ENERGY STORAGE IN OUR FUTURE LOW CARBON SOCIETY (ENERGILAGRING!)

An Extended Literature Review

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CONTENTS

LIST OF ABBREVIATIONS

AC	Alternating Current
aCAES	Adiabatic Compressed Air Energy Storage
AEC	Alkaline Electrolysis Cells
AEP	Annual Estimated Production
aFRR	Automatic FRR
At	Annual cost at year
BRP	Balance Responsible Party
CAES	Compressed Air Energy Storage
CSP	Concentrated Solar Power
dCAES	Diabatic Compressed Air Energy Storage
DR	Discount Rate
EPS	European Project Semester
ESS	Energy Storage System
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal operation
FFR	Frequency Restoration Reserve
FRR	Frequency Restoration Reserve
HEV	Hybrid Electric Vehicles
HTF	Heat Transfer Fluid
HTS	High Temperature Superconducting
iCAES	Isothermal Compressed Air Energy Storage
ICB	Iron Chromium Flow Battery
IRR	Internal Rate of Return
LAES	Liquid Air Energy Storage
LCA	Life Cycle Assessment
LCOC	Levelized Cost of Capacity
LCOE	Levelized Cost of Energy

LCOS	Levelized Cost of Storage
Li	Lithium
LIB	Lithium-Ion Batteries
$LiCoO_2$	Lithium cobalt oxide
Li-ion	Lithium-ion
LTS	Low Temperature Superconducting
mFRR	Manual FRR
$MgCO_3$	Magnesite
MOF	Metal-Organic Frameworks
$NaAlCl_4$	Sodium chloraluminate
NaS	Sodium Sulfur
Ni-Cd	Nickel-Cadmium
$NiCl_2$	Nickel chloride
Ni-Mh	Nickel-Metal hydride
Novia	Novia University of Applied Sciences
NPV	Net Present Value
NQ	Nesquehonite
O&M	Operation & Maintenance
PbA	Lead-Acid
PbO_2	Lead dioxide
PCM	Phase Change Material
PEMEC	Proton Exchange Membrane Electrolysis Cells
PHES	Pumped Heat Electrical Storage
PHS	Pumped Hydro-Power Storage
PSP	Pumped hydropower storage
PtG-SNG	Power to gas - Synthetic Natural Gas
PtG-H_2	Power to gas- Hydrogen
PV	Photovoltaic
R&D	Research and Development

RFB	Redox Flow Batteries
RH	Relative Humidity
ROE	Return on Equity
ROI	Revenue of Investment
SG	Silica gel
SMES	Superconducting Magnetic Energy Storage
SOEC	Solid Oxide Electrolyzer Cell
TES	Thermal Energy Storage
V	Vanadium
VAMK	Vaasa University of Applied Sciences
VFB	Vanadium Redox Flow Batteries
VRLA	Valve Regulated Lead-Acid
ZBB	Zinc-Bromine
ZEBRA	Sodium Nickel Chloride
Zn-Br	Zinc-Bromium
ÅAU	Åbo Akademi University

ABSTRACT

The increase of intermittent wind and solar energy has created a global demand for developing Energy Storage Systems (ESS), which can cope with the fluctuating production. The global energy storage capacity has been based on the technology where water is pumped up to the upper reservoir and used as hydropower when energy is needed. This Pumped Hydro-Power Storage (PHS) had in 2017 a market share of 96 %. There are estimates that the deployment of pumped hydro will grow outside of Europe, but it will lose its market share to lithium-ion batteries and Thermal Energy Storage (TES). The leading technology within TES is the molten salt solution which is used especially in combination with Concentrated Solar Power.

The main objective of the project is to construct a demonstration environment of energy storage for teaching and Research and Development (R&D) purposes in the Technobothnia Research and Education Center. This report discusses problems and challenges concerning energy storage and the methods commonly utilized for evaluating the economics of energy storage. Within this project, there have been two empirical studies. The first one mapped the views of Finnish Balance Responsible Parties (BRP) about the business opportunities within electricity storage. This study confirmed that energy storage is an important question to BRPs and also that the day-ahead or intra-day electricity markets do not provide good business opportunities for electricity storage like the capacity and reserve markets mastered by Fingrid. The second empirical study was done among university researchers and industry representatives within the Vaasa region in order to map the competences within energy storage. This study showed that within the field there are very many players in the region and there is some lack of coordination between different players and the information flow concerning the energy storage R&D activities.

Based on this review, it can be suggested that a pumped hydro, a lithium-ion battery and a TES demonstration environment should be constructed in the Technobothnia Research and Education Center. Also, flywheel solutions will most likely have their role in the future energy storage mix and an adiabatic Compressed Air Energy Storage can provide students insight into how heat and electricity can be stored.

Keywords

energy, storage, renewable energy sources, teaching materials

ABSTRAKT

Användning av vind- och solenergi som energiform har ökat i snabb takt under den senaste tiden. Detta har medfört ett utökat behov av olika typer av energilagringssystem, vilka kan hantera den varierande energiproduktionen. Den globala energilagringskapaciteten är baserad på en teknologi där vatten pumpas från en lägre vattenreservoar till en högre belägen reservoar och används som vattenkraft när det finns behov för energi. Under 2017 hade pumpvattenkraft en marknadsandel på 96 %. Det uppskatttas att utnyttjandet av pumpvattenkraft kommer att öka utanför Europa, men däremot kommer pumpvattenkraften att tappa marknadsandelar till litiumbatterier och olika värmelagringsteknologier. Den ledande teknologin inom värmelagring är för tillfället smält saltlagring i kombination med termisk solkraft.

Den främsta målsättningen med detta projekt är att bygga upp olika demonstrationsmiljöer som kan påvisa energilagringskonceptet. Dessa miljöer ska i framtiden kunna användas inom undervisning och forskning vid forsknings- och undervisningscentret Technobothnia. Denna rapport behandlar teorin bakom olika energilagringsformer, de problem som kan uppstå då man lagrar energi samt de utmaningar som kan förekomma vid användning av de vanligaste metoderna för att mäta lönsamhet inom energilagringsområdet. Inom detta projekt har två stycken empiriska studier genomförts. I den första har en utredning utförts för att undersöka hur finska balansansvariga parter upplever affärsmöjligheter inom elektricitetslagring. Studien visar att energilagring är ett viktigt område för organisationerna. Däremot uppvisar dagen-före- eller intradagmarknaderna inte samma affärslönsamhet för elektricitetslagring som kapacitet- och reservmarknaderna visar, vilka hanteras av Fingrid. Den andra empiriska studien har genomförts med representanter från olika regionala högskolor och från industrin i Vasaregionen för att kartlägga kompetenser inom energilagring. Resultaten visar att det finns många aktörer inom energilagring i regionen, men att det delvis saknas en koordinering av informationsflödet mellan organisationerna gällande forskning och utveckling av energilagring.

Baserat på denna rapport, kommer olika demonstrationsmiljöer gällande pumpvattenkraft, värmelagring samt litiumbatterier att byggas upp i Technobothnia. Energilagring med hjälp av svänghjul kommer förmodligen även att inneha en roll i en framtida energilagring och kommer därför även att förevisas som en energilagringsmetod. Ytterligare kan komprimerad luft som energilagringsmetod bidra till en ökad kunskap hos studerande gällande hur värme och elektricitet kan lagras.

Nyckelord

energi, lagring, förnybara energikällor, undervisning

TIIVISTELMÄ

Sään mukaan vaihtelevien tuuli- ja aurinkoenergian lisääntyminen on luonut maailmanlaajuisen kysynnän energian varastointijärjestelmille, jotka pystyvät tasaamaan vaihtelevaa tuotantoa. Globaali energian varastointikapasiteetti on perustunut perinteisesti pumppuvoimalaitostekniikkaan, jossa vesi pumpataan ylempään säiliöön varastoon ja käytetään vesivoimana, kun energiaa tarvitaan. Pumppuvoimalaitosten (PHS) markkinaosuus vuonna 2017 oli 96%. Pumppuvoimalaitosten rakentaminen jatkuu tulevaisuudessa erityisesti Euroopan ulkopuolella, mutta PHS-teknologia tulee menettämään markkinaosuuttansa erityisesti litiumioniakkuille ja lämpöenergian varastoinnille (TES). TES:n johtava tekniikka on sulasuolaliuos, jota käytetään erityisesti yhdessä keskittävien aurinkovoimaloiden kanssa.

Hankkeen päätavoitteena oli rakentaa opetus- ja tutkimus- ja kehitystarkoituksiin tarkoitetun energianvarastoinnin esittely-ympäristö Technobothnia -tutkimus- ja koulutuskeskukseen. Tässä raportissa käsitellään energian varastointiin liittyviä ongelmia ja haasteita sekä menetelmiä, joita yleisesti käytetään energian varastoinnin taloudellisuuden arviointiin. Tässä projektissa on tehty kaksi empiiristä tutkimusta. Ensimmäinen kartoitti Suomen tasevastaavien näkemyksiä sähkön varastointiin liittyvistä liiketoimintamahdollisuuksista. Tämä tutkimus vahvisti, että energian varastointi on tärkeä kysymys tasevastaaville ja että päivittäiset tai päivänsisäiset sähkömarkkinat eivät tarjoa yhtä hyviä liiketoimintamahdollisuuksia sähkön varastointiin, kuten Fingridin hallitsemat kapasiteetti- ja reservimarkkinat. Toinen empiirinen tutkimus tehtiin yliopistojen tutkijoiden ja teollisuuden edustajien keskuudessa Vaasan seudulla energian varastoinnin osaamisen kartoittamiseksi. Tämä tutkimus osoitti, että alueella on hyvin monia toimijoita, ja eri toimijoiden välinen koordinointi ja energian varastointia koskevaan tutkimus ja kehitystoimintaan liittyvä tiedonkulku on hyvin puutteellista.

Tämän tarkastelun perusteella Technobothnian tutkimus- ja koulutuskeskukseen on rakennettu osana hanketta pumppuvoimalaitos-, litiumioniakku-, vauhtipyörä- ja TES-esittely-ympäristö. Näiden lisäksi hankkeessa on opiskelijoiden toimesta tehty adiabaattinen paineilman energianvarastointidemo, joka antaa opiskelijoille tietoa lämmön ja sähkön varastoinnista paineilman avulla.

Avainsanat

energia, varastointi, uusiutuvat energialähteet, oppimateriaali

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This report consists of four following articles:

Article 1. **Introduction to energy storage** (chapter 1) and **Different technical solutions for storage** (chapter 2): authors: *Ossi Koskinen, Sami Lieskoski, Cynthia Söderbacka, Shiva Sharma.*

Article 2. **Evaluating economics of energy storage** (chapter 3) author: *Ossi Koskinen.*

Article 3. **Empirical Study of Energy Storage** (chapter 4) *Cynthia Söderbacka and Ossi Koskinen.*

Article 4. **Conclusion** (chapter 5) authors: *Ossi Koskinen, Cynthia Söderbacka and Jessica Tuuf.*

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1. INTRODUCTION TO ENERGY STORAGE

The main objective of the project is to construct a demonstration environment of energy storage for teaching and R&D purposes in Technobothnia Education and Research Center, Vaasa, Finland. The aim of this report is to support this objective by providing knowledge and understanding about the current and future state of different energy storage solutions.

