31	[28 - 34] 31	[28 - 34] 31	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[18 - 22] 20	[18 - 22] 20	[18 - 22] 20	[18 - 22] 20	[18 - 22] 20
	Total ESS Installed Cost*	$/kW	[1523 - 1862] $1,693	[2163 - 2644] $2,404	[2811 - 3436] $3,123	[3461 - 4230] $3,845	[4111 - 5025] $4,568	[1391 - 1700] $1,546	[1995 - 2438] $2,216	[2606 - 3185] $2,895	[3219 - 3934] $3,576	[3832 - 4684] $4,258	[1294 - 1581] $1,438	[1863 - 2277] $2,070	[2439 - 2980] $2,710	[3016 - 3686] $3,351	[3595 - 4393] $3,994
	Total ESS Installed Cost*	$/kWh	[762 - 931] $846	[541 - 661] $601	[468 - 573] $521	[433 - 529] $481	[411 - 502] $457	[695 - 850] $773	[499 - 609] $554	[434 - 531] $483	[402 - 492] $447	[383 - 468] $426	[647 - 791] $719	[466 - 569] $517	[406 - 497] $452	[377 - 461] $419	[359 - 439] $399
Operating Costs	Fixed O&M	$/kW-yr	[4.32 - 5.28] 4.80	[6.11 - 7.47] 6.79	[7.91 - 9.67] 8.79	[9.7 - 11.86] 10.78	[11.5 - 14.05] 12.77	[3.94 - 4.82] 4.38	[5.65 - 6.91] 6.28	[7.36 - 8.99] 8.18	[9.07 - 11.08] 10.07	[10.77 - 13.17] 11.97	[3.68 - 4.5] 4.09	[5.3 - 6.48] 5.89	[6.92 - 8.46] 7.69	[8.55 - 10.44] 9.49	[10.17 - 12.43] 11.30
Operating Costs	Variable O&M	$/MWh	0.5125					0.5125					0.5125				
Operating Costs	System RTE Losses	$/kWh	0.0144					0.0144					0.0144				
Performance Metrics	Round Trip Efficiency	%	68%					68%					68%				
Performance Metrics	Response Time	sec	1-4					1-4					1-4				
Performance Metrics	Cycle Life	#	5,201					5,201					5,201				
Performance Metrics	Calendar Life	yrs	15					15					15				
Performance Metrics	Duration Corresponding to Cycle Life**	yrs	15					15					15				

* Does not include warranty, insurance, or decommissioning costs
** Assumes 90% depth of discharge, one cycle/day, and 5% downtime

Table 10:Vanadium Redox Flow 2020 [43]

