KTH Industrial Engineering
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Energy Storage Technology Comparison

- A knowledge guide to simplify selection of energy storage technology

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Abstract

The purpose of this study has been to increase the understanding of some of the most commonly used energy storage technologies. Also, the work aimed to collect numeric values of a number of common parameters used to analyze energy storage. These numeric values could then be used as basis for a first evaluation of the energy storage technology that is best suited to a given situation.

The method was divided into three main phases. The first phase was to gather information on the different technologies and to assess which of the information that was relevant to present in a technical survey called Energy Storage Technology Mapping. This part was done to achieve the goal of increase the insight of different energy storage technologies. The following phase was, on the basis of the numeric values presented in the technical survey, to develop a tool to facilitate the choice of energy storage technologies in different situations. The final phase consisted of a case study that was done to demonstrate the tool's utility and evaluate its performance.

Without comparing the studied technologies with a specific application in mind, the following was stated regarding the four categories of energy storage technologies:

- Electrochemical: high efficiency, short storage period
- Mechanical: large capacity and power, high initial investment costs and geographically limited
- Chemical: very long storage period, low efficiency
- Thermal: long lifetime and high efficiency, variable depending on the medium studied

From the literature study and the results a number of conclusions were drawn. Among other things, it was possible to conclude that environmental-, social- and ethical aspects should be taken into account as well as the geographical- and geological conditions. It was also possible to conclude that the technologies compared were found at different stages in terms of maturity and commercial use, which was reflected in the ability to find more general numeric values relative to the values linked to a specific application.

Sammanfattning

Syftet med denna studie har varit att öka förståelsen för några av de vanligaste energilagringsteknikerna. Utöver det syftade arbetet till att samla in numeriska värden för ett antal gemensamma parametrar som kan anses relevanta för att analysera energilagring. Dessa numeriska värden kunde sedan användas som underlag vid en första bedömning av vilken energilagringsteknik som är bäst lämpad i olika situationer.

Metoden var uppdelad i tre olika huvud faser. Den första fasen bestod i att samla in information om de olika teknikerna samt bedöma vilken av informationen som var lämplig att presentera i en teknisk kartläggning vid namn Energy Storage Technology Mapping. Denna del gjordes för att uppnå målet om ökad förståelse för de olika energilagringsteknikerna. Den efterföljande fasen bestod i att utifrån de numeriska värdena som presenterats i den tekniska kartläggningen ta fram ett redskap för att underlätta valet av energilagringsteknik vid olika situationer. Den sista fasen bestod av en fallstudie som gjordes för att demonstrera verktyget användbarhet samt utvärdera dess prestanda.

Utan att jämföra de studerade teknikerna med ett specifikt användningsområde i åtanke kunde följande konstateras gällande de fyra undergrupperna av energilagringstekniker:

- Elektrokemiska: hög effektivitet, kort lagringstid
- Mekaniska: stor kapacitet och kraft, stora investeringskostnader och geografiskt begränsade
- Kemiska: mycket lång lagringstid, låg effektivitet
- Termiska: lång livslängd och hög effektivitet, varierande beroende på studerat medium

Från litteraturstudien och resultatet kunde ett antal slutsatser dras. Bland annat var det möjligt att dra slutsatsen att miljö-, sociala- och etniska aspekter bör tas i beaktan liksom geografiska- och geologiska förutsättningar. Det gick också att dra slutsatsen att teknikerna som jämfördes befanns sig på olika stadier vad gäller mognad och kommersiellt bruk vilket återspeglades i förmågan att finna mer generella numeriska värden i förhållande till värden kopplade till ett specifikt användningsområde.

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Nomenclature

Abbreviation	Denomination
CAES	Compressed Air Energy Storage
CES	Chemical Energy Storage
ECES	Electrochemical Energy Storage
EST	Energy Storage Technologies
LAB	Lead Acid Batteries
LHS	Latent Heat Storage
LIB	Lithium Ion Batteries
MES	Mechanical Energy Storage
PCM	Phase Change Materials
PCT	Phase Change Temperature
PEM	Proton-Exchange Membrane
PHES	Pumped Hydro Energy Storage
RFB	Redox Flow Batteries
SHS	Sensible Heat Storage
SSB	Sodium Sulfur Batteries
TCES	Thermo-Chemical Energy Storage
TES	Thermal Energy Storage
TRL	Technology Readiness Level

1. Introduction

Before the industrial revolution during the 19th century, the need of energy was modest compared with today's situation. The energy need in the industrialized world increase in line with the technology advances made during the industrialization. One of the most important technical inventions is the discovery of electricity. Ever since electricity, in the 20th century become a matter of course in many industrialized societies; the energy need have increased significantly [1]. Today, comforts like hot water, air conditioner and outlets provided with electricity is taken for granted. Historically, the sources converting energy into electricity, heat and cold have been mainly non-renewable. Fossil fuels such as oil, petroleum and natural gas have filled our needs for a long period of time [1]. Production of heat, cold and electricity from these sources have the ability to adapt to demand, hence the need of supplementary energy storage is low. However, these energy sources are finite and have shown negative environmental impact. Apart from global warming, the increase in the different greenhouse gases contribute to ocean acidification, smog pollution, ozone depletion as well as changes to plant growth and nutrition levels [2].

Based on increased demand, the price of fossil fuels has firmly risen and a number of "crises" have had big economic impact. E.g. the first oil crisis in 1973 more than doubled the price of oil over night and led to great reactions worldwide [3]. Among other things, France then embark on a major nuclear power program to ensure its energy independence. Ever since, nuclear power accounted for the bulk of the electricity produced in France, corresponding to 75% of the electricity [4]. As a result of the decision, France has today (2016) almost the lowest cost of electricity in Europe and is highly energy independent. Also, the country has extremely low level of CO_2 emissions per capita from electricity generation because of the high proportion of nuclear power. Nevertheless, nuclear power has caused a number of serious accidents that has led to devastation results due to dangerously high concentrations of radioactive substances [2]. No major accidents have occurred in France but the radionuclides spread has affected large parts of the world, not only within the area where the accident happened.

Nuclear accidents and global warming as well as the rising price and limited amount of fossil fuels has increased the number of different energy sources and at the present time the proportion of renewable energy sources have increased [5]. Renewable energy sources such as sun- and wind power are less harmful to the environment and inexhaustible. However, they are unpredictable and more difficult to control. Therefore, one of today's largest challenges is to match the available energy with the energy demand in time, place and quantity [6]. This applies not only electricity but also thermal energy in the form of heat and cold. For example, if it is possible to store the energy generated from the sun during sunny days or summer seasons to times with less sun it can minimize the loss in heat from production to consumption. In that way it is possible to use the residual heat later on instead of using e.g. additional electricity to generate heat from an electrical source of heat during times with less sun.

Presently there is a great number of Energy Storage Technologies (EST) available on the market, often divided into Electrochemical Energy Storage (ECES), Mechanical Energy Storage (MES), Chemical Energy Storage (CES) and Thermal Energy Storage (TES). All the technologies have certain design and operational parameters that put constraints to when each are suitable to use. All of the technologies have their advantages and disadvantages therefore which are ideal in different situations and applications. The more mature technologies currently used are pumped hydro energy storage (mechanical), some batteries e.g. lead-acid- and sodium sulfur batteries (electrochemical) as well as sensible heat storage (thermal) [7] [8]. Even though the conventional technologies all are well known, the development in the field is vast and fast. This creates a need to a more in-depth knowledge of each technology to be able to find the one most suitable for each situation.

2. Background

Renewable energy sources is a hot topic due to global warming, several numbers of natural disasters etc. In order to optimize its use, energy storage have become interesting and there is quite a lot of ongoing research in the area. Research and many of the previous studies only examine and compare EST within the same category (electrochemical, mechanical etc.). This has been done in studies such as: [9], [10] and [11]. Also, many studies compare different EST with a particular application in mind or conversely, comparing different applications with a particular EST. This is exemplified in following studies: [12], [13] and [14]. However, there are gaps regarding more comprehensive comparison that makes it possible to analyze and compare the storage technologies independently of applications or category. This project is focusing on a bigger perspective and within this section the problem definition, the purpose, the scope of the project and the limitations encountered is presented.

2.1 Problem definition

Energy storage is a relatively new topic for research and many EST are immature and not commercially used at present (2016). This makes the lack of knowledge for several numbers of EST [15]. The often-limited knowledge makes it difficult to understand the advantages and disadvantages of different technologies but also to decide which storage technology that is most suitable for what application. Currently, these are the two major problems within this subject.

2.2 Purpose

The purpose with this study is to increase understanding of the most common EST. It is also to gather and present information and numeric values to develop a tool for facilitating a first evaluation of the type of the EST that is the most suitable for particular applications and geographical locations. By fulfilling these purposes the result aim to answer the question “which of the presented EST are most suitable for a given application?”.

2.3 Limitations

The number of EST available today is many and to be able to present a profound analysis some limitations have been necessary. The technologies treated within this thesis are limited to a number of eleven. The number of methods for further categorization of EST is many. In this study one of the most widely used method have been applied. That method is based on the form of energy stored in the system [15]. The technologies treated in this study have been divided into four categories. These categories and including technologies are presented in Figure 1 that aims to clarify the categorization. The choice of technologies is based on availability but also on the technology's potential and variation possibility. Some of the rather common technologies, e.g. flywheels have been excluded since some of its disadvantages makes it useful in only a limited range of application. Also, many of the technologies are available in different variants but since this project aims to facilitating a first evaluation, the technologies are limited to its basic design. The study is not geographically limited to France but it has been made with the country's conditions and currently energy storage situation in mind. Meaning, the purpose has been to provide a knowledge guide and a tool that could be used worldwide but examples and discussion have had focus on France.