Background and objectives of the project

The extensive and rapid increase of intermittent wind and solar energy has both globally and especially in Europe created a demand for developing cost-efficient Energy Storage systems, which can secure the energy supply with fluctuating production. IRENA (IRENA, 2017, p. 14) estimates that, if the share of renewables in the world´s energy system by 2030 is doubled, there is a need to triple (5 TWh → 15 TWh) the global electricity storage capacity. The European Union has put an extensive emphasis on measures mitigating global warming and reaching the climate targets by decreasing the usage of coal power and increasing the proportion of renewable energy sources. The increase of renewable energy production in Europe is practically based on new solar photovoltaic (PV) and wind power capacity where e.g. biomass has played a marginal role (Figure 1).

In 2011, a feed-in tariff-based governmental subsidy scheme, which boosted the Finnish wind power capacity (MW) and energy production, was launched in Finland (Figure 2). At the end of 2020, Finland had 2586 MW installed wind power capacity and the annual production was 7.8 TWh accounting for 10% of the Finnish electricity consumption (Finnish Wind Power Association, 2021). Due to the lowered investment cost and improved efficiency also solar PV energy production is growing rapidly in Finland and the production capacity of grid-connected PV has increased from 120 MW in 2018 to 197 MW in 2019 according to preliminary 2019 data. There is estimated to be a further 20 MW of off-grid solar PV capacity (Energiavirasto, 2020).

Although wind and solar electricity production compensate each other on a monthly basis (more solar energy in the summer and more wind energy in the winter) the weekly, daily and hourly production fluctuate remarkably depending on the weather conditions. Figure 3 illustrates the fluctuations of the Finnish wind electricity production during a few days (23.2-26.2.2021). Although the future production can be estimated remarkably preciously (in Figure 3 there are two forecasts and the true production), the production variations are challenging for the power system.

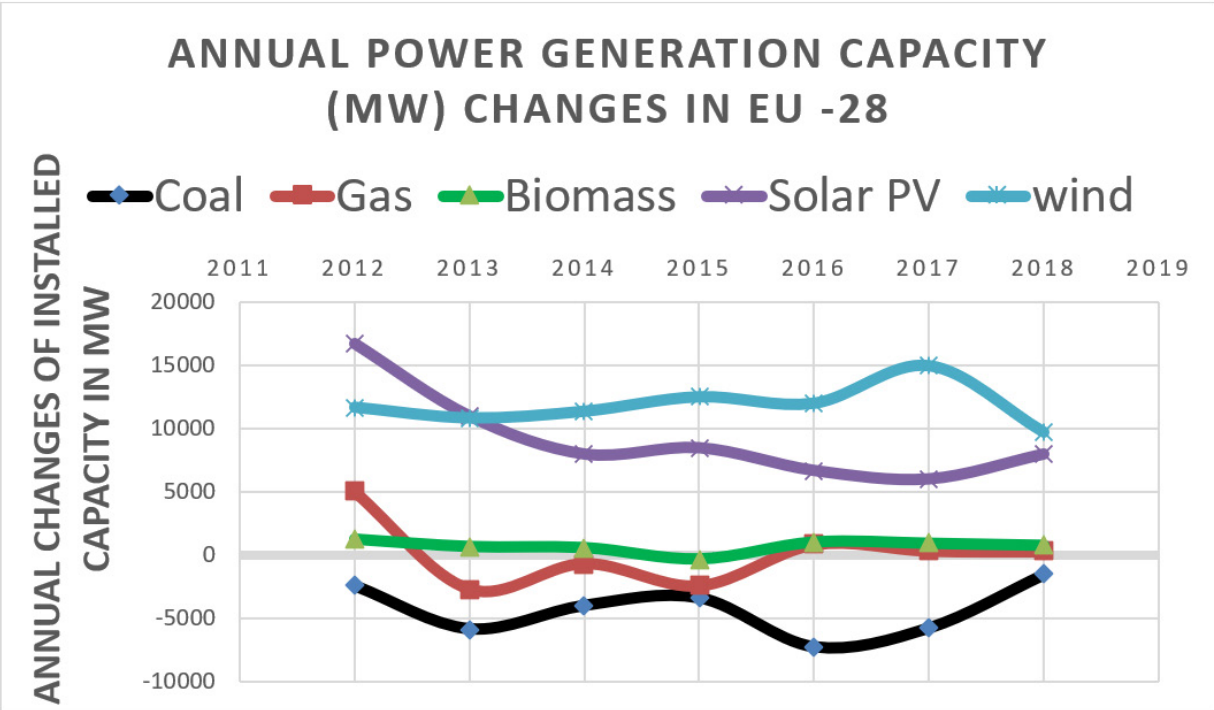


Figure 1. Net changes (commissioned – decommissioned) of electricity production capacity in EU (WindEurope, 2019; WindEurope, 2018; WindEurope, 2017; EWEA, 2016; EWEA, 2015; EWEA, 2014; EWEA, 2013).

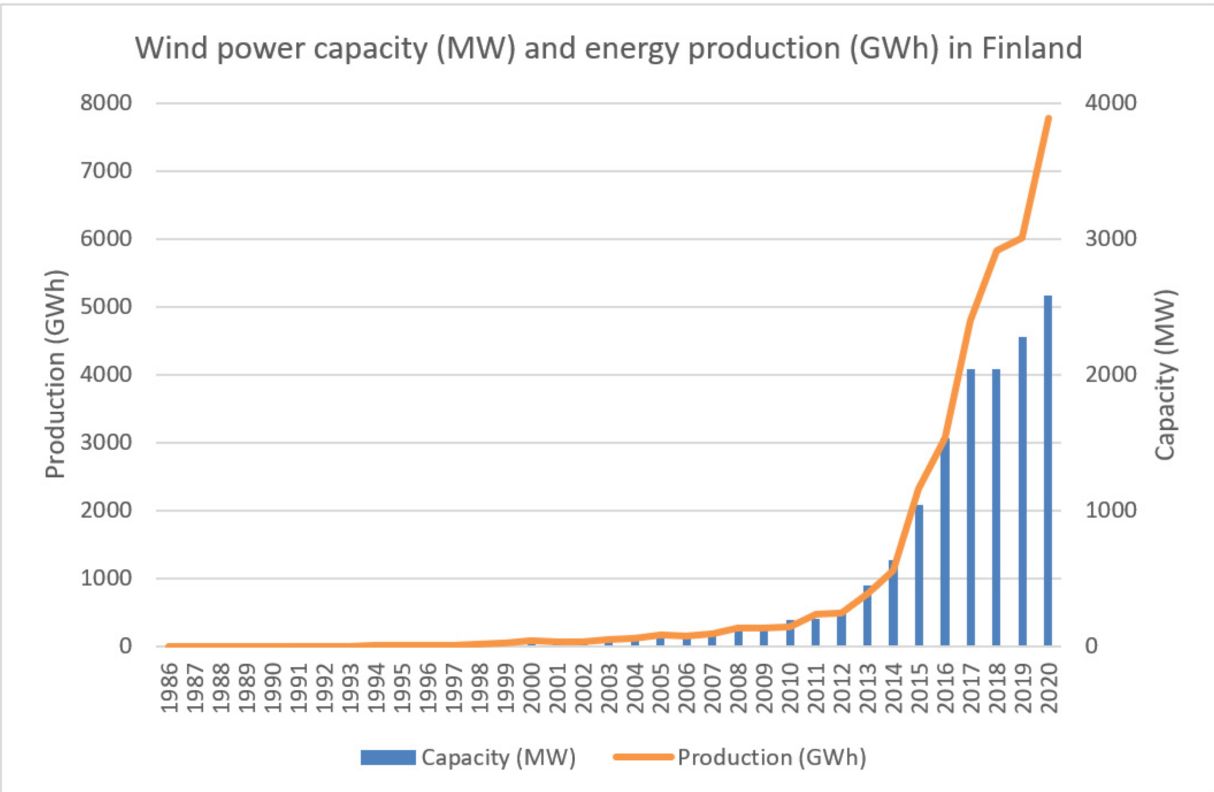


FIGURE 2. The growth of wind power production capacity (MW) and energy production (GWh) in Finland 1986 -2019. Based on: (Holttinen & Kiviluoma, 2000; Rissanen & Holttinen, 2015; Finnish Wind Power Association, 2016; Finnish Wind Power Association, 2017; Finnish Wind Power Association, 2018; Finnish Wind Power Association, 2019; Finnish Wind Power Association, 2020; Finnish Wind Power Association, 2021).

FIGURE 3. Wind energy (MWh) production fluctuations 23.2-26.2.2021 (Fingrid Oyj, 2021).

In order to cope with the dramatically increasing and fluctuating renewable energy production the three following main approaches can be applied;

- To **add more load-following power plants** (e.g. hydropower) to the system to smooth the fluctuating production of wind and solar.
- To **steer consumption** according to production (smart grids, smart cities, etc.).
- To **store energy** with high supply and to discharge the storage when there is a deficit.

This project concentrates on energy storage and puts a special emphasis on issues in the Ostrobothnian context. This region was in 2020 in second place in Finland in terms of installed wind power capacity (16,8 %) (Finnish Wind Power Association, 2021) and the coastal location provides better wind circumstances and more sun hours for PV than most inland sites. The Levelized Cost of Energy (LCOE) for wind power has been reduced rapidly due to higher turbine towers and thus better wind circumstances (positive wind shear) and larger rotors (larger swept area and higher capacity factor). According to Ecofys (2014b), LCOE can be defined as "*the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life*".

Due to the rapidly improved profitability of wind power, 5 wind farm projects without any governmental subsidy have been launched in the year 2020 in Finland. The number of these non-subsidized wind projects has been increasing and in 2021, 16 of these wind farms are expected to come online, of which 2 will be erected in Ostrobothnia (Finnish Wind Power Association, 2021). Onshore wind and utility-scale PV have been found to be the cheapest electricity production methods in Germany (Figure 4) and Finnish developers have announced that they can reach a cost as low (LCOE) as 35 €/MWh on their sites. The trend of lowering production cost will lead to a significant increase in wind power in the region and thus the need for future energy storage will grow dramatically.