Vanadium Redox Flow
2030 Cost & Performance Estimates

	Parameter	Units	1 MW					10 MW					100 MW				
			2hr	4hr	6hr	8hr	10hr	2hr	4hr	6hr	8hr	10hr	2hr	4hr	6hr	8hr	10hr
ESS Installed Cost / Energy Storage System / Storage System	Storage Block	$/kWh	[244 - 350] 307	[183 - 263] 231	[163 - 234] 205	[153 - 219] 193	[147 - 210] 185	[232 - 333] 293	[175 - 250] 220	[155 - 223] 196	[146 - 209] 183	[140 - 200] 176	[221 - 316] 278	[166 - 238] 209	[148 - 211] 186	[138 - 198] 174	[133 - 190] 167
ESS Installed Cost / Energy Storage System / Storage System	Storage Balance of System	$/kWh	[46 - 63] 54	[35 - 47] 40	[31 - 42] 36	[29 - 39] 34	[28 - 38] 32	[44 - 60] 51	[33 - 45] 38	[29 - 40] 34	[28 - 38] 32	[26 - 36] 31	[42 - 57] 49	[31 - 43] 37	[28 - 38] 33	[26 - 36] 31	[25 - 34] 29
ESS Installed Cost / Energy Storage System	Power Equipment	$/kW	[108 - 141] 133	[108 - 141] 133	[108 - 141] 133	[108 - 141] 133	[108 - 141] 133	[93 - 121] 114	[93 - 121] 114	[93 - 121] 114	[93 - 121] 114	[93 - 121] 114	[80 - 104] 99	[80 - 104] 99	[80 - 104] 99	[80 - 104] 99	[80 - 104] 99
ESS Installed Cost / Energy Storage System	Controls & Communication	$/kW	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[24 - 33] 28	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[5 - 6] 5	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1	[1 - 1] 1
ESS Installed Cost / Energy Storage System	Systems Integration	$/kWh	[57 - 70] 63	[41 - 50] 45	[36 - 44] 40	[33 - 41] 37	[32 - 39] 35	[52 - 64] 58	[38 - 47] 42	[33 - 41] 37	[31 - 38] 34	[30 - 37] 33	[49 - 60] 54	[35 - 44] 39	[31 - 38] 34	[29 - 36] 32	[28 - 34] 31
ESS Installed Cost	Engineering, Procurement, and Construction	$/kWh	[64 - 79] 71	[47 - 57] 52	[41 - 51] 46	[38 - 47] 43	[37 - 45] 41	[60 - 74] 67	[43 - 53] 48	[38 - 47] 42	[36 - 44] 39	[34 - 42] 38	[56 - 69] 62	[40 - 49] 45	[35 - 44] 39	[33 - 41] 37	[32 - 39] 35
ESS Installed Cost	Project Development	$/kWh	[81 - 99] 89	[59 - 73] 66	[52 - 65] 58	[49 - 60] 54	[47 - 58] 52	[73 - 90] 81	[54 - 67] 60	[48 - 59] 53	[45 - 56] 50	[43 - 53] 48	[68 - 84] 75	[50 - 62] 56	[45 - 55] 49	[42 - 51] 46	[40 - 49] 45
ESS Installed Cost	Grid Integration	$/kW	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[23 - 28] 25	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[18 - 23] 20	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16	[15 - 18] 16
	Total ESS Installed Cost*	$/kW	[1139 - 1523] $1,356	[1614 - 2163] $1,922	[2095 - 2811] $2,495	[2578 - 3461] $3,070	[3062 - 4112] $3,645	[1040 - 1393] $1,240	[1488 - 1996] $1,773	[1941 - 2608] $2,314	[2397 - 3221] $2,856	[2852 - 3835] $3,399	[967 - 1296] $1,153	[1388 - 1864] $1,656	[1815 - 2440] $2,165	[2244 - 3018] $2,676	[2673 - 3597] $3,187
	Total ESS Installed Cost*	$/kWh	[569 - 761] $678	[403 - 541] $480	[349 - 468] $416	[322 - 433] $384	[306 - 411] $365	[520 - 696] $620	[372 - 499] $443	[324 - 435] $386	[300 - 403] $357	[285 - 383] $340	[483 - 648] $576	[347 - 466] $414	[303 - 407] $361	[281 - 377] $334	[267 - 360] $319
Operating Costs	Fixed O&M	$/kW-yr	[3.55 - 4.37] 3.94	[5.03 - 6.18] 5.57	[6.5 - 8] 7.21	[7.98 - 9.81] 8.84	[9.45 - 11.62] 10.47	[3.24 - 3.99] 3.59	[4.65 - 5.71] 5.15	[6.05 - 7.44] 6.70	[7.45 - 9.17] 8.26	[8.86 - 10.89] 9.82	[3.02 - 3.72] 3.35	[4.36 - 5.36] 4.83	[5.69 - 7] 6.31	[7.03 - 8.64] 7.79	[8.36 - 10.28] 9.26
Operating Costs	Variable O&M	$/MWh	0.5125					0.5125					0.5125				
Operating Costs	System RTE Losses	$/kWh	0.0129					0.0129					0.0129				
Performance Metrics	Round Trip Efficiency	%	70%					70%					70%				
Performance Metrics	Response Time	sec	1-4					1-4					1-4				
Performance Metrics	Cycle Life	#	5,201					5,201					5,201				
Performance Metrics	Calendar Life	yrs	15					15					15				
Performance Metrics	Duration Corresponding to Cycle Life**	yrs	15					15					15				

* Does not include warranty, insurance, or decommissioning costs
** Assumes 90% depth of discharge, one cycle/day, and 5% downtime

Table 11:Vanadium Redox Flow parameters 2030 [43]