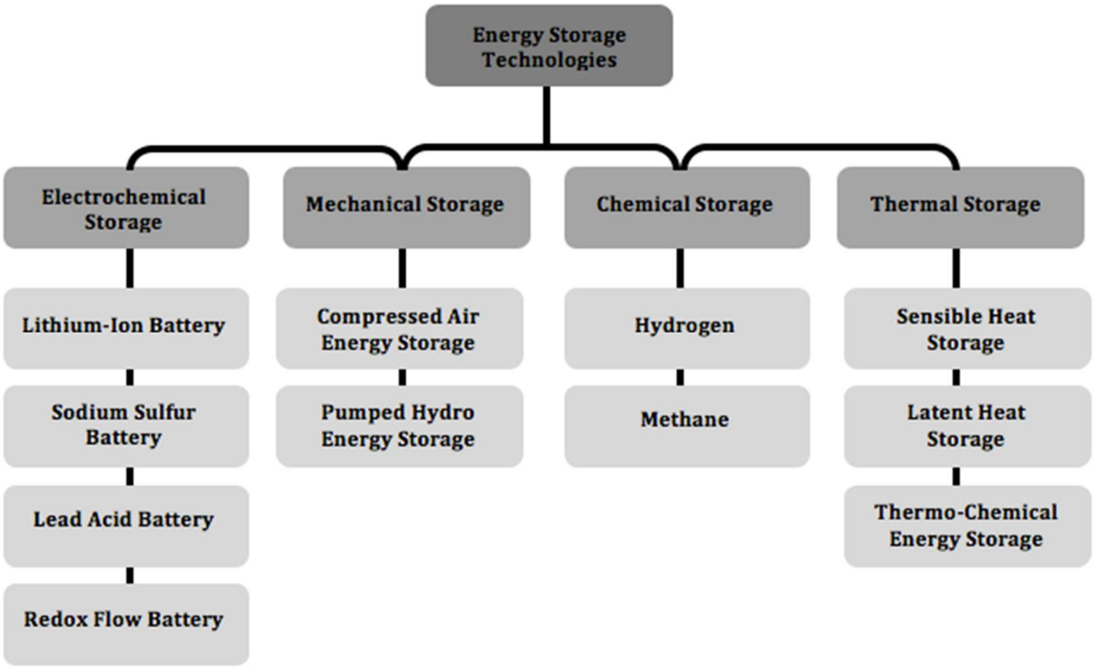

Figure 1: *Schematic illustration of the four categories and associated EST.*

3. Methodology

The methodology can be divided into three main phases. Initially, information about different EST were retrieved from various sources including scientific literature and publications but also relevant information found on web pages belonging to different organizations and companies. After enough data was gathered, the following phase was to critically analyze the data obtained and sort out relevant information to present in the literature study named Energy Storage Technology Mapping. The main approach was to map all of the applications and storage technologies based on a number of important parameters that the technologies had in common. These two phases main purpose was to collect and present relevant information in order to increase the knowledge of different EST.

Once the critical analysis and mapping was done, the terminative phase begun. This phase was a comparison of the technologies treated in the literature study. This comparison was based on the numeric values for each of the common parameters. The purpose of this phase was to present substrate and a tool to facilitating a first evaluation of what kind of EST that was most suitable for a given application. To finally demonstrate the tool's function and be able to evaluate its performance a small case study was done. A graphic illustration of the workflow and each part's purposes are presented in Figure 2.

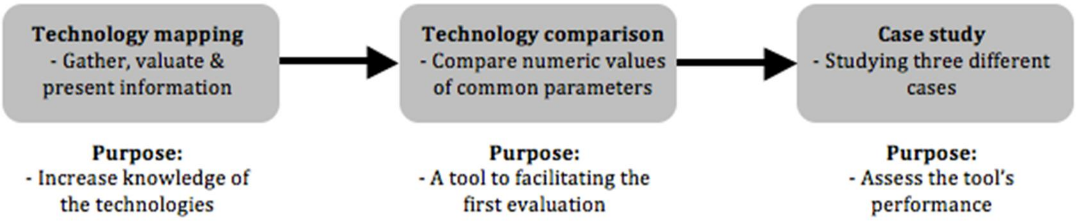

Figure 2: *Graphic demonstration of the workflow and purpose of each part.*

4. Energy Storage Technology Mapping

This part of the thesis is designed on the basis of the divisions presented in Figure 1. It therefore consists of sections (4.1 Electrochemical Storage, 4.2 Mechanical Storage, 4.3 Chemical Storage and 4.4 Thermal Storage) representing the four categories of technologies: ECES, MES, CES and TES. Furthermore, every section consists of two to four different sub sections (4.1.1 Lithium Ion Battery, 4.1.2 Sodium Sulfur Battery etc.) depending of the number of treated EST in each section. The name and number of technologies treated in each sub section is also illustrated in Figure 1.

Within each section presenting an EST the technology's technical construction including major components are described. Also, commonly used applications at the present time (2016) and the most crucial conditions and design and operational criteria are considered. Every section presenting an EST (4.1.1 Lithium Ion Battery, 4.1.2 Sodium Sulfur Battery etc.) lastly contains a table with numeric values of critical design and operational parameters, presented at the end of each section. This part aims to provide in-depth knowledge of each EST. In order to increase the understanding of each and every technology's readiness level, already at this point, Figure 3 is presented before the following sub sections. The rating is based on the extent to which the technology is applied and used in daily life.

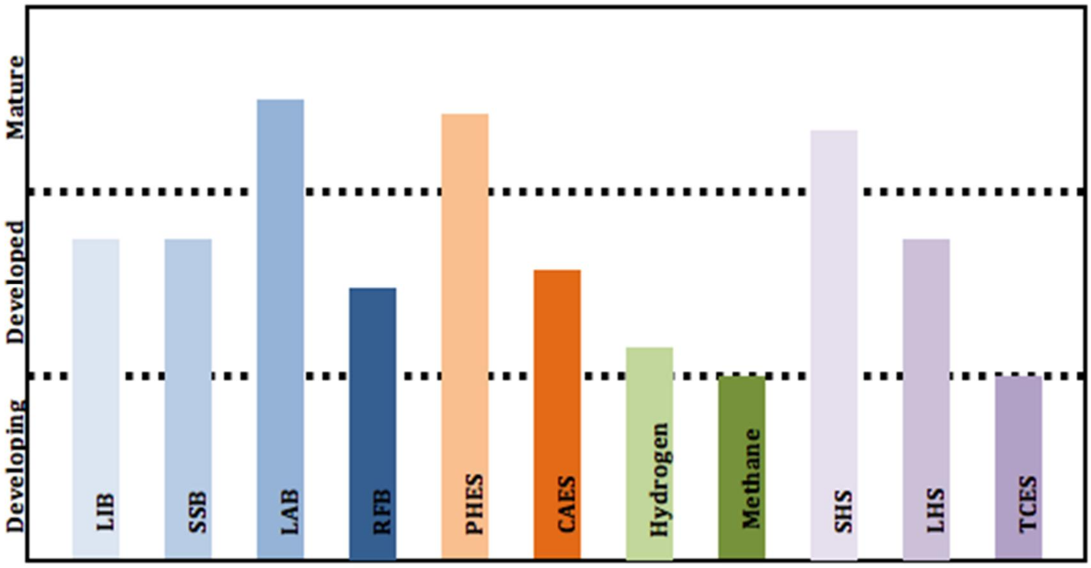

Figure 3: *Figure demonstrating the technology readiness level (TRL) of the different technologies* **[16]**.

4.1 Electrochemical Storage

ECES is a generic name for batteries being used to store energy. Batteries are electrochemical devices with the ability to readily convert the stored energy into electrical energy. Since they are portable and often quite small they can be located anywhere without geographical considerations [16]. Batteries can be either non-rechargeable (primary) or rechargeable (secondary), only rechargeable batteries are of interest for large-scale energy storage [2]. Batteries can also be either solid-state batteries or flow batteries. This section present a number of ECES technologies, including both flow- and solid state batteries.

4.1.1 Lithium Ion Battery

Lithium Ion batteries (LIB), in their most common form, consist of a positive electrode (cathode) of lithium oxides, a negative electrode (anode) of graphite and an electrolyte of a lithium salt and organic solvent [2]. Figure 4 is intended to clarify the technical design of the battery.

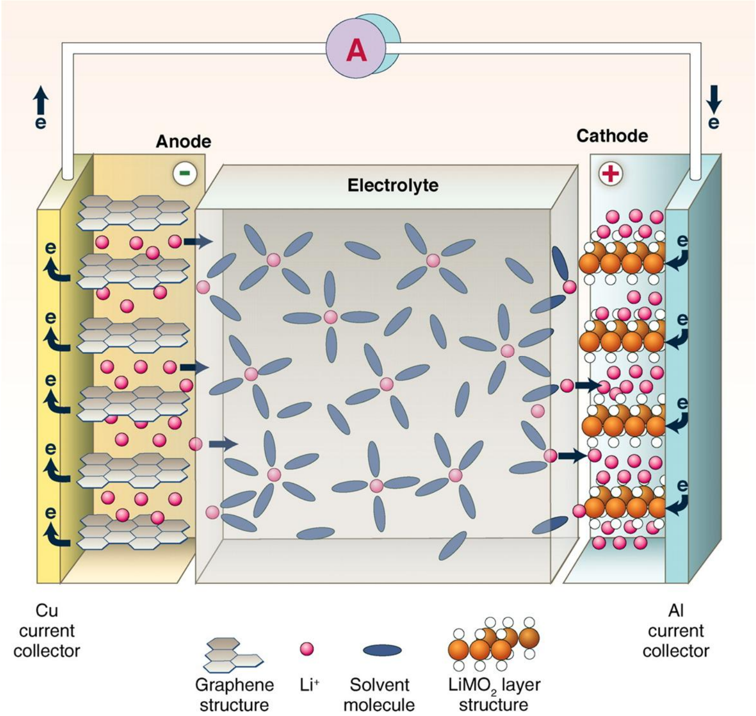

Figure 4: *Schematic diagram describing the design of a LIB* **[17]**.