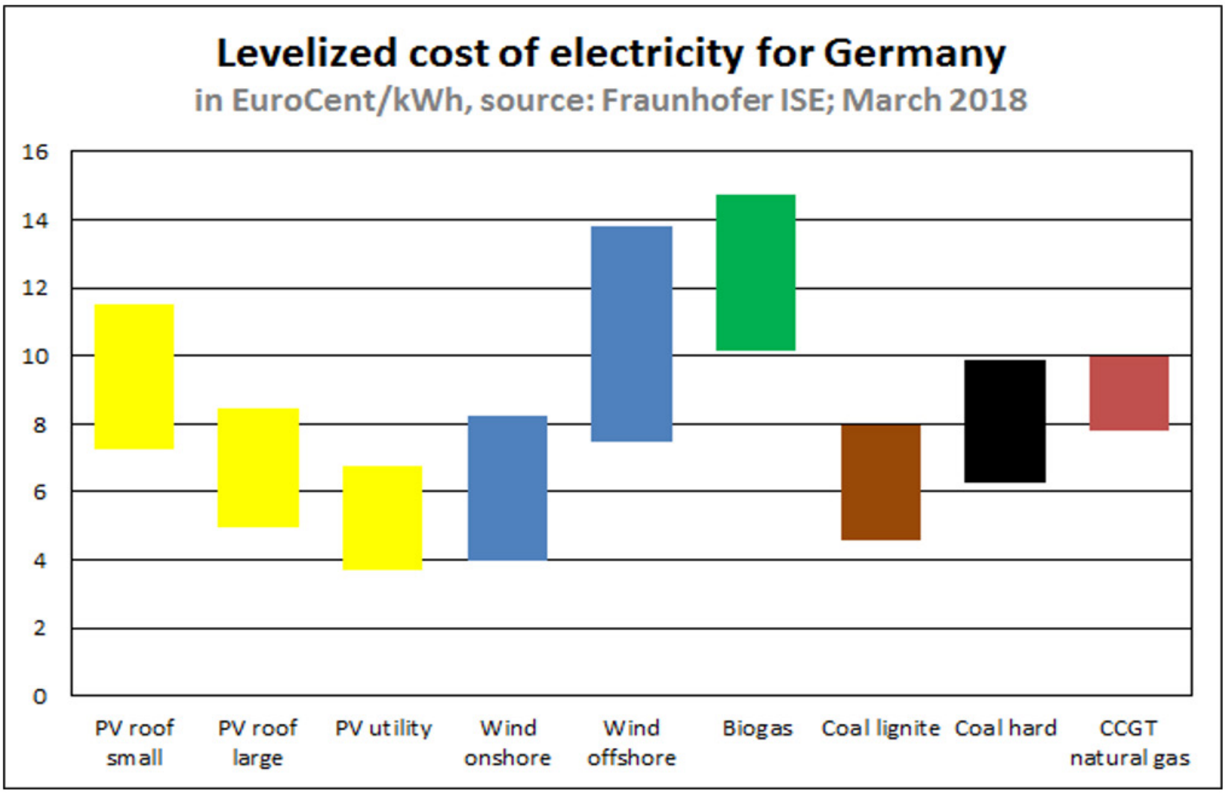


FIGure 4. Levelised Cost of Electricity in Germany (Fraunhofer ISE, 2018).

The objective of this project is to study energy storage from a regional Ostrobothnian perspective and thus support the three universities (ÅA, Novia and VAMK) to be proactive and take the future energy storage need of the region into account. The aim of the project is to support the participating universities to establish a demo environment in the Technobothnia laboratory facilities which serve both education and R&D in the field of energy storage.

Project (Research) problem and questions

The growth of the energy storage market up to 2030 will not be a one-horse race, although Lithium-ion batteries are most likely to dominate the electric vehicle market. The stationary electricity storage application market will remain diverse because different solutions have different pros and cons and the need for storage varies (IRENA, 2017, p. 13).

The main question (research problem) of the project is what kind of energy storage demonstration environment in the research facilities of Technobothnia will best serve educational and R&D purposes based on the regional energy storage circumstances. From this starting point, the following study questions can be conducted;

- How do the energy storage options look from the technical and the economical perspective studied with current knowledge?
- What special features and opportunities do the Ostrobothnian region have in terms of future energy storage needs and possibilities?
- How to establish and intensify energy storage collaboration between other national and international universities and other stakeholders?
- What kind of energy storage demonstration environment is feasible to be established in Technobothnia so that it fulfills the future requirements of the university teaching and R&D activities as well as the needs of the local energy industry?

Pumped hydro storage was the clear market leader in 2017 with a share of 96 % (169 GW) (IRENA, 2017, p. 29), but it is evident that the market situation among the energy storage technologies will change dramatically until 2030 (Figure 5). In mid-2017, China had a PHS capacity of 32 GW, Japan 28 GW, the US 23 GW and Spain 8 GW (IRENA, 2017, p. 30).

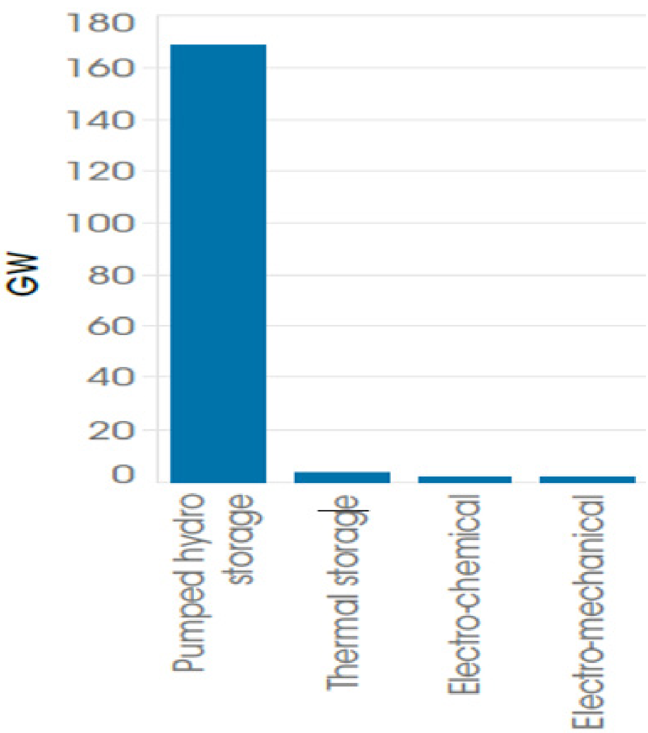


Figure 5. Global energy storage power capacity by technology (IRENA, 2017, p. 29).

Figure 6 shows that molten salt is the market leader within thermal storage. Lithium-ion batteries and flywheel are technology leaders in their own categories.

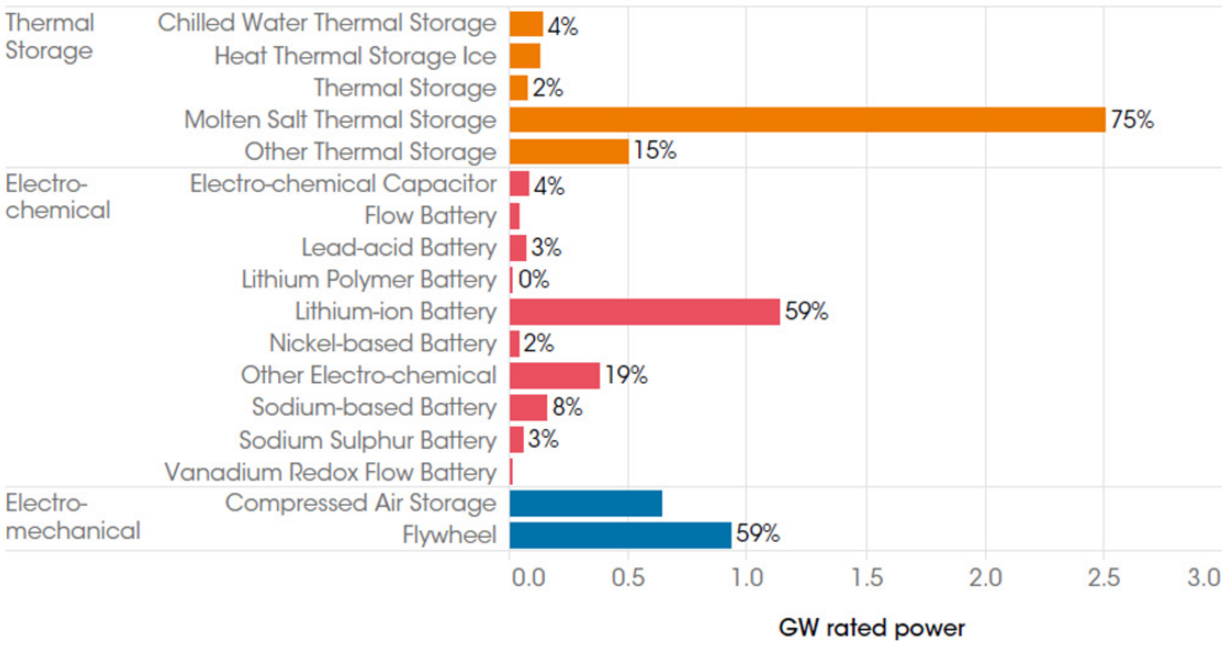


FIGURE 6. Global electricity storage capacity by technology and their share in their own category in mid-year 2017 (IRENA, 2017, p. 22).

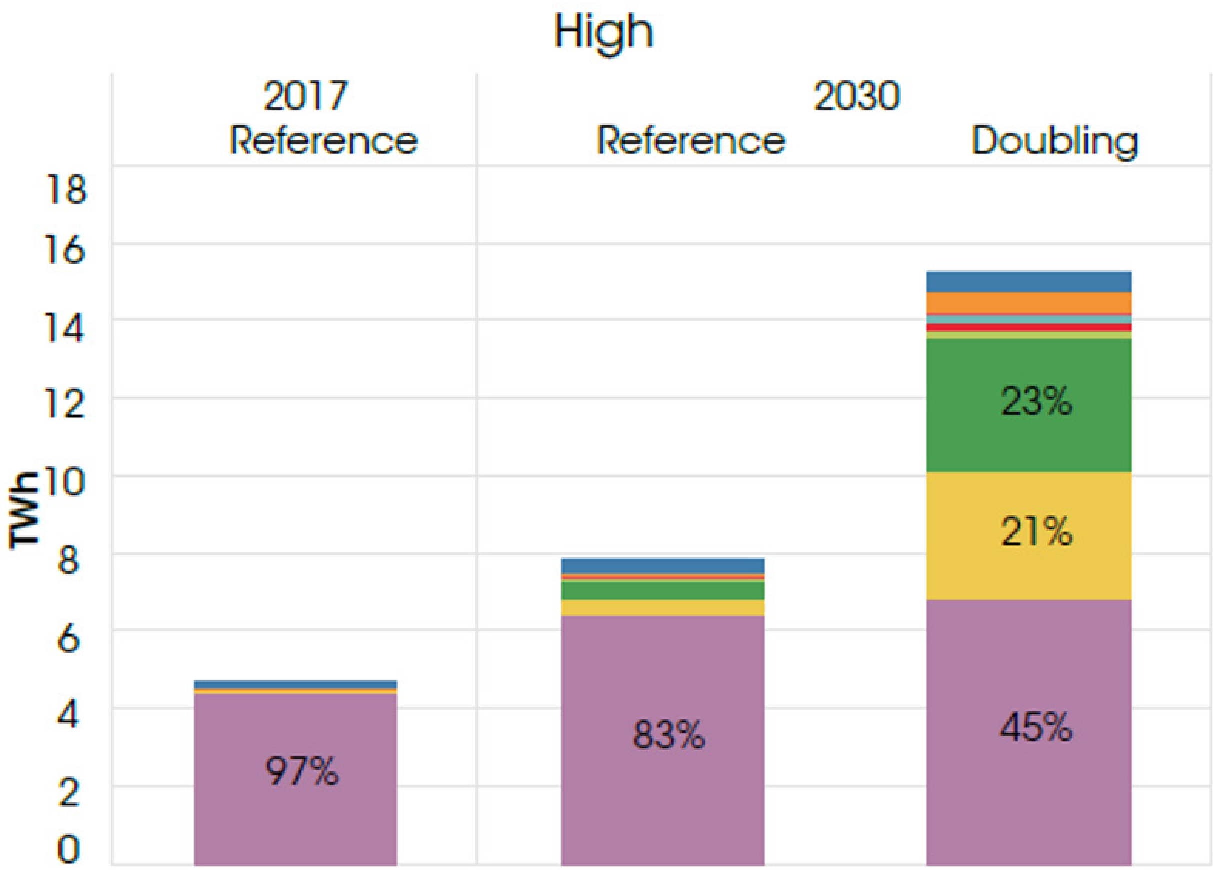


FIGURE 7. Estimation of electricity storage technologies 2030; PHS (lilac/purple), batteries of vehicles (yellow) and CSP/molten salt solution (green) as market leaders (IRENA, 2017, p. 15).

In the “Doubling” scenario in which the share of renewables will be doubled until 2030, the storage mix will look quite different from the “Reference” scenario according to (IRENA, 2017, p. 15). In 2030 PHS (lilac/purple in Figure 7) will account for only 45 % of the total energy storage capacity and the Lithium-ion batteries of electric vehicles (yellow in Figure 7) will be in third place with a share of 21 %. The growth of the Concentrated Solar Power (CSP) plants with thermal energy storage (green in Figure 7) is estimated to be tremendous and this kind of energy storage is estimated to come second place with a market share of 23 % (IRENA, 2017, p. 104). This solution uses molten salt and can store production of a large CSP for nighttime usage and thus make solar power available also in dark periods.

Structure of the report

There is a wide range of purposes and services that energy storage can provide for both in the areas of thermal and electricity storage. IRENA (2017) has divided electricity storage into seven different kinds of services, of which each serves a different need of storage (Figure 8).

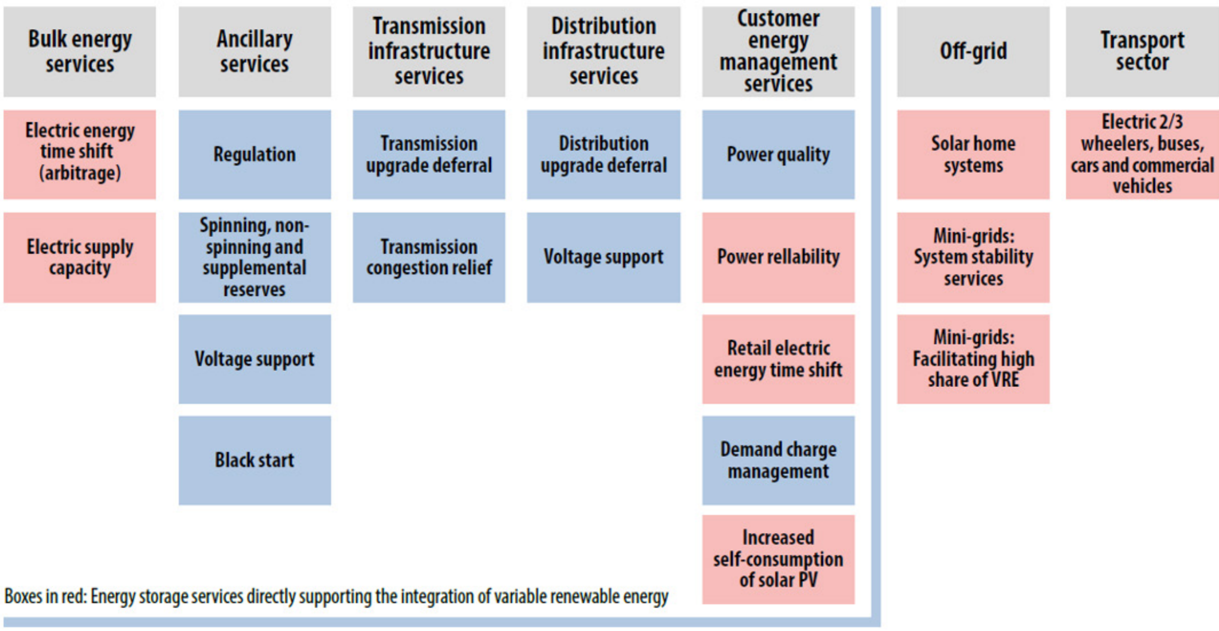


FIGURE 8. Different kinds of electricity storage needs and services (IRENA, 2017).

This report is divided into five chapters and the introduction chapter is proceeded by a chapter presenting the different energy storage technologies. In the third chapter, the economics of energy storage is discussed with different kinds of measurements like Levelized Cost of Storage (LCOS) and Life Cycle Assessment (LCA) methods. The fourth chapter presents how the empirical study is conducted and the report ends with a conclusion chapter.

2. DIFFERENT TECHNICAL SOLUTIONS FOR STRORAGE

Energy storage solutions can be categorized in different ways and the most common classification is probably made according to the method of storage. In Figure 9 the methods (technologies) are divided into mechanical, electrochemical, electrical, chemical and thermal energy storage.

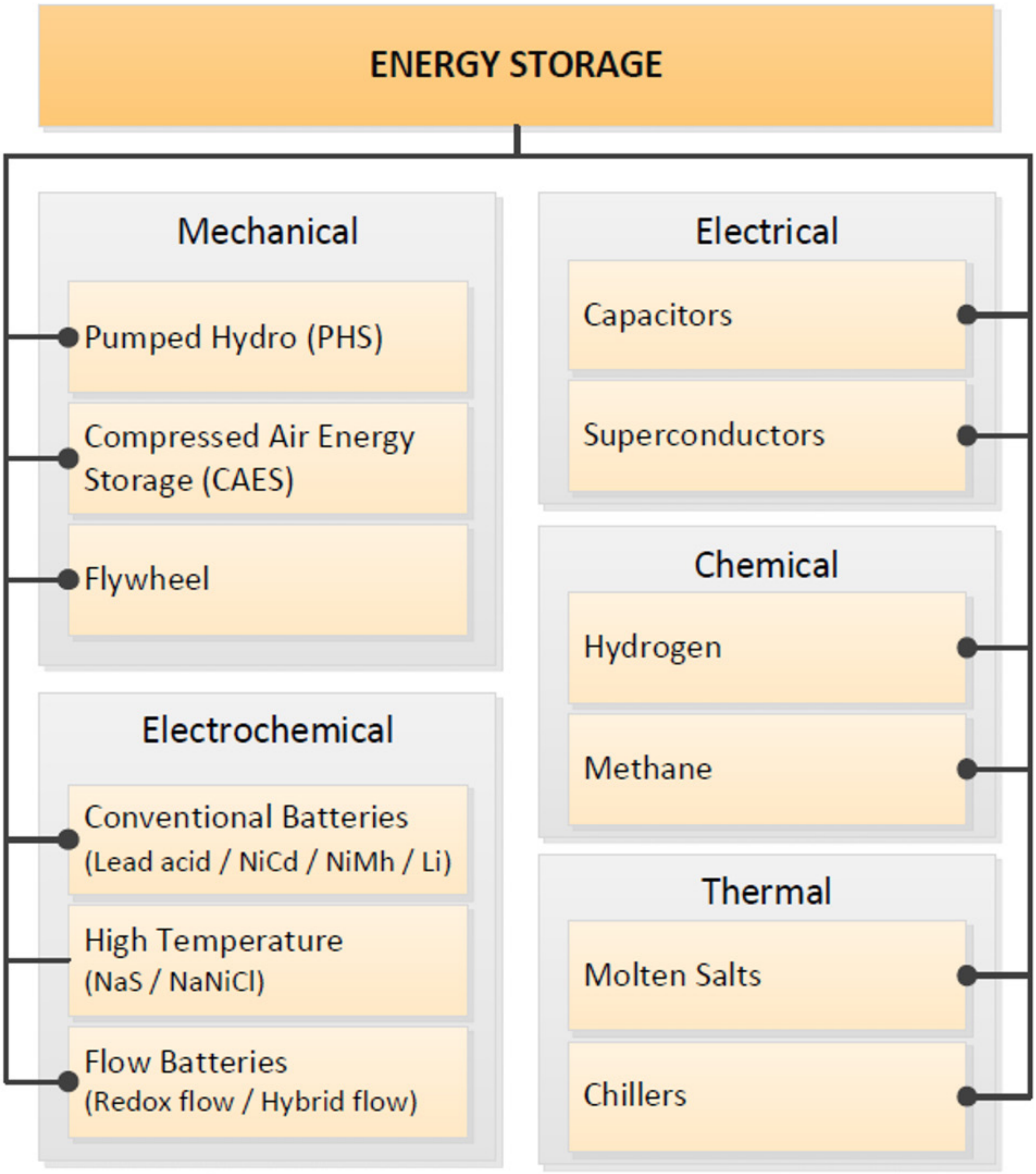


FIGURE 9. Different energy storage technologies (AECOM, 2015).

In Figure 10, different kinds of energy storage technologies are grouped by the discharge time and the storage capacity (from KWh to TWh) for different purposes.