Lithium has low density and large standard electrode potential resulting in batteries with low weight and high operating voltage [2]. Furthermore LIB have no memory effect[a], low self-charge and one of the best energy-to-mass ratio which makes them the main energy storage devices for portable electronics such as mobile phones, TVs and iPads [18]. Table 1 includes numeric values for several parameters in order to enable comparison between LIB and other EST. The properties have proven to be advantageous also for electric traction of vehicles, power tools and storage of intermittently available renewable energy hence LIB is increasingly common in these application areas [17]. Although LIB are extensively used in portable electronic devices and are the main focus for electrical vehicle applications, they are at present (2016) too expensive for large-scale grid storage. However, the research is extensive and in the United States there is a number of lithium-ion-based demonstrations that have recently been installed and tested. These systems would be capable of providing short-term power output stabilization for wind turbines but, compared with other options LIB are still too costly to use for application in longer term storage of wind energy [19].

France has one of the strongest economies in Europe and most of the French citizens have the ability to own portable electronics, including LIB. Therefore, the number of LIB is quite extensive in the country [20]. Furthermore, the number of plug-in hybrid and electrical vehicle has increased dramatically in France over the last couple of years [21]. The plug-in hybrid cars often use Nickel-metal batteries (NiMH) but all of the most bought electrical cars, such as Nissan Leaf and Ford Focus EV use LIB [22] [23].

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[a] No memory effect – the capacity is not reduced even though the battery is not fully discharged between charge cycles.

LIB has a large impact on metal depletion and the lithium mining's toxicity and location in natural environment can cause significant environmental-, social- and health impacts. Therefore its continued use needs to be monitored even if there is no immediate shortage of lithium at present (2016). Although, LIB are concededly less toxic than many other batteries, e.g. lead-acid batteries [24].

Advantages:
High efficiency [8]
Low weigh, small battery [26]

Disadvantages:
Expensive [25]

Table 1: *Numeric values of critical parameters for LIB*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
0.001-0.1 [27]	0.25-25 [28]	Day-month [29]	75-200 [8]	300 [30]	85-100 [27]	1000-4500 [31]	175-4000 [16][b]	500-2500 [16][c]

4.1.2 Sodium Sulfur Battery

Sodium Sulfur Batteries (SSB) consist of two active materials; molten sulfur as the positive electrode and molten sodium as the negative electrode. The battery is often referred to as NaS battery due to the chemical abbreviations of its two main components sodium (Na) and Sulfur (S). A solid ceramic, sodium alumina, separates the electrodes and serves also as the electrolyte [32]. A SSB is presented in Figure 5 that aims to clarify the battery's technical design.

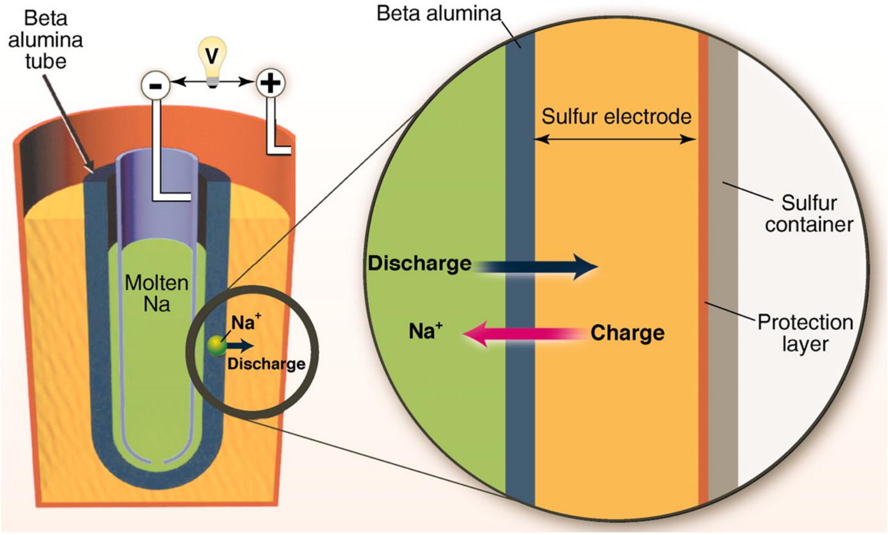

Figure 5: *Schematic diagram describing the design of a SSB* **[17]**.

These materials have the advantages of low density and cost. The specific energy of a SSB is high, the cycle lifetime is long compared to many other batteries and the charge efficiency is high [2]. Because of these advantages SSB are considered an attractive candidate for large-scale energy storage applications [16]. Even so, both sodium and sulfur have a common characteristic of being highly corrosive

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[b] From 2015
[c] From 2015

which might cause corrosive problems. Combined with the fact that the SSB operates at a temperature of around 300°C makes the batteries, as mentioned most suitable for large-scale energy storage such as for the power grid [2]. Numeric values for several parameters are presented in Table 2 that aims to enable a comparison between SSB and other EST.

Reunion Island Pegase Project is a project where SSB have been used to facilitate load leveling and renewable integration at the Reunion Island, an insular region of France located in the Indian Ocean. The SSB have a power level of 1MW and can provide the average usage of 2000 households [33]. Also, over the last decade SSB has seen the largest number of demonstrations and field tests globally, e.g. over 190 sites in Japan. Although, further uptake appears to have slowed down due to recent safety concerns [19].

Advantages:	Disadvantages:
Long lifecycle [8]	Highly corrosive behavior [8]
	High production cost [34]
	High operating temp. [35]

Table 2: *Numeric values of critical parameters for SSB*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
1-50 [36]	≤300 [28]	Day [37]	150 [2]	150-250 [15]	75-90 [8]	2500 [16]	1000-3000 [16][d]	300-500 [8][e]

4.1.3 Lead Acid Battery

Lead Acid Batteries (LAB) was invented by the French physicist Gaston Planté already in 1859 and was the first practical rechargeable battery. LAB normally consists of lead oxide (PbO_2) cathodes and lead (Pb) anodes immersed in sulfuric acid (H_2SO_4), with each cell connected in series [38]. The technical design is illustrated in Figure 6 including the main components just mentioned.

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[d] From 2015

[e] From 2015

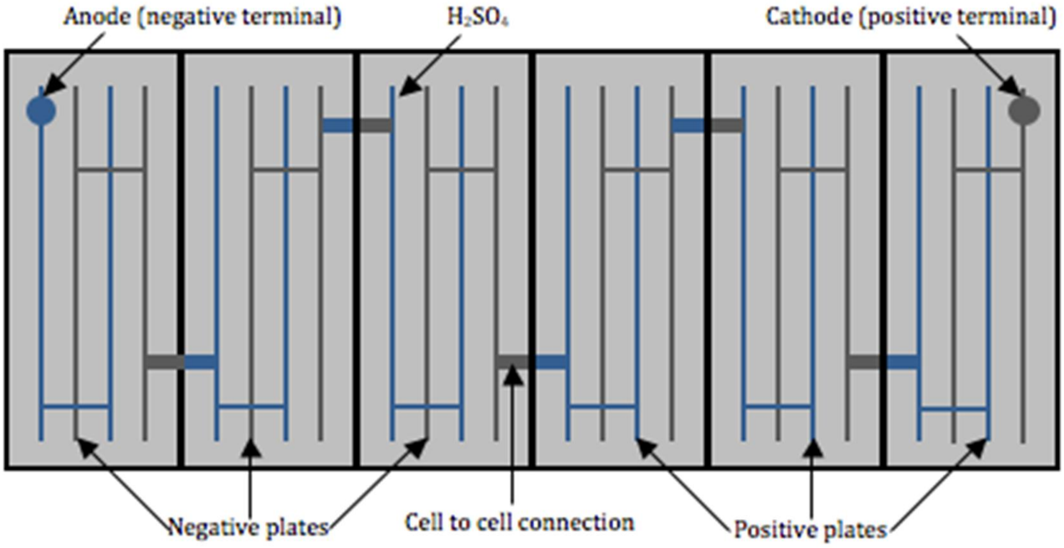

Figure 6: *Lead acid battery with six cells: output voltage ≈12V* [2].

Comparing with other solid state batteries, the density is quite low but it can provide a large current that is a great advantage in many applications such as starting a car [2]. LAB is widely used even when surge current[f] is not important and other designs could provide higher energy densities. This is because LAB is cheap compared to newer technologies. Therefore LAB is also used for storage in backup power supplies as well as for wheelchairs, golf cars, personnel carriers and emergency lighting [39]. LAB emits lead, which is toxic heavy metal with severe impacts on the global bioaccumulation, also with potential risks to human health. However, LAB can be recycled several hundred times and are currently the most recycled consumer product. Given that the LAB is recycled these batteries' disposal is extremely successful from both cost- and environmental perspectives [40]. Table 3 includes numeric values for several parameters and aims to enable comparison between LAB and other EST.

Advantages:	Disadvantages:
Can provide high current [2]	Contains toxic substance [8]
Mature technology [8]	Short lifetime [8]
Highly recycled [40]	

Table 3: *Numeric values of critical parameters for LAB*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
0-40 [8]	0.25-50 [41]	Day-month [29]	20 [2]	70 [30]	70-90 [8]	500-1000 [16]	300-600 [16][g]	200-400 [8][h]

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[f] Surge Current - a sudden increase in current.