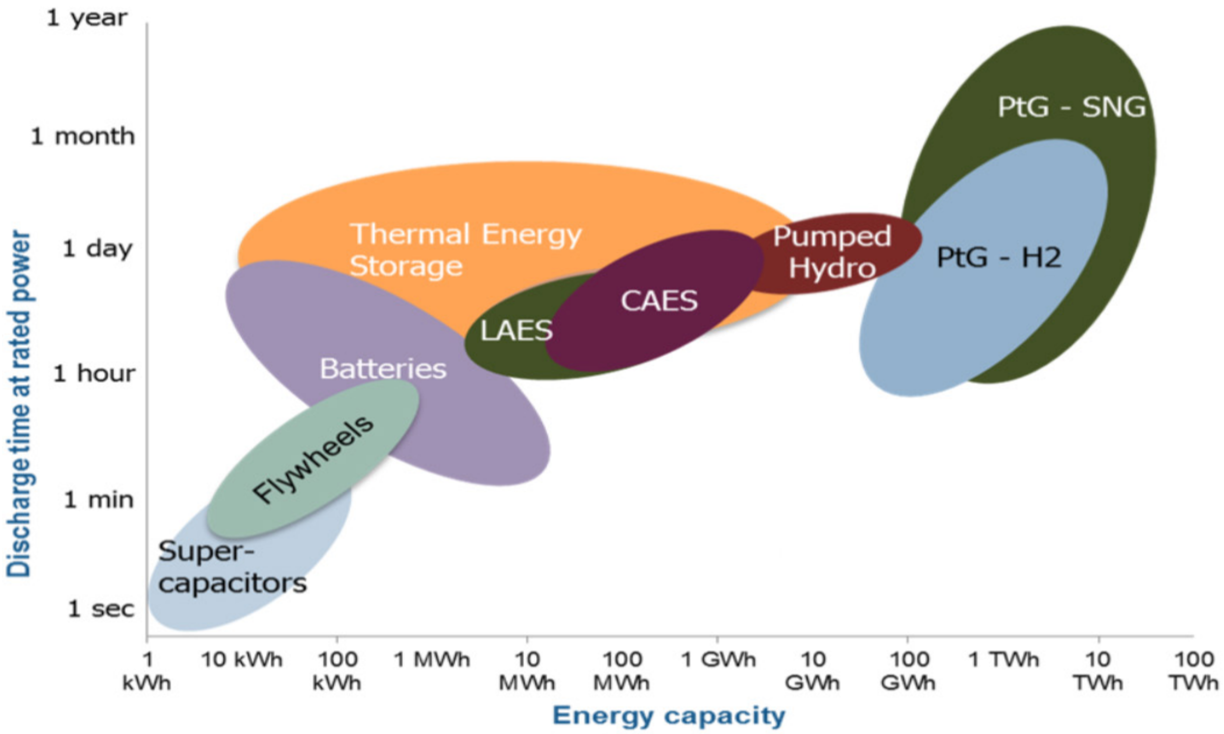


FIGURE 10. Different energy storage technologies mapped by discharge time and energy capacity (WEC, 2016, p. 11).

Different kind of technologies are used for different purposes and the global energy storage power capacity shares by main-use are the following (IRENA, 2017, p. 13);

Pumped hydro storage

- Electric Energy Time Shift: 88 % of PHS
- Electric Supply Capacity: 5 % of PHS

Electro-chemical (batteries)

- Frequency Regulation 50 % of batteries
- Electric Supply Reserve Capacity – Spinning 9 % of batteries

Electro-mechanical (CAES and flywheels)

- On-Site Power 55% of CAES and flywheels
- Black Start 22 % of CAES and flywheels

Thermal storage

- Renewables Capacity Firming 73 % of thermal storage
- Renewables Energy Time Shift 14 % of thermal storage

The electricity energy storage technologies presented by global installed capacity (GW) and divided by primary-use case to 27 services/purposes of energy storage are presented in Appendix 1. Appendix 4 lists the characteristics of some energy storage technologies. In Table 1 stationary energy storage capacities are presented country-wise by technology.

TABLE 1. Stationary storage capacity by country and technology (IRENA, 2017, p. 30).

COUNTRY	ELECTRO MECHANICAL	ELECTRO CHEMICAL	THERMAL STORAGE	PUMPED HYDRO STORAGE	GRAND TOTAL (GW)
China		0.1	0.1	32.0	32.1
Japan		0.3		28.3	28.5
United States	0.2	0.7	0.8	22.6	24.2
Spain	0.0	0.0	1.1	8.0	9.1
Germany	0.9	0.1	0.0	6.5	7.6
Italy		0.1	0.0	7.1	7.1
India		0.0	0.2	6.8	7.0
Switzerland	0.0	0.0		6.4	6.4
France	0.0	0.0	0.0	5.8	5.8
Republic of Korea		0.4		4.7	5.1
Grand total (GW)	1.1	1.6	2.3	128.1	133.1

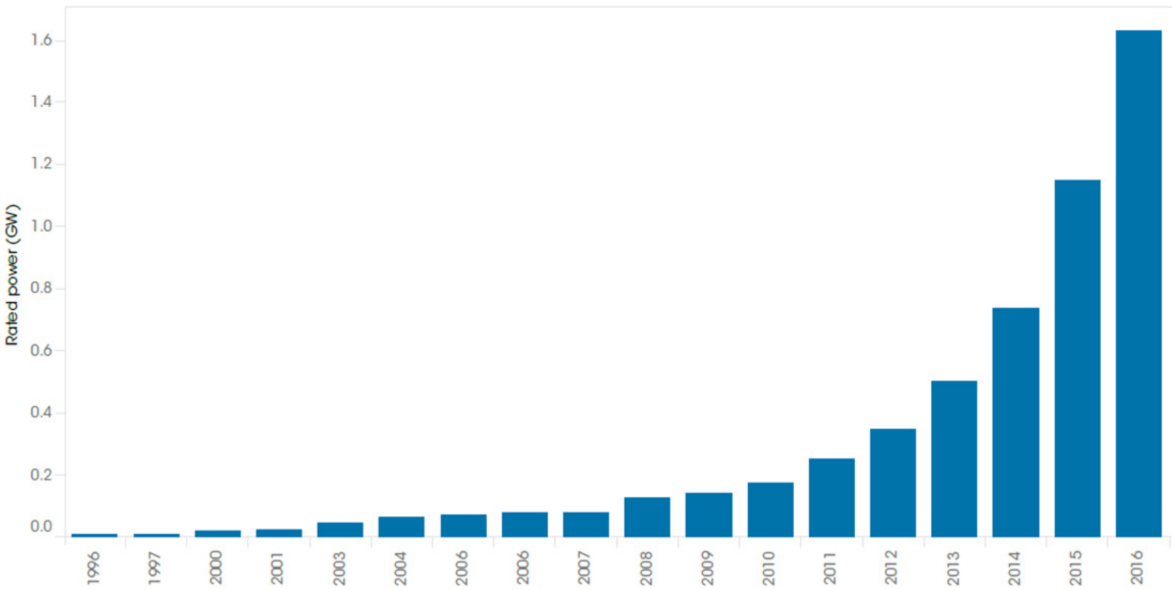
Electrochemical energy storage

Electrochemical energy storage includes all types of rechargeable batteries, also known as secondary batteries. Chemical energy stored in the active materials of the batteries is converted into electric energy through a reversible electrochemical oxidation-reduction reaction. There is a variety of different technologies used in these batteries. These technologies differ in the system used for the battery and the materials used for the electrodes and the electrolytes which the battery consists of (Krivik & Baca, 2013; Zakeri & Syri, 2015).

Batteries can be divided into conventional rechargeable batteries and flow batteries. In conventional batteries, the electroactive materials are stored within the electrode, while in flow batteries, the electroactive materials are dissolved in electrolyte solutions stored in two tanks; one on the cathode side and one on the anode side (IRENA, 2017, p. 19). Both of these types of batteries have many different applications. There has been much discussion about the role of batteries as one type of energy storage method and IRENA (2017, p. 21) summarizes this as follows:

> *"There is significant confusion regarding when electricity storage is essential in the energy transition, as opposed to when it is an economic opportunity. Pumped hydro storage can be economic at present when providing flexibility to the electricity system. Battery costs — although falling rapidly— remain high at present with their economic applications mainly found in off-grid markets, transport and, increasingly, behind-the-meter uses. As costs fall further, batteries will provide more grid services."*

The growth of conventional batteries has been steady and significant during the last decades as seen in Figure 11.



urce: US DOE, 2017.

FIGURE 11. Global battery storage capacity growth 1996 to 2016 (United States Department of Energy, 2017).

In Table 2, the battery capacities by country and battery type are presented.

TABLE 2. Announced, contracted and under construction storage capacity by battery type (United States Department of Energy, 2017).

COUNTRY	ELECTRO CHEMICAL (UNSPECIFIED)	ELECTRO CHEMICAL CAPACITOR	LITHIUM ION BAT TERY	FLOW BAT TERY	VANADIUM REDOX FLOW BAT TERY	LEAD ACID BATTERY	METAL AIR BATTERY	SODIUM BASED BATTERY	TOTAL (KW)
United States	500 398		61 959	3 030	20 250	21 500	14 250		621 397
Australia	122 010		9 400						131 410
Germany	30 000		92 000	210					122 210
India	110 000		125						110 215
Republic of Korea			48 500						48 500
Canada	12 150		12 010	4 000	5 000				33 160
Egypt			30 000	1 950					30 000
Italy			20 000	25 000				4 000	27 870
Kazakhstan		1920		140					25 000
United King- dom	1 000		20 300	4.7					21 440
Top 10	775 558	1920	294 304	34 330	25 250	21 500	14 250	4 000	1 171 112
World	784 258	2920	333 404	34 965	25 250	21 500	5 650	4 800	1 212 747

In Figure 12, a typical battery storage unit is presented, equipped with energy and thermal management systems and the system auxiliaries (power electronics, transformer, fire protection).

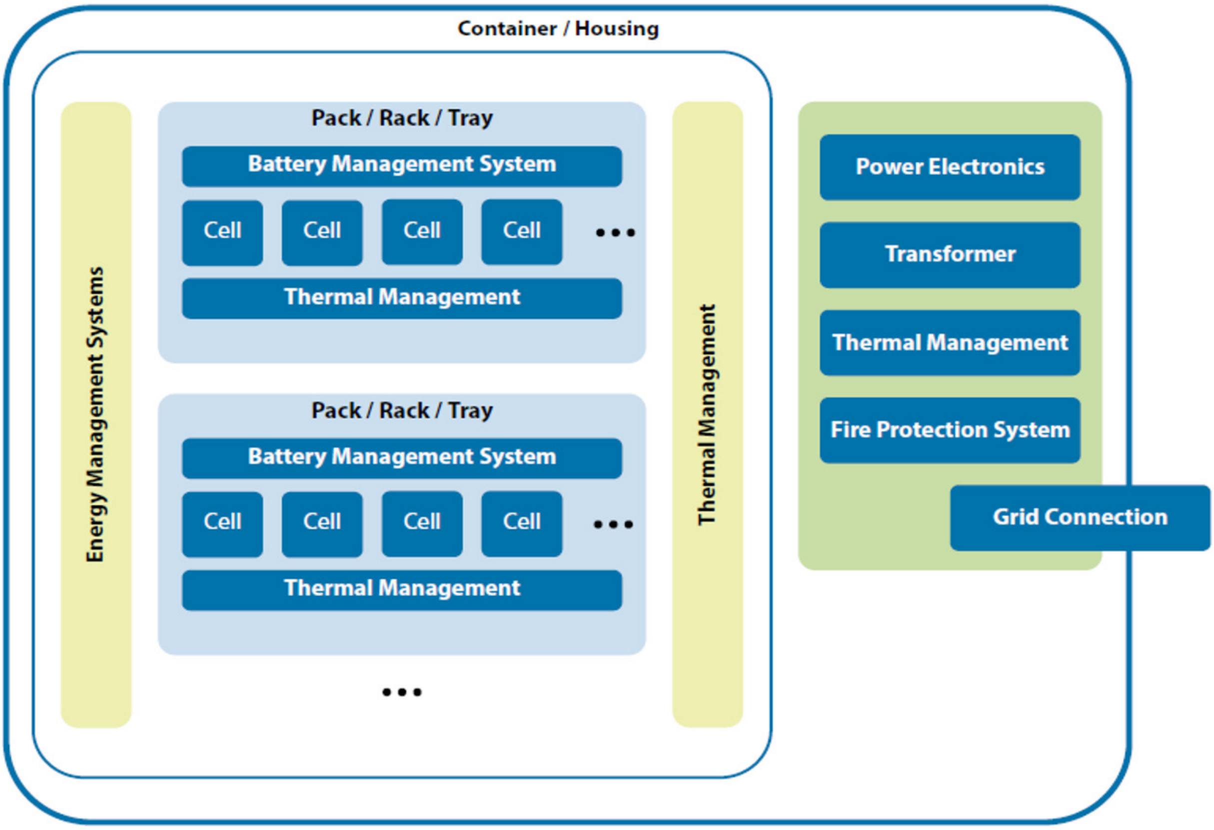


FIGURE 12. An example of a battery storage system, including system auxiliaries (IRENA, 2017).

Lead-acid (PbA) batteries

Lead-acid batteries, invented in 1859, are the most technologically mature type of battery. They are extensively used in vehicles and stationary equipment. The electrolyte is sulfuric acid (H_2SO_4), the material of the anode is lead (Pb), and the material of the cathode is lead dioxide (PbO_2) as observed in Figure 13. The reactions taking place at the anode and cathode when discharging a lead-acid battery are given in Equations 2.1 and 2.2 (Argyrou, et al., 2018).

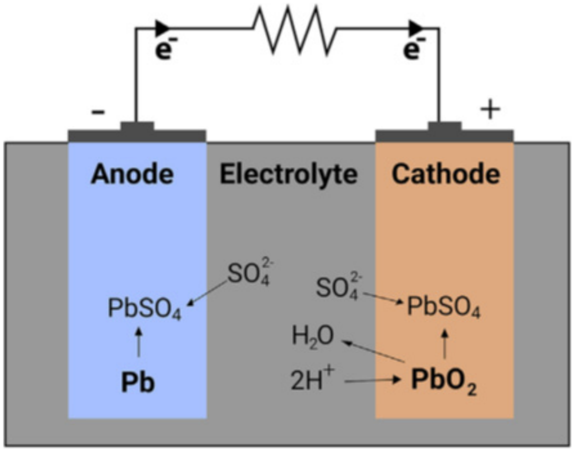


FIGURE 13. The functioning of a PbA battery (Argyrou, et al., 2018).

$$Anode: Pb + SO_4^{2-} \rightleftharpoons PbSO_4 + 2e^- \qquad 2.1$$

$$Cathode: PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightleftharpoons \mathrm{PbSO_4} + 2H_2O \qquad 2.2$$

Lead-acid cells have a rated voltage of 2V and a lifetime of 3-12 years. The cost of lead-acid batteries is low ($150-500/kWh), the efficiency is rather high (65-80%), the self-discharge rate is low (<0.3%/day) and their response time is fast (<5 ms). Suitable uses for lead-acid batteries include maintaining power quality and as a spinning reserve. The disadvantages of lead-acid batteries are their low energy density (25-45 Wh/kg), low specific power (180-200 Wh/kg), narrow cycle life (200-1800 cycles), slow charging and that they require quite much maintenance (Argyrou, et al., 2018). Lead-acid batteries also have some environmental impacts as they discharge explosive gas and acid fumes. The performance of lead-acid batteries at low temperatures is inadequate, requiring a thermal management system. In order to extend the lifetime of lead-acid batteries, larger batteries have to be installed because the lifetime depends on the depth of discharge of the batteries. The lifetime is shorter if the batteries are completely discharged (Argyrou, et al., 2018).

Traditional PbA batteries are called flooded lead-acid batteries. A technological variation of the traditional PbA battery is the Valve Regulated Lead-Acid (VRLA) battery. The VRLA has an improved cycle life of 1500 cycles at 80% depth of discharge and requires less maintenance. In flooded lead-acid batteries, oxygen and hydrogen gases produced during overcharge are released to the atmosphere, and this causes a loss of water from the electrolyte. Due to this, the flooded lead-acid batteries require maintenance for refilling water. The VRLA battery operates with an internal oxygen cycle, which removes the problem of refilling water. Examples of advantages of VRLA batteries have over flooded lead-acid batteries include no acid spilling, no acid stratification and decreased gassing rates (Berndt, 2006). There are two categories of VRLA batteries, the categories differ by their method of retaining the electrolyte: absorbed glass mat and gel VRLA. In absorbed glass mat VRLAs, a glass matrix is used to contain the liquid, and in gel VRLAs, a thickening agent is added to turn the liquid electrolyte into a gel (Gallo, et al., 2016; Krivik & Baca, 2013).

More advanced PbA batteries are under development, and some of them have achieved a power capability nine times greater and a cycle life four to ten times greater than traditional PbA batteries (Parra, et al., 2017). One example is a lead-acid battery with the anode being split into two parts, with one lead electrode connected in parallel with a modified carbon electrode. The cathode material is the same,

PbO_2. This advanced lead-battery is called an ultra-battery, and it has a longer cycle life of up to 17,000 cycles. The capital cost is higher than for a traditional lead-acid battery, but the cost could be lowered with a larger scale of production (Argyrou, et al., 2018).

Lithium-Ion (Li-ion) Batteries

There are various batteries based on lithium, as shown in Figure 14. They are usually classified according to the negative electrode (anode) type and the electrolyte type. This report focuses on Lithium-ion batteries with a liquid electrolyte, circled in Figure 14 (IRENA, 2017, p. 63). However, it should be noted that also lithium-metal batteries exist. For lithium-metal batteries, lithium metal is used as the material for the anode. However, lithium-metal batteries have shown various problems, such as safety issues. This led to the development of lithium-ion batteries, which became commercially successful (Kamali-Heidari, et al., 2018). There are also lithium polymer batteries that rely on the same chemistry as regular lithium-ion batteries, however, they use a solid polymer as an electrolyte instead of the organic liquid electrolyte. Lithium polymer batteries have better safety and their cell design is more flexible, but they are more expensive and have worse scalability (Soloveichik, 2011).

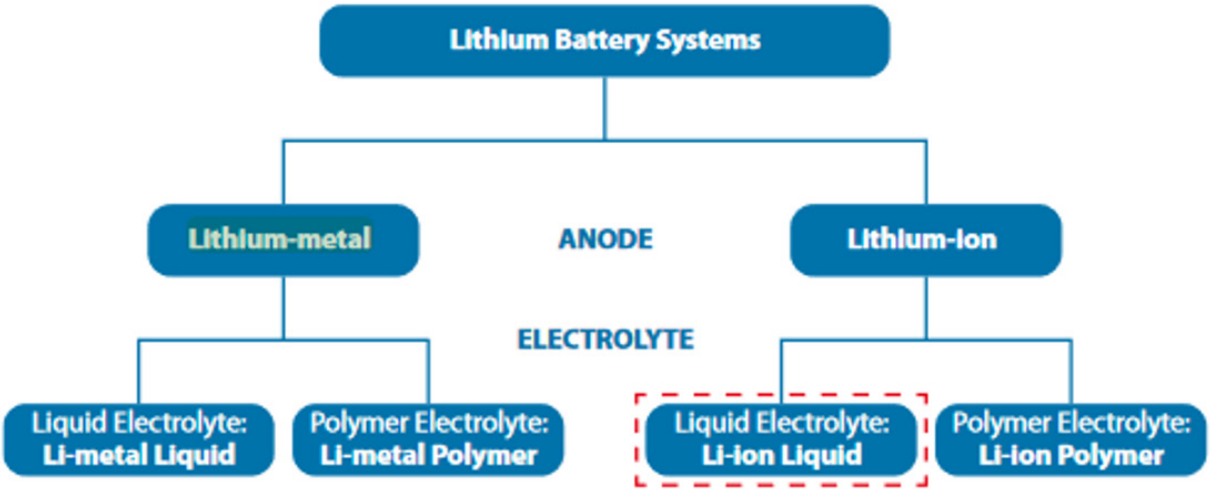
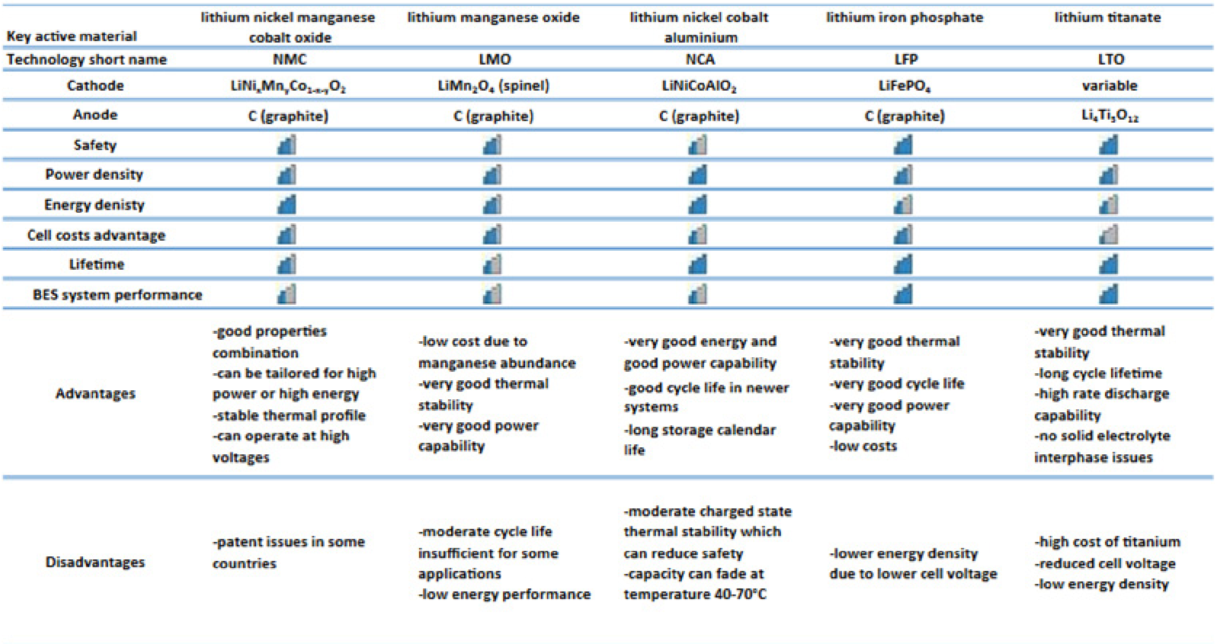


FIGURE 14. The lithium battery family (IRENA, 2017, p. 63).

Lithium-ion batteries are dominant in the portable consumer electronics market and the electric vehicle market. The continued development of lithium-ion batteries for these markets and the economies of scale gained from manufacturing on a larger scale can lead to these batteries having a larger role in grid energy storage. On a utility-scale, lithium-ion batteries can be used for regulation and power management for some minutes of runtime (Poullikkas, 2013).

The main components in Lithium-Ion Batteries (LIB) are the cathode, anode, electrolyte, and separator. LIBs work by reversible intercalation of lithium (Li)-ions in the cathode and the anode. The most common material used for the cathode is lithium cobalt oxide, $LiCoO_2$, and usually, carbon in some shape is used for the anode. In most cases, the electrolyte is a non-aqueous solution consisting of an organic solvent and a dissolved lithium salt, such as $LiClO_4$ (Luo, et al., 2015).