[g] From 2015

[h] From 2015

4.1.4 Redox Flow Battery

In Redox Flow Batteries (RFB), two liquid electrolytes are pumped to the opposite sides of the electrochemical cell. The two liquid electrolytes contain dissolved metal ions as active masses and they stay dissolved in the fluid electrolyte, hence no phase change of these active masses takes place. The negative and the positive redox species are contained in separate storage tanks and are separated by an ion-selective membrane. Redox-active ions undergo reduction- or oxidation reactions when they are in contact or very near the current collector. However, the membrane allows the transport of non-reaction ions to maintain electrolyte balance and electro neutrality [27]. Figure 7 represents the basic principle of a RFB with the intent to enhance understanding of the battery's appearance and function.

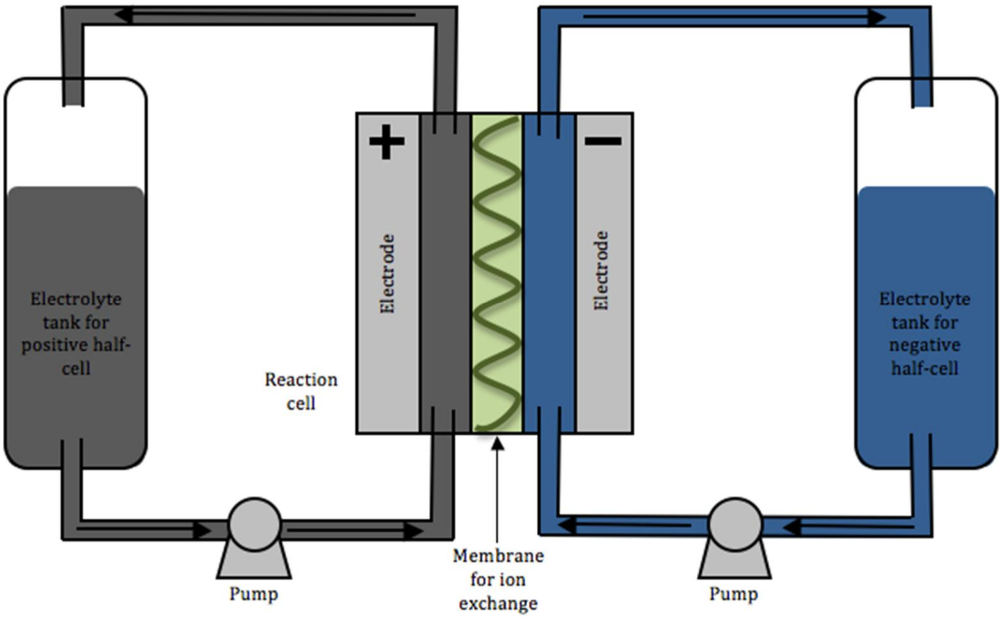

Figure 7: *Basic concept of a Redox Flow battery. Based on* [19].

Unlike traditional, solid state batteries that store energy within their electrodes, RFB store their electrical energy within one or more electro-active[i] species dissolved into liquid electrolytes. The size and design of the electrochemical cell defines the power density while the energy density or output depends on the size of the tanks [42]. Some of the advantages of the RFB are high efficiency, long cycle life, flexible layout and an ability to store large amount of energy [43]. Although, compared with other batteries their density is rather low and the design might be complicated due to the fact that it often includes pumps, sensors, control units etc. To enable comparison between RFB and other EST some numeric values for several parameters are presented in Table 4. For a number of reasons, including the relatively bulky size of RFB, they are most suitable for high power rechargeable storage. Thus, most of the batteries are currently used for grid energy storage, such as being attached to electrical grids or power plants. France has, at the present time (2016) no RFB plants used for greater amount of energy storage [44].

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[i] Electro-active - exhibiting electrical activity or responsive to electrical stimuli.

Advantages:	Disadvantages:
Short time to fully charge [8]	Low specific energy [8]
High design flexibility [19]	Electrical current leakage [8]
Fully charged/discharged without loss of capacity [19]	

Table 4: *Numeric values of critical parameters for RFB*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m^3]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
0.03-7 [27]	<10 [8]	Day-month [29]	10-30 [8]	25-35 [15]	75-85 [27] [8]	12000 [45] [16]	600-1500 [16][j]	150-1000 [8][k]

4.2 Mechanical Storage

To store mechanical energy, kinetic energy is converted into electrical energy by using physical movements. Two of today's most common technologies; compressed air and pumped hydro storage are described within this section. Both of these two ECES technologies are location limited that makes it difficult to store energy over longer distances [8]. The MES technologies have however many other advantages that will be mentioned within this section. The section includes technical descriptions of the two MES technologies include general information and technical design as well as numeric values of some of the most impacting parameters.

4.2.1 Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) is based on air being pumped by an external electricity source to a high pressure into a large reservoir during periods of low demands (off-peak) and is released later during periods of high demands (peak-load) [2].

Regarding large-scale energy storing CAES systems can store the air either adiabatically or diabatically. An adiabatic process occurs without gain or loss of heat, where for a diabatic process the opposite is true [46]. Rather technically, in a diabatic CAES system, a compressor driven by a motor compresses the air during the charging process. During the compression process the air heats up and a radiator removes the heat. The energy is stored as compressed air in a cavern. During discharging, the air cools down due to its expansion and has to be heated up by burning conventional fuel or biofuel. After being heated, the air drives a turbine/generator unit, which feeds power into the grid. However, when the CAES is adiabatic the heat generated during the compression process is stored. The stored heat is then used to heat up the air while it expands in the discharging process. Therefore a much higher efficiency, increased by around 20% can be achieved if the heat of compression is recovered and stored adiabatic. Also, the operation is then completely CO_2-free as no fuel is required which is desirable in an environmental perspective [47]. All part of the process is

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[j] From 2015

[k] From 2015

illustrated for both a diabatic and an adiabatic system in Figure 8 that depicts a schematic of a CAES system.

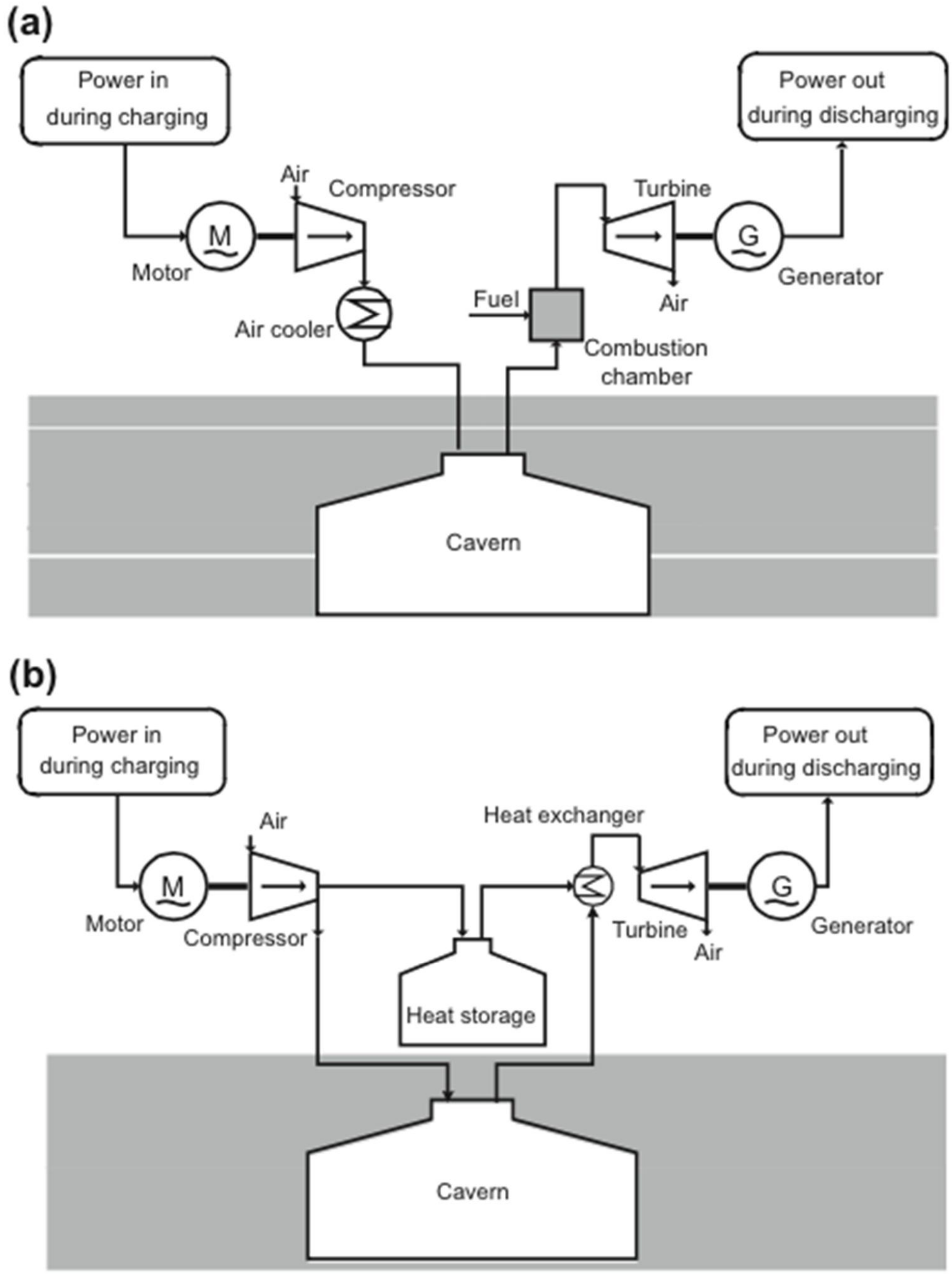

Figure 8: *Schematic diagram of (a) diabatic and (b) adiabatic CAES system* **[47]**.

At present time there are only two CAES plants in operation worldwide. The oldest one was put in operation 1978 and is located in Huntorf, Germany (320MW) and the newer one was put in operation 1991 and is located in McIntosch, USA (110MW). Both of these CAES system store the air diabatically and use natural gas as a heat source for the discharging process, which reduced the overall efficiency (current efficiency: 42% respectively 54%) [47]. Nevertheless, adiabatic stored air is a subject of ongoing studies, with no utility scale plants at the year of 2016 [48].

Due to the low storage density very large storages are required independent of the air being stored adiabatic or diabatic. Salt is self-sealed under pressure and consequently salt caverns are practically suitable for CAES. It is also possible to use natural aquifers if no suitable salt formations are present [2]. The used storage media is inexpensive leading to the advantage of a low energy cost for CAES. Other advantages are quick start-up (typically 10 minutes), long storage capability and large storage capacity [49]. Numeric values for some parameters are presented in Table 5 in order to be able to compare CAES with other EST.

One of the reason there is no CAES system operating in France at the present time (2016) is due to the fact that CAES systems need certain geological requirements (e.g. salt caverns) for their installation. These requirements are limited worldwide and potential locations in Europe are located in the United Kingdom, northern Germany and in the Netherlands; hence France not included. Nevertheless, several concepts are under development for air tanks so that it will be possible to overcome these restrictions [47].

Advantages:	Disadvantages:
Large storage capability [28]	Geological requirement [47]
Long life (reservoir, compressor, turbine) [47]	High investment cost [47]
Small footprint on surface (underground storage) [47]	

Table 5: *Numeric values of critical parameters for CAES*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
5-300 [50]	≤250 [28]	Day [29]	30-60 [50]	2-6 at 70-200bar [47]	60-79 [16]	8000-12000 [7]	1250 [47][l]	50-100 [8][m]

4.2.2 Pumped Hydro Energy Storage

In Pumped Hydro Energy Storage (PHES) systems, water is pumped to an uphill reservoir from a low-level reservoir during periods of low demands. This process is followed by discharging the stored water back to the lower reservoir during periods of peak demands. The discharged water then drives the generator to produce electricity when needed. The same generator is being used for pumping the water uphill, consequently used as a reversible pump-turbine [2]. A detailed layout of a PHES system is illustrated in Figure 9.

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[l] From 2014

[m] From 2015

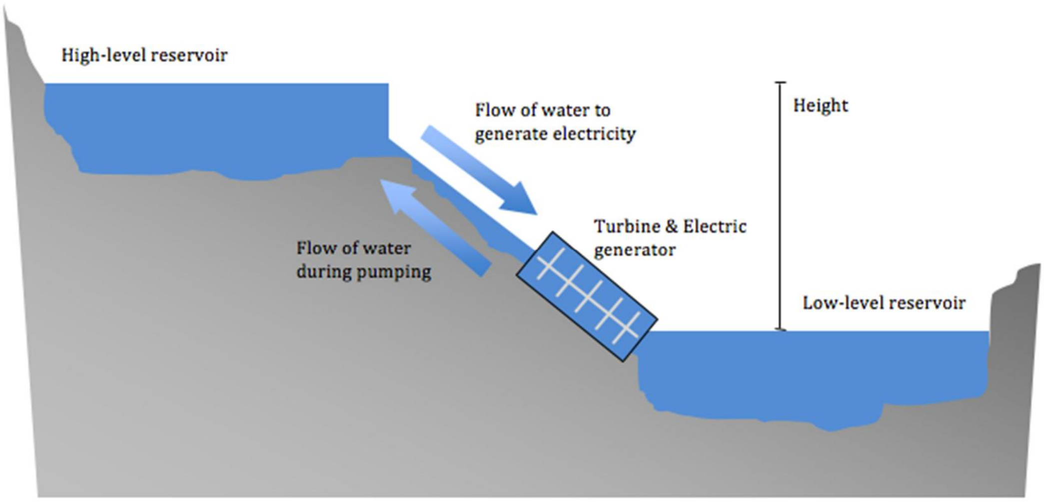

Figure 9: *Schematic of PHES with a combined turbine and electric generator. Redrawn based on* [51].

PHES help utilities to avoid using expensive backup power plants and can make the power network less volatile. Compared to other EST, PHES has the largest storage capacity and efficiency of around 70-85% [34]. Because of its ability to provide high power and capacity the technology is favored by high demand. It is however stationary and have geographical restrictions which makes its flexibility rather low [52]. PHES have short start-up time and can continuously respond to fluctuations and to a sudden surge in demands, which is a major advantage [2]. The technology has however geographical restrictions and requires height differences and major quantities of water [47]. A number of parameters including numeric values for PHES are presented in Table 6 that aims to enable comparison between PHES and other EST.

This storages technology is often combined with nuclear power production, since the nuclear reactor needs to produce a steady output in order to minimize ageing effects and to maintain reactor stability [2]. Due to the fact that France is one of the world's biggest nuclear producer and also has hilly areas in the southeast this is an advantageous storage technology for France. Currently, France has a dozen plants in operation with Grand'Maison Dam as the most powerful [53]. Grand'Maison Dam with an impressive drop of 950 meters and a storage capacity of 140 million m^3 of water is located in the Romanche valley, not very far from the Italian border. The power station, including 12 turbine sets has a total output of 1820MW and an annual production of 1420GWh [54]. Also, globally PHES is the major energy storage technology at present (2016) and was set in operation already in the early twentieth century. These systems are normally used as medium-term storage systems, typically able to store between 2 and 8 hours. Besides being the most widely used technology for energy storage, PHES is also a very developed and mature technology [47].

Advantages:	Disadvantages:
Mature technology [8]	Geographical restrictions [47]
Very long lifetime [47]	Long construction time [8]
	Low energy density [47]
	High surface footprint [55]

Table 6: *Numeric values of critical parameters for PHES*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
<3100 [55]	Small: ≤5000 Large: ≤140000 [41]	Day-month [47]	0.28 at 100m [30]	0.28 at 100m [30]	65-82% [56] [47]	10000-30000 [7]	600-2000 [52][n]	80-200 [8][o]

4.3 Chemical Storage

Endothermic chemical reactions require energy to build chemical bonds in a high-energy product while exothermic reactions release energy, forming a lower-energy product. This makes it possible to develop energy storage systems that store electricity and heat in the bonds of chemical compounds (atoms and molecules) to use them for a future energy supply. The following section describes two different technologies of storing energy chemically.

4.3.1 Hydrogen

Hydrogen can be produced by reforming of natural gas with steam or by the electrolysis of water into oxygen and hydrogen. Presently, reforming of natural gas is more common but electrolysis of water is more convenient in an environmental perspective. That is due to the fact that electrolysis of water can be done directly from renewable power. The efficiency is lower using electrolysis of water but carbon dioxide, which is a by-product during the reforming of natural gas, is absent [57]. The electrolysis operates as follows: Water (H_2O) consists of hydrogen (H) and oxygen (O) and by using electrical energy the electrolysis can split water into these two basic elements. Technically, two electrodes in a basic electrolysis are connected to a direct current (DC) supply and once a sufficient high cell voltage is applied to the cell, a redox reaction occurs. The redox reaction produces oxygen at the anode (positive electrode) and hydrogen at the cathode (negative electrode) [58]. In order to separate the reaction compartments for hydrogen and oxygen a proton conducting polymer membrane is used. The membrane is called Proton-Exchange Membrane (PEM) and besides from separating the compartments it also provides the ionic contact between the electrodes, which is essential for the electrochemical process [30]. Figure 10 shows how the production of the actual gas takes place on the surface of the two precious metal electrodes.

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[n] From 2014

[o] From 2015

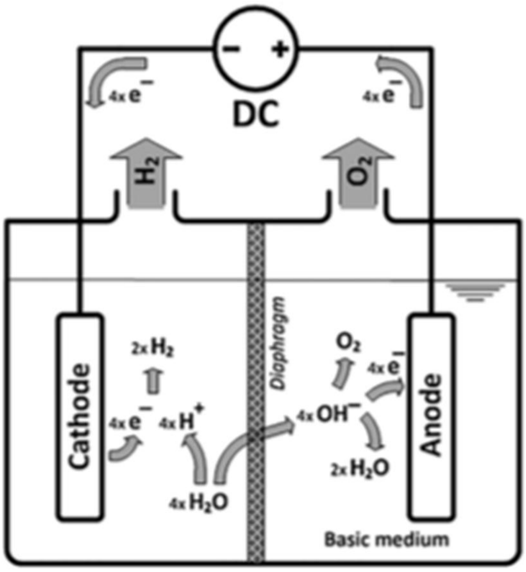

Figure 10: *The electrolysis of water; showing where the hydrogen and oxygen are produced as well as the semipermeable diaphragm between the two half-cells that allows the separation of the two gases* **[58]**.

Independent of production technique small amounts of hydrogen has to be either compressed into pressurized vessels or liquefied in order to get stored. Also, nanotubes or solid metal hydrides can serve as storage units for hydrogen with a very high density while man-made underground salt caverns can store truly great amounts of hydrogen. This enables long-term storage; hence this technology permits leveling during longer periods of flaws or excess/deficit of wind- and solar production and can even balance seasonal variations [59]. After storing, hydrogen can be converted back to heat or electricity in an internal combustion engine or a fuel cell. At present (2016), this technology plays only a minor role in the energy sector and can be used as a fuel for portables (vehicles) such as rockets [30]. Although, in recent years energy storage systems based on hydrogen are receiving increasing attention; the reason is particularly the technology's possibility to integrate renewable energy sources [50]. To be able to compare hydrogen storage with other EST a number of numeric values for several parameters are presented in Table 7.