Other compounds than cobalt used in the cathode commercially are manganese and phosphate (Poullikkas, 2013; Yoshino, 2014). $LiCoO_2$ is used in the consumer electronics market, but they are not commonly used in the stationary applications market (IRENA, 2017). The materials used depend on the purpose the LIB will be used for. If high power is needed, high power LIBs like lithium titanate could be used. If the LIB is to be used for load leveling and solar self-consumption, cheaper LIB technologies such as nickel-manganese-cobalt or lithium iron phosphate are the more likely option (IRENA, 2017). The electrolyte is usually made up of an organic liquid such as ether containing dissolved salts such as $LiBF_4$, $LiClO_4$ and $LiPF_6$ (Krivik & Baca, 2013). Figure 15 shows a comparison of lithium-ion batteries using different materials (IRENA, 2017, p. 65).



Key active material	lithium nickel manganese cobalt oxide	lithium manganese oxide	lithium nickel cobalt aluminium	lithium iron phosphate	lithium titanate
Technology short name	NMC	LMO	NCA	LFP	LTO
Cathode	$LiNi_xMn_yCo_{1-x-y}O_2$	$LiMn_2O_4$ (spinel)	$LiNiCoAlO_2$	$LiFePO_4$	variable
Anode	C (graphite)	C (graphite)	C (graphite)	C (graphite)	$Li_4Ti_5O_{12}$
Safety					
Power density					
Energy denisty					
Cell costs advantage					
Lifetime					
BES system performance					
Advantages	-good properties combination -can be tailored for high power or high energy -stable thermal profile -can operate at high voltages	-low cost due to manganese abundance -very good thermal stability -very good power capability	-very good energy and good power capability -good cycle life in newer systems -long storage calendar life	-very good thermal stability -very good cycle life -very good power capability -low costs	-very good thermal stability -long cycle lifetime -high rate discharge capability -no solid electrolyte interphase issues
Disadvantages	-patent issues in some countries	-moderate cycle life insufficient for some applications -low energy performance	-moderate charged state thermal stability which can reduce safety -capacity can fade at temperature 40-70°C	-lower energy density due to lower cell voltage	-high cost of titanium -reduced cell voltage -low energy density

FIGURE 15. Comparison of lithium-ion battery materials (IRENA, 2017, p. 65).

When a LIB is completely discharged, Li-atoms are only found in the cathode. When the battery is charging, Li-ions are released from the cathode and move through the electrolyte into the carbon found in the anode as seen in Figure 16. When discharging, the reverse reaction occurs and this enables electric energy to be stored by repeating these reversible reactions (Yoshino, 2014).

LIBs produce a high average cell voltage of about 3.7 V, they have a high energy density of 70-250 Wh/kg, low self-discharge rate (0.1-0.3%/ day), a high efficiency of 85-95%, do not suffer from a memory effect and require exceptionally little maintenance (Argyrou, et al., 2018; Gallo, et al., 2016; Krivik & Baca, 2013). A drawback of lithium-ion batteries is the safety issue caused by the metal oxide electrodes. These electrodes are thermally unstable, which means that they can decompose at higher temperatures, releasing oxygen and thermal energy. This safety issue is minimized by having monitoring units for lithium-ion batteries which avoid over-discharging and over-charging. Also, most batteries have a maximum charge and discharge current (Argyrou, et al., 2018).

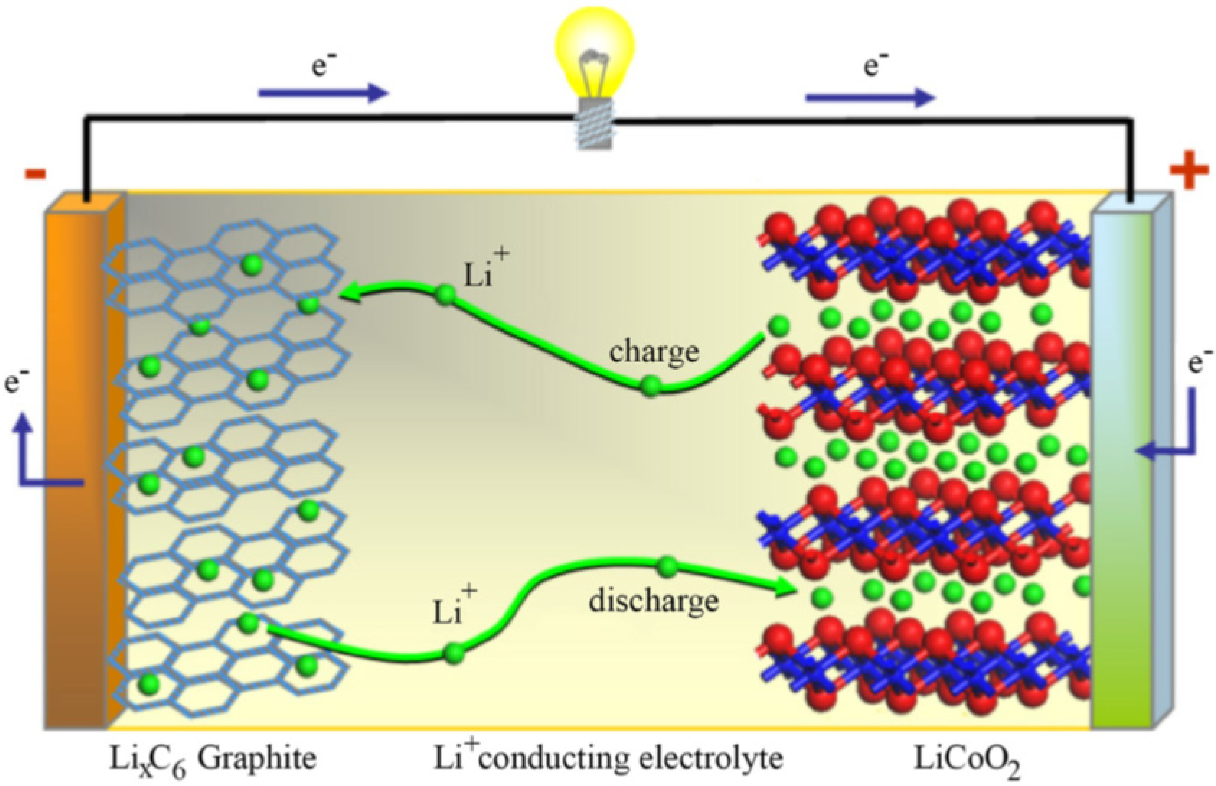


FIGURE 16. Operation principle of a Li-ion battery (Gallo, et al., 2016).

Nickel-Cadmium (Ni-Cd) Batteries

A Ni-Cd battery consists of a positive electrode with nickel oxyhydroxide, a negative electrode with metallic cadmium, and a nylon divider as the electrode separator. The electrolyte in the battery is potassium hydroxide (KOH), which does not undergo any notable changes during operation. The overall reaction in the cell is shown in Equation 2.3 (Menictas, et al., 2015).

$$2NiOOH + 2H_2O + Cd \underset{\text{Discharge}}{\overset{\text{Charge}}{\leftrightarrows}} 2\mathrm{Ni(OH)_2} + \mathrm{Cd(OH)_2} \quad (\mathrm{V^0} = 1.29\ \mathrm{V}) \tag{2.3}$$

Figure 17 shows how a Ni-Cd cell operates. When discharging, the nickel oxyhydroxide combines with water, producing divalent nickel hydroxide and a hydroxide ion. Metallic cadmium is oxidized, yielding cadmium hydroxide at the negative electrode. During charging the process is reversed, but oxygen might be released at the positive electrode, and hydrogen could form at the negative electrode. Due to this, some venting and addition of water are required (Menictas, et al., 2015).

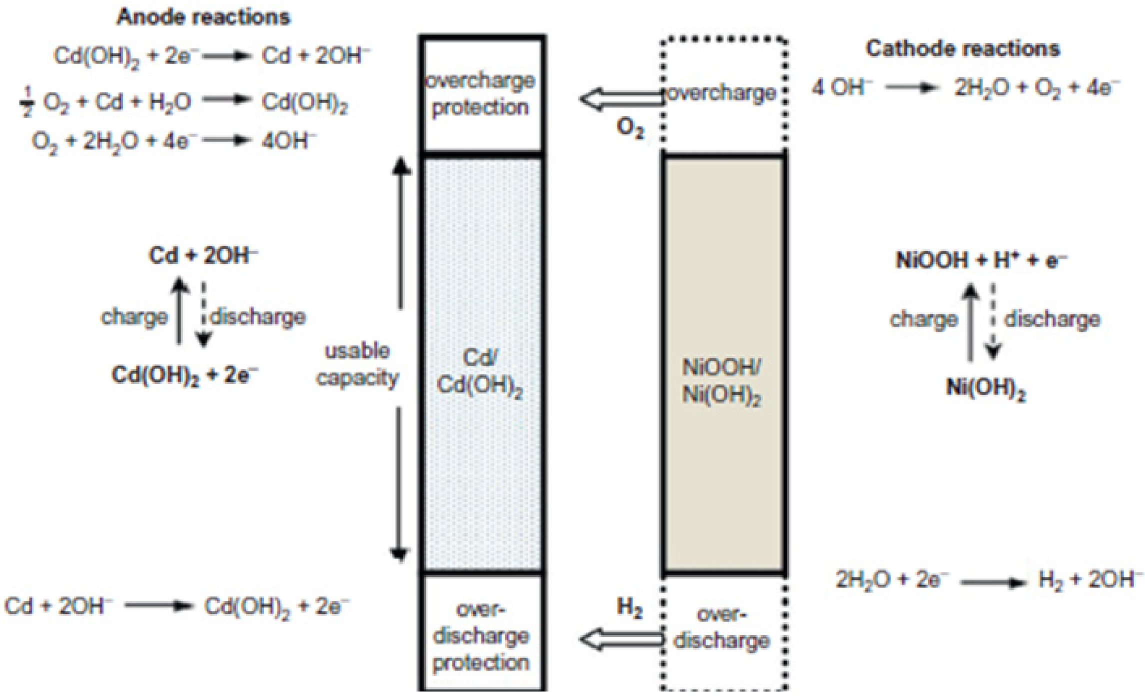


FIGURE 17. Operation of a Ni-Cd cell (Menictas, et al., 2015).

There are two main designs of Ni-Cd batteries: sealed and vented types. The sealed type is more commonly used in portable equipment, while the vented type is used for larger applications such as diesel engine starters. The vented type has a pressure release valve allowing for the release of oxygen or hydrogen gas if the battery overcharges or undergoes rapid discharging. One downside that Ni-Cd batteries may encounter is the memory effect, which is a loss of capacity or voltage drop due to repetitive cycling at shallow discharges. This is not common in the larger vented cells, it is more common for the smaller sealed types (Menictas, et al., 2015).