France has a rather unique test platform with this kind of energy storage. The platform was commissioned 2012 and is called the MYRTLE platform. The platform connects solar panels to a hydrogen-based energy storage system. The system is joined with the power grid, which gives the opportunity to solve problem of intermittency. The system also offers greater flexibility for grid operations. Using this unique system the research team at the University of Corsica associated with CNRS (Centre national de la recherche scientifique) and CEA (Commissariat à l'énergie atomique et aux énergies alternatives) have the opportunity to plan and test various energy management scenarios [60].

Advantages:	Disadvantages:
Can store long time [34]	Low efficiency [55]
No emission (coupled to renewable sources) [34]	Require costly components [34]
Environmentally benign operating characteristics [8]	

Table 7: *Numeric values of critical parameters for hydrogen*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
Varies	Varies	Hours-months [31]	33330 [61]	2.7-160 at 1-700bar [29]	20-50 [8]			6-20 [8][p]

4.3.2 Methane

Methane can be created in a multi-step process. The process starts with electrolysis where water is divided into hydrogen and oxygen (see section 4.3.1 Hydrogen) followed by a methanation reaction such as the Sabatier process. In the Sabatier process methane and water are being produced by letting the hydrogen react with carbon dioxide (CO_2). The produced methane can then be stored in gas caverns or more ideally in the natural gas grid and used temporarily and spatially, adaptably for balancing power by producing electricity during periods of high demand [6]. The Sabatier process is nowadays often discussed as “Power to Gas” approach [62]. The interest of methane-based energy storage has risen because of its ability to effectively reduce gas emissions [63]. Methane is easy to store and in most countries around the world, including France there are existing infrastructures for domestic transport and international trade [64]. The two by-products of this process; water and carbon dioxide are both being recycled for further electrolysis and as means to boost the Sabatier process respectively. Due to the fact that it is possible to store methane in the already existing natural gas grid and that the by-products are all recyclable this technology is favorable for both social and environmental aspects.

A result of both the electrolysis and the methanation is excess heat, providing an additional area of use for this technology. By supplementing the process with heat storage devices to take care of the excess heat this technology can contribute conditions for balancing the need for heat as well.

Advantages:	Disadvantages:
Can store long time [65]	Low efficiency [6]
Easy to store [64]	
Long distance transport available [64]	

Table 8: *Numeric values of critical parameters for methane*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
Varies	Varies		10000 [61]	360-1200 at 200bar [31]	28-45 [6]			

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[p] From 2015

4.4 Thermal Storage

By using TES technologies it is possible to store thermal energy by heating or cooling a storage medium. The stored energy can then be used later on for cooling- and heating applications as well as for power generation. Sensible heat, latent heat and chemical reactions are the three primary ways materials can reserve heat [66]. These three different technologies will hereafter be explained by presenting technical process, general information as well as numeric numbers for several critical parameters.

4.4.1 Sensible Heat Storage

Sensible Heat Storage (SHS) is a mature technology and is about storing thermal energy by cooling or heating either a liquid or a solid storage medium [67]. The name SHS is often used regardless of it is heating or cooling that is being applied. The storage is based on the temperature difference in the material. The technology offers a capacity that is limited by the specific heat of the storage medium [11]. Compared with other SHS media, water has the highest specific heat, which currently (2016) makes it the most favorable material for heat storage in residential applications. Two of the most common water-based storage systems are water tanks and aquifer storage systems. Figure 11 shows a hot water tank used to store the solar energy collected via a solar collector. As seen in the figure cold water enters at the bottom of the hot water tank. While passing the collector, the cold water gets heated by the thermal energy converted from solar energy emitted from the sun. Finally the water delivers heat at the top portion of the water tank. Regarding the water tank, water stratifies naturally because the density increases at lower temperature. Therefore, the hot water flows to the top while the cold water remains at the bottom, and the intermediate region is the thermocline [68].

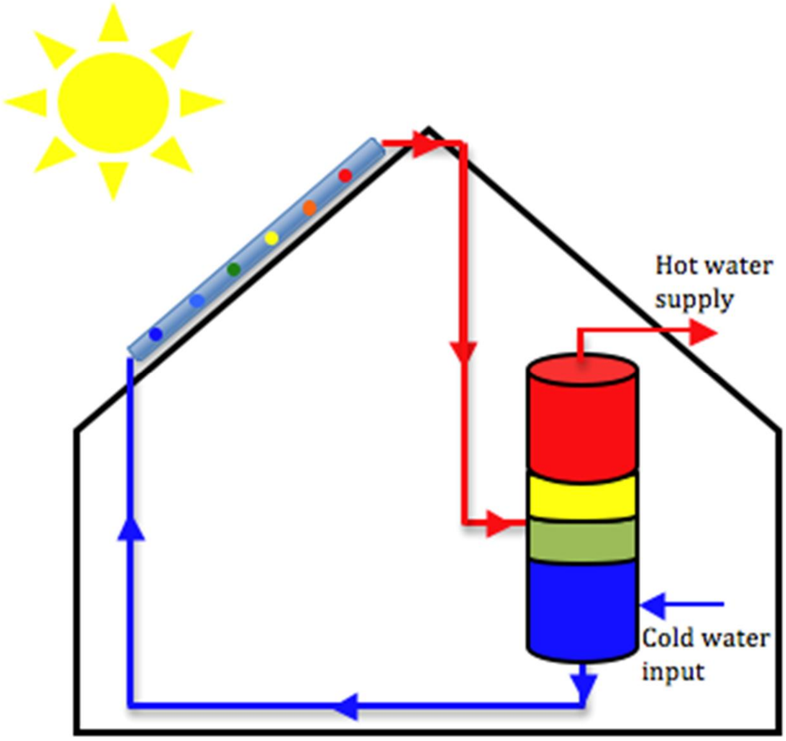

Figure 11: *Hot water tank connected to a solar collector, common application for SHS systems. Based on* **[68]**.

In order to minimize the thermal losses during storage, the heat transfer medium is usually kept in storage tanks with high thermal insulation. For customarily large-scale applications of storing sensible heat in both solid and liquid media underground storage is being used. SHS requires large quantities and volumes of materials, as well as proper design due to low energy density and the possibility to discharge thermal energy at constant temperatures. The storage capacity and the efficiency are quite variable as they depend on the specific heat of the storage medium and thermal insulation technologies that could be quite varying [11]. To enable comparison between SHS and other EST numeric values for several parameters are presented in Table 9.

Advantages:

Simple application with available materials [8]
Long lifetime [8]
Cost-effectively [11]
Can store long time [11]

Disadvantages:

Large volume needed [8]
Geological requirements [68]
Heat loss to the ambient [68]

Table 9: *Numeric values of critical parameters for SHS*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m^3]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
0.001-10 [11]		Day-year [11]	10-50 [11]	25 [11]	50-90 [11]			0.1-13 [11][q]

4.4.2 Latent Heat Storage

Latent Heat Storage (LHS) involves storing thermal energy in a material, known as a phase change material (PCM). PCM change phase at a certain temperature called the phase change temperature (PCT). Rather technically, the chemical bonds in the PCM will start to break up when the temperature increase above a certain point, the PCT. Also at that point, the material changes from solid to liquid due to the fact that the material, in an endothermic reaction, will absorb the heat. Similarly, as the temperature decrease, the material will return to a solid state since the PCM desorbs heat in an exothermic reaction. By controlling the temperature within a specific rate it is possible to store the energy used to alter the phase of the material [69]. In order to store cold, the process is reversed but the name of the technology usually refers to the same name, LHS.

The storage capacity of a PCM is equal to the phase change enthalpy at the PCT plus the sensible heat/cold stored over/under the whole temperature range of the storage. Therefore the storage capacity is greater for this technology than for SHS. This is due to the additional storage capacity associated with the latent heat/cold of the PCT, per mass or volume of material. Numeric values for capacity and several other parameters are presented in Table 10 that aims to enable comparison between LHS and other EST. By using this technology it is also possible to determine a target-oriented discharging temperature that is set by the almost constant PCT [11]. Beyond, the solid-liquid state there are three other states that can classify the changing of the material: solid-solid, gas-solid

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[q] From 2013

and gas-liquid [66]. The technology is well suited for temperature regulation as a result of the sharp change in the storage capacity at a point of a single temperature, the PCT. E.g. mixing PCM into a building material could increase the thermal capacity of a wall manifold [70]. Using a variety of techniques and materials, LHS can be used for both short-term (daily) and long-term (seasonal) energy storage [11].

<u>Advantages:</u>	<u>Disadvantages:</u>
Small volumes [8]	Low thermal conductivity [8]
High storage density (within a small temp.) [71]	Corrosive nature of material [8]

Table 10: *Numeric values of critical parameters for LHS*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m^3]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
0.001-1 [11]		Hour-week [11]	50-150 [11]	100 [11]	75-90 [11]			10-56 [11][r]

4.4.3 Thermo-Chemical Energy Storage

Thermo-Chemical Energy Storage (TCES) is based on storing thermal energy using chemical reactions. The basic principle of TCES is following; the initial condition is two or more components combined in a chemical compound. The compound is than broken by adding heat and the divided components are then stored separately until a demand arises. During periods of high demand the components are reunited into a chemical compound and heat is released. The released heat from the reaction constitutes the storage capacity [11]. Both SHS and LHS are most often limited in time due to heat losses. TCES differs since it enables to bridge long duration periods between demand and supply. This makes TCES particularly suitable for large-scale electricity generating [29].

Thermo-chemical reactions can be used to accumulate and discharge cold and heat on demand but also to regulate humidity in a variety of applications using different chemical reactants. The efficiency of this technology is in the range of 75% to nearly 100% and the TCES materials have among the highest density of all storage media, hence this technology has great potential. However, storage technologies based on TCES are mostly under development and demonstration and further improvements are necessary to make this technology commercially available [11]. Table 11 includes numeric values for several parameters that aims to enable comparison between TCES and other EST.

<u>Advantages:</u>	<u>Disadvantages:</u>
Long distance transport available [8]	Expensive [8]
High efficiency [11]	Technically complex [8]
Highly compact energy storage [8]	High capital cost [72]

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[r] From 2013

Table 11: *Numeric values of critical parameters for TCES*

Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]
0.01-1 [11]		Hour-week [29]	120-250 [11]	120-250 [29]	75-100 [11]			

5. Technology Comparison – Results and discussion

It is well recognized that no single EST can meet the requirements for all applications, which creates a need for a comprehensive analysis of the different EST. This section presents the results of this study to enable a comparison between the technologies and be able to answer the question “which of the presented EST are most suitable for a given application?”. The section also includes a case study and an overall discussion.

5.1 Comparison of different energy storage technologies

In the literature study, in section 4. Energy Storage Technology Mapping, values describing the characteristics of each EST included in the study have been explored. The result can be seen in Table 12, which gives the ability to compare and analyze the different EST in a simplified matter. Table 12 is also the basis of the following case studies and the overall discussion. The numeric values for Power Cost and Energy Cost are from year 2015 if nothing else is specified.

Table 12: *Energy storage technology comparison table*

Storage Technique	Output	Power [MW]	Capacity [MWh]	Storage Period [time]	Specific Energy [kWh/ton]	Energy Density [kWh/m³]	Efficiency [%]	Lifetime [#cycles]	Power Cost [$/kW]	Energy Cost [$/kWh]	Maturity
LIB	Electricity [55] [72]	0.001-0.1 [27]	0.25-25 [28]	Day-month [29]	75-200 [8]	300 [30]	85-100 [27]	1000-4500 [31]	175-4000 [16]	500-2500 [16]	Commercialized [7]
SSB	Electricity [55] [72]	1-50 [36]	≤300 [28]	Day [37]	150 [2]	150-250 [15]	75-90 [8]	2500 [16]	1000-3000 [16]	300-500 [8]	Commercialized [7]
LAB	Electricity [72]	0-40 [8]	0.25-50 [41]	Day-month [29]	20 [2]	70 [30]	70-90 [8]	500-1000 [16]	300-600 [16]	200-400 [8]	Mature [7]
RFB	Electricity [55] [72]	0.03-7 [27]	<10 [8]	Day-month [29]	10-30 [8]	25-35 [15]	75-85 [27] [8]	12000 [45] [16]	600-1500 [16]	150-1000 [8]	Demo/early commercialized [41]
CAES	Electricity [55] [72]	5-300 [50]	≤250 [28]	Day [29]	30-60 [50]	2-6 at 70-200bar [47]	60-79 [16]	8000-12000 [7]	1250 [47][s]	50-100 [8]	Demo/early commercialized [41]
PHES	Electricity [55] [72]	<3100 [55]	Small: ≤5000 Large: ≤140000 [41]	Day-month [47]	0.28 at 100m [30]	0.28 at 100m [30]	65-82% [56] [47]	10000-30000 [7]	600-2000 [52][t]	80-200 [8]	Mature [7]
Hydrogen	Electricity [55] [72], Thermal	Varies	Varies	Hours-months [31]	33330 [61]	2.7-160 at 1-700bar [29]	20-50 [8]			6-20 [8]	Developing/demo [15]
Methane	Electricity [63]	Varies	Varies		10000 [61]	360-1200 at 200bar	28-45 [6]				Developing [73]

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[s] From 2014

[t] From 2014

						[31]					
SHS	Thermal [55]	0.001-10 [11]		Day-year [11]	10-50 [11]	25 [11]	50-90 [11]			0.1-13 [11][u]	Commercialized [8]
LHS	Thermal [55]	0.001-1 [11]		Hour-week [11]	50-150 [11]	100 [11]	75-90 [11]			10-56 [11][v]	Commercialized for some temperature and materials [8]
TCES	Thermal [55] [72]	0.01-1 [11]		Hour-week [29]	120-250 [11]	120-250 [29]	75-100 [11]				Developing/demo [8]

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[u] From 2013

[v] From 2013

Reviewing the results in Table 12 it is noted that the ECES technologies (LIB, SSB, LAB and RFB) in general have the highest efficiencies but are expensive and have fairly limited storage periods. Based on that it is possible to say that these technologies are the most suitable for short-term energy storage applications such as frequently regulations, voltage support and variable supply resource integration.

The two MES technologies (CAES and PHES) have the highest power and capacity but are less effective. Both of these two technologies have high initial investment costs and long lifetime that make them profitable mainly in the mid/long-term perspective. That is reflected also in columns 10 and column 11 in Table 12, the cost is rather low despite the large initial investment cost. Therefore, these technologies can be considered the most suitable for applications such as arbitrage, black start and off-grid.

The EST with the lowest efficiency is linked to the two CES technologies (Hydrogen and Methane). Although, as presented in column five they both have the ability to store energy during long time periods, which is an advantage compared to the other technologies. Due to the very long storage period these two technologies can be considered the most suitable technologies for applications such as seasonal storage.

The TES technologies are more problematic to directly compare with the other technologies since they have a different output. Also, since the results of the three TES technologies differ rather significantly it is more difficult to make considerations linked to the TES technologies in general. However, they have the advantage of long lifetimes and high efficiency. It must be noted that, as mentioned in section 4.4 Thermal Storage the efficiency depends on the storage medium and is therefore quite variable. These technologies are the most suitable for applications such as combined heat and power, waste heat utilization since their desired output matches the output of the TES technologies.

Without having a particular application in mind, it is difficult to make further comparison based on the results presented in Table 12. Therefore, a number of applications will be studied in a case study in order to be able to answer the thesis's main question “which of the presented EST are most suitable for a given application?”.

5.2 Case study: energy storage comparison at three different cases

This sub section presents a case study based on three different cases. The case study is based on three different kinds of applications that are further described within Appendix A. Other common applications are also described within that appendix so that similar studies can be done in the future using other applications but still based on the results presented in Table 12.

5.2.1 Case nr 1 – Voltage support

From Appendix A it is possible to find following conditions for given application:
Output: Electricity
Size: 1-40MW
Storage period: 1second-1minute

Cycles: 10-100 per day

From the first condition (output) it is possible to exclude all three TES technologies since their output is thermal. From the second condition (size) it is possible to exclude the two MES technologies because they provide significantly more power. Also, two of the four ECES technologies can possibly be excluded since their power is rather limited and the price higher, namely, LIB and RFB. The third condition (storage period) makes it possible to also exclude the two CES technologies since they are more ideal in terms of long-term energy storage. This means that it remains only two possible technologies: SSB and LAB.

Their efficiencies and ability to provide power is rather equal. If choosing SSB it can be assumed that the lifetime would be more than doubled than if choosing the other technology. SSB also have the advantage of higher capacity as well as higher specific energy and energy density. LAB, on the other hand is a more mature technology and has a lower power cost. However, SSB has a lower energy cost and it is therefore relevant to assume that SSB is the best solution in this case. In summary: SSB is the most suitable EST when the given application is voltage support.

5.2.2 Case nr 2 - Arbitrage

From Appendix A it is possible to find following conditions for given application:
Output: Electricity
Size: 100-200MW
Storage period: 8-24hours
Cycles: 0.25-1 per day

From the first condition (output) all three TES technologies can be excluded since their output is thermal. The second condition (size) gives the ability to exclude every technology except for the MES technologies since they are the only two technologies that can provide enough power. Regarding the two other conditions, both of the remaining technologies can be considered suitable. Meaning, either CAES or PHES can be considered most suitable in this case.

To begin with, there are only two actual plants of CAES operating today while PHES is a more mature technology with several plats in operation worldwide. The PHES systems can be designed to provide between a few MW up to about 3000MW, which of course makes the numeric values of the parameters differ. In order to make the two technologies comparable it will be assumed that the PHES system will be rather small. That of course will decrease the power and capacity as a result. Nevertheless, PHES have the advantage of higher efficiency, longer lifetime and lower costs. This makes PHES the most suitable EST when the application is arbitrage.

5.2.3 Case nr 3 – Waste heat utilization

From Appendix A it is possible to find following conditions for given application:
Output: Thermal
Size: 1-10MW
Storage period: 1hour-1day
Cycles: 1-20 per day

From the first condition (output) it is possible to exclude every technology except for the three TES technologies. The second condition (size) gives the ability to exclude two of the three TES technologies, namely LHS and TCES since none of them can provide enough power at the present time (2016). The only remaining technology, SHS also meets the two remaining requirements. In summary: SHS is the most suitable EST when the application is waste heat utilization.

5.3 Other aspects and overall discussion

It is important to understand that all of the parameters interact and affect each other. Therefore, the parameters have to be set in a holistic perspective in order to find the most suitable energy storage solution for a certain application. Similarly, it is important to understand that other none-technical aspects should be considered when choosing an EST. Other aspects such as environmental-, social- and ethical aspects should be taken in account. Also should geographical and geological conditions. This study aims to develop a knowledge guide only for a first evaluation, therefore these none-technical parameters are not considered in the case study. They will however be discussed within this section in order to understand its possible impact of the final decision.

It must be noted that consciousness to the environment, seldom leads to less expensive solutions, at least in the short term. Nevertheless, it is difficult to ignore the drastic environmental transformation that has occurred over the last decades. The climate is changing and the changes have led to an increased number of natural disasters. Phenomenon such as floods, tidal waves and droughts presently occurs with an increased frequency. In order to avoid an escalation of the climate change it is important to carefully consider the environmental aspect when comparing different EST. For example, as mentioned in section 4.1 Electrochemical Storage all of the ECES technologies contain substances that are, more or less, harmful to the environment and the people in its vicinity. The two chemical storage technologies presented in this thesis, hydrogen and methane, only consist of natural processes containing substances that are natural for the environment. That makes these two technologies less harmful for the environment and the social demographic, which should be kept in mind while comparing these different technologies.

Regarding social- and ethical aspects it is important to set energy storage in a human and social perspective. It is necessary to consider questions such as:

- What is the good/right thing to do?
- How should one behave?

E.g., as mentioned in section 4.2.2 Pumped Hydro Energy Storage PHES requires certain height differences and access to water. This is regardless of the surrounding area and the people who might live there. Meaning, in order to install a PHES system the people who might have used this area and water will be forced to relocate themselves. Even if this system would fill a great function, it is relevant to consider if it is the right thing to do in a social- and ethical perspective.

Correspondingly, SSB could provide rather inexpensive energy storage with relatively high power and capacity. As mentioned in section 4.1.2 Sodium Sulfur Battery, it is therefore often considered an attractive candidate for large-scale energy storage applications. However, it must be considered that these batteries consist of materials that should be recycled to avoid damage the environment and the people who live there. It is reasonable to assume that there is a risk the batteries will never be recycled. From a social-, ethical- and an environmental perspective the possibility to recycle the components of the systems should also be evaluated. Furthermore, many of these materials found in the ECES technologies are limited and to maintain the natural balance it is necessary to put the consumed amount in proportion to the available. If this is not complied e.g. lead will be expended within a period of 20 years [7].

In order to choose the most suitable EST for a given application it is necessary to consider the geological and geographical conditions in the area where the need of energy storage are asked for. Different areas have different assets that can be either an advantage or a disadvantage depending on the most favorable conditions for the EST. As mentioned in section 4.2 Mechanical Storage PHES and CAES can provide high power and capacity but are location limited which makes it difficult to transfer the stored energy over longer distances. Therefore, they are favored by high demand within a limited area. Hence, if the studied area is limited and with high demands, the MES technologies are favored but if the studied area instead is fairly small, isolated and without major demands the MES technologies are unfavorable.

Another example is SHS and LHS. If compare a country having access to sunlight for an increased portion over the year and constantly high temperature with another country having a lot of snow and rather low temperatures the needs and assets are different. The warm country can easily store energy from the sun in order to provide heat while the cold country can store cold from the snow (ice) in order to provide cold. If these two countries should be able to exchange and take advantage of each other’s differences it is necessary to find an energy storage solution that store and enable transportation rather than store energy over a longer period of time. It is also reasonable to examine whether it is more effective to use the stored energy from the sun to generate electricity, as compared to a turbine-based generation system. Maybe one solution is more efficient financially while the other solution is more suitable in an environmental perspective. Instead, if there is an area with rather different climate-conditions depending on the season the challenge is to find an EST that could provide long-term storage.

It is also most often important to see energy storage in a future perspective. The research within this subject is rather new when it comes to many of the technologies and the possibilities as well as the conditions might change over time. E.g. the only CAES systems in use today are using salt caverns to store the compressed air. France, at the present time (2016) does not have rather favorable conditions since the country lacks large salt deposits. However, as mentioned in section 4.2.1 Compressed Air Energy Storage there is a lot of ongoing research. Much of the new research and prototypes being made within CAES is about finding new storage containers independent on the availability of salt deposits. There are promising concepts with submarine air tanks and since France has both the English Channel, the Bay of Biscay and the Balearic Sea the conditions are remarkably different if that research can be successfully applied [47]. Therefore, it is important to understand both the future and the historic perspective (earlier tryouts, failures etc.) of the storage technology in order to consider it suitable or not.

To summarize the prospects for energy storage in France, certain things should be mentioned: the country's hilly areas in the southeast combined with the many nuclear power plants advocating wide use of energy storage by using PHES while the lack of salt caverns unfavorable energy storage by using CAES. However, CAES systems might be more convenient if the ongoing research mentioned in section 4.2.1 Compressed Air Energy Storage could provide possibilities to successfully use alternative storage tanks. The unique test plant called the MYRTLE platform that was mentioned in section 4.3.1 Hydrogen provides good conditions for progress in hydrogen-based energy storage. Furthermore, the country, particularly the south part has many hours of sun during summer. That creates the possibility to use TES technologies more widely but since the price of electricity, as mentioned in section 1. Introduction, is among the lowest in Europe the cost for the TES technologies probably has to decrease in order to fully compete with heat systems generated by electricity.

6. Conclusions and future work

Even with a comprehensive evaluation, with the limited time and resources a thesis always has some aspects remaining that can complement the study with future work. This section therefore includes conclusions from this study and future work for coming studies on the subject.

6.1 Conclusions

- Section 4. Energy Storage Technology Mapping includes information regarding all of the 11 technologies and can be used to fulfill the purpose to increase the knowledge of different EST.
- Table 12 that aims to facilitate the first evaluation of what EST that is most suitable for given application can be used for the ECES technologies and the MES technologies. However, Table 12 has some gaps regarding the CES technologies and the TES technologies leading to certain restrictions. As an example, numeric values for cost are missing for some of the CES and TES technologies. That makes it difficult to compare these technologies in an economic perspective. Although, it is still possible to compare the technologies based on many other parameters (e.g. storage period, density, efficiency), which should facilitate the choice at least partly.
- The study can be used as a knowledge guide to facilitate a first evaluation of the most suitable technology for a given application but other aspects,

such as environmental, social and ethical have to be considered in order to make the final decision. Also, this study only includes a number of technologies and in its most basic technical design. In order to make a final decision it might be relevant to examine additional technologies and specific variants of the technologies studied within this study.

- This study is based on the French-context and therefore adapted by the circumstances and the current situation within the country. The study can be used in other geographic areas but it is reasonable to study that area's specific conditions and situation in order to present similar examples of currently used applications etc. that has been made within this study.
- The ability to find relevant and proven numeric values of the different technologies in many cases goes in line with the technology's readiness level. The numeric values for the developing technologies (e.g. methane and TCES) is often linked to a certain research example or so, which makes the values differ rather widely. In order not to present a misleading result, these values have not been presented within this study.

6.2 Future work

Future studies should continue were this study ends. The gaps in Table 12 should be filled in order to complete the comparison tool. Most of the gaps are based on the fact that the given EST is still rather undeveloped and not commercially used. However, there is a lot of ongoing research, most certainly within these undeveloped technologies. Namely, there will most likely be numeric values to fill the gaps within a near future.

The technologies mentioned above are mainly CES and TES. These will need to be further investigated. Especially the more recent technologies; hydrogen, methane and TCES should be studied in-depth in order to get more accurate values but also greater understanding of its potential and possible applications.

This study treats some of the technologies on today's market, but far from all. It would be interesting to examine additional technologies in future studies. In that way one can make the knowledge guide even more useful. It would also be interesting to develop an electronic program based on this study. It could be a program where one fill in the given conditions and desired application and based on this model get one or several purposed EST. A computerized program could also enable the ability to continuously fill the gap or change certain values based on new advances.

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Appendix A

Table 13: *Common applications in the energy system, including some characteristic parameters. Based on* **[55]**.

Application	Output	Size [MW]	Storage period [time]	Cycles [#cycles]	Definition
Seasonal storage	Electricity, thermal	500-2000	Days to months	1-5 per year	Compensation for longer supply disruption or for higher and lower demands depending on different seasons
Arbitrage	Electricity	100-2000	8hours-24hours	0.25-1 per day	Storing energy when the demand is low and the price is cheap to subsequently sell it during periods of high priced energy, a trade between two energy markets
Frequency regulation	Electricity	1-2000	1minute-15minutes	20-40 per day	To balance shifting in supply and demand that happens continuously, the balancing will be in a control area under normal conditions
Load following	Electricity, thermal	1-2000	15minutes-1day	1-29 per day	Dealing with system fluctuations either manually or through automatic generation control, a time frame between a couple of min. to 24 hours
Voltage support	Electricity	1-40	1second-1minute	10-100 per day	Inject or absorb reactive power in order to maintain voltage levels in the transmission and distribution system under normal conditions
Black start	Electricity	0.1-400	1hour-4hours	<1 per year	Allow electricity supply resources to restart without pulling electricity from the grid in case the power system and all other ancillary mechanisms have collapsed
Demand shifting & peak reduction	Electricity, thermal	0.001-1	Minutes-hours	1-29 per day	To match energy demand with supply and to assist in the integration of variable supply resources energy demand can be shifted. By changing the time at which certain activities take place these shifts are facilitated. This also gives the opportunity to actively facilitate a reduction in the maximum energy demand level
Off-grid	Electricity, thermal	0.001-0.01	3hours-5hours	0.75-1.5 per day	To support higher levels of local resources use and mostly to ensure reliable off-grid energy supplies, storage can be used to fill gaps due to differences in demand and supply resources
Variable supply resource integration	Electricity, thermal	1-400	1minute-hours	0.5-2 per day	To optimize the output from variable supply resources, mitigating changes (rapid or seasonal) in output and in order to increase supply quality and value bridging gaps (temporal or geographic) between supply and demand
Waste heat utilization	Thermal	1-10	1hour-1day	1-20 per day	Temporally or geographically decoupling heat supply and demand by using previously wasted heat