The good aspects of Nickel-Cadmium batteries are tolerance of high discharge rates, long cycle life (1000-1500 cycles at 80% depth of discharge (Gallo, et al., 2016)), a wide operating temperature range, versatile sizing from small sealed types to large vented cells, low maintenance, and mechanical robustness. Ni-Cd batteries have a specific energy of 55-75 W h/kg (Gallo, et al., 2016). The downsides of Ni-Cd batteries are the memory effect and the toxicity of Cd which has limited its use in many areas. In the EU area, portable batteries or accumulators containing more than 0.002 weight-% of cadmium are banned since 2006 (European Parliament and Council Directive, 2006). Ni-Cd batteries used to have a significant share in the portable consumer electronics market, however, the relatively higher energy density of lithium-ion batteries and their great cycling performance led to them taking over this market. Ni-Cd batteries are today only used for a few niche applications, in which their robustness prevails over Li-ion batteries (Menictas, et al., 2015).

The company Saft has developed Sunica.plus, a Ni-Cd battery intended for use in remote, hard to access, off-grid solar photovoltaic installations (Menictas, et al., 2015). The construction of the battery is robust, it is low maintenance (water only has to be added every 6 years), the operating temperature range is -20 °C-50 °C and it has a high cycling capacity (10,000 cycles when the depth of discharge is 15%).

Nickel-Metal hydride (Ni-Mh) Batteries

Ni-Mh batteries are similar to Ni-Cd batteries, except that the cadmium electrode has been replaced by a metal alloy that absorbs hydrogen. The Ni-Mh battery is thus more environmentally friendly than the Ni-Cd battery, as it does not contain cadmium. Ni-Mh batteries are used in over 95% of all hybrid electric vehicles (Mahlia, et al., 2014). Ni-Mh batteries have a higher energy density (~70-100 W h/kg) than Ni-Cd batteries. Ni-Mh batteries also suffer from the memory effect like Ni-Cd batteries (Krivik & Baca, 2013). However, Ni-Mh batteries have two disadvantages over Ni-Cd batteries: the discharge rate is higher at 0.4-1.2 %/day as dissolved hydrogen acts with the positive electrode, and they have a shorter life cycle (800-1200 cycles at 80% depth of discharge) (Gallo, et al., 2016).

The reaction taking place in the cell during discharge is shown in Equation 2.4 (Krivik & Baca, 2013).

$$NiOOH + MH \leftrightarrows Ni(OH)_2 + M \qquad 2.4$$

The voltage is in the range of 1.32-1.35 V, depending on the alloy used. Unlike the Ni-Cd battery, water is not included in the cell reaction (Krivik & Baca, 2013).

Sodium Sulfur (NaS) Batteries

NaS batteries are rechargeable batteries operating at high temperatures of 300-350 °C in order to keep sodium and sulfur in their molten states. Due to the high operating temperatures and the corrosiveness of the sodium polysulfide formed when the battery is discharged, NaS batteries are mostly suitable for non-mobile applications such as large-scale electric utility energy storage (Poullikkas, 2013).

A NaS battery is made up of molten sulfur at the positive electrode and molten sodium at the negative electrode. Usually, a solid beta alumina ceramic electrolyte is used as a separator in NaS batteries. The shell of the battery is ordinarily made of stainless steel as sodium polysulfide is very corrosive, and the shell also functions as a cathode current collector (Zhang, et al., 2018). The high operating temperature of the NaS battery increases the corrosiveness, as Na and S are much more corrosive in their molten state than in their solid state (Xin, et al., 2014). The materials used in the NaS battery are non-toxic and highly recyclable (about 99% of the materials can be recycled) (Argyrou, et al., 2018). When discharging the battery, positive sodium ions flow through the electrolyte and then combine with the sulfur, producing sodium polysulfides. The reaction is shown in Equation 2.5 and Figure 18 shows the operation of the NaS battery (Menictas, et al.,

$$2Na + xS^{-} \underset{\text{Discharge}}{\overset{\text{Charge}}{\leftrightarrows}} \mathrm{Na_2S_x} \quad (\mathrm{V^0} = 1.78 - 2.08\ \mathrm{V}) \qquad 2.5$$

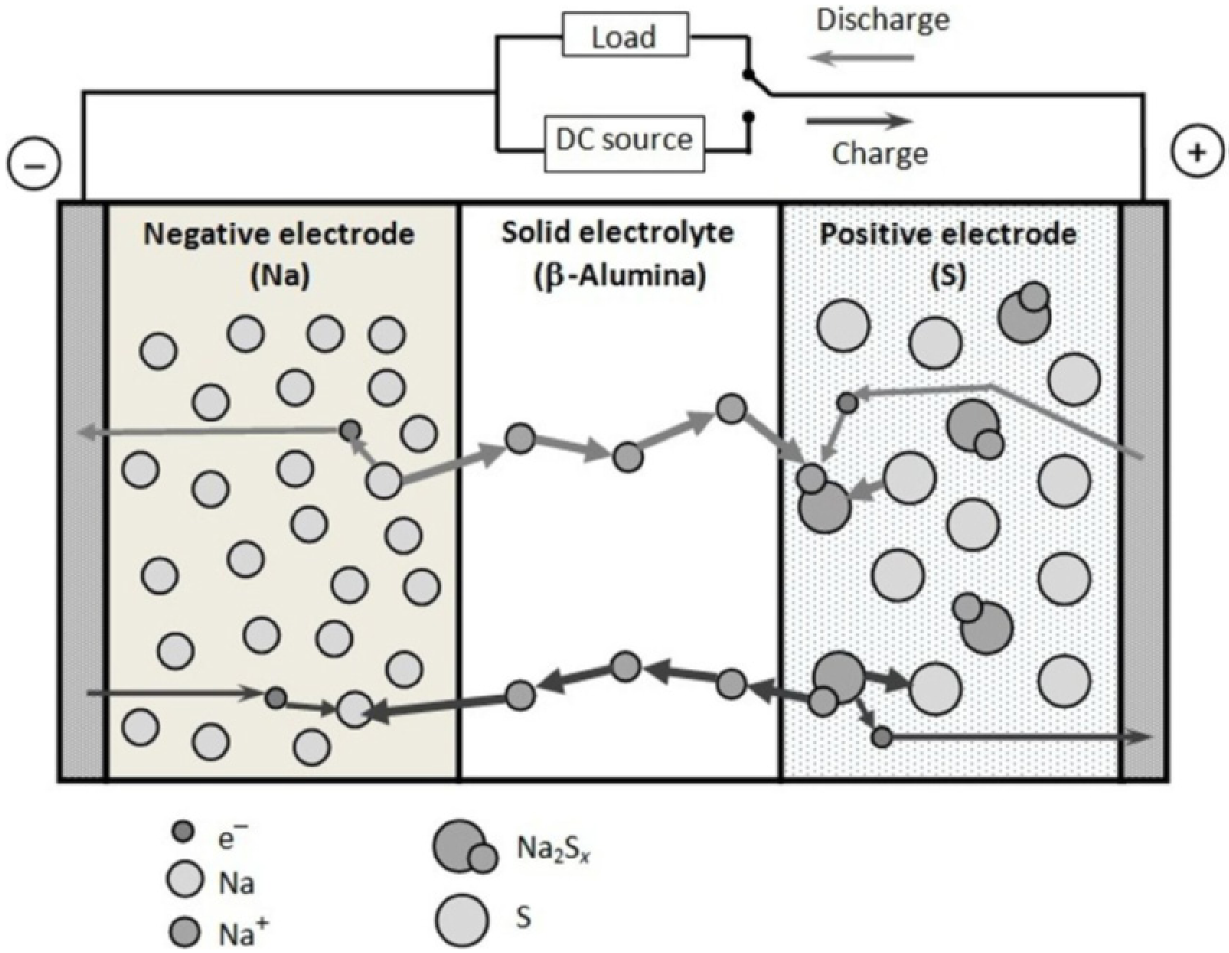


FIGURE 18. Operation principle of the sodium-sulfur battery (Menictas, et al., 2015).

The materials of NaS batteries are cheap, the batteries have a long cycle life (~4500-5000 cycles at a depth of discharge (DOD) of 80%), they have a lifetime of 10-15 years, the efficiency of charge/discharge is high (75-90%), they have a high energy density (150-240 Wh/kg (Argyrou, et al., 2018)) and low self-discharge. Self-discharge losses can be as low as 0.05%, however, when the batteries are on standby for long periods when they are not being used, electric heaters have to keep the temperature of the battery above 290 °C and this can cause self-discharge losses of up to 20% per day. Possible applications of NaS batteries include renewable energy management and integration, managing the power quality, load leveling and peak shaving (Gallo, et al., 2016; Poullikkas, 2013).

A special characteristic of NaS batteries is pulse power delivery, which enables the battery to exceed the nominal power rating when delivering electricity for periods on the scale of seconds to hours. The longer the period is, the lower the pulse power. For instance, a NaS battery can provide 500% of the power rating for 30 seconds or 150% for three hours (Gallo, et al., 2016).

There are some safety concerns with NaS batteries. If the solid beta alumina electrolyte in the NaS battery would break and a short circuit is formed, the liquid Na and S would be in direct contact and an exothermic reaction would take place. This reaction causes fires and the temperature reaches 2000 °C. The solid beta alumina electrolyte is fragile and can be damaged when struck by an external force or exerted to mechanical stress. Mechanical stress can be caused by freeze-thaw cycles of the battery, so due to this, it can be better to maintain the battery at a high temperature at all times to avoid any damage to the beta alumina electrolyte (Santhanagopalan, et al., 2014; Zhang, et al., 2018).

To address the safety and corrosion issues posed by the high operating temperature of the NaS battery, there is ongoing research on NaS batteries operating at room temperature. It is hoped these NaS batteries would be more durable, be safer and have higher energy output (Xin, et al., 2014). However, there is a range of challenges to overcome with operating a NaS battery at room temperature. The research in room temperature NaS batteries is still in its early stages and the batteries are a long way from commercialization (Kumar, et al., 2017).

Sodium Nickel Chloride (ZEBRA) Batteries

Sodium nickel chloride batteries are also known as ZEBRA (Zero Emission Battery Research) batteries. The technology of ZEBRA batteries is similar to that of NaS batteries, they also operate at high temperatures of 250-350 °C. The characteristics of the ZEBRA battery are similar to the NaS battery, although the energy density and specific energy of the ZEBRA battery are slightly lower. The major difference between the NaS and ZEBRA batteries is that in the ZEBRA battery, the sulfur cathode is substituted with a nickel chloride ($NiCl_2$) cathode. The cathode can also be made up of a mixture of $NiCl_2$ and ferrous chloride ($FeCl_2$). Another difference between the NaS battery and the ZEBRA battery is the electrolyte; the NaS battery has a solid ceramic beta-alumina electrolyte, while the ZEBRA battery has a molten sodium chloraluminate ($NaAlCl_4$) electrolyte in addition to the solid ceramic beta-alumina electrolyte (Argyrou, et al., 2018; Gallo, et al., 2016).

The reactions taking place at the anode and cathode during discharge are given in Equations 2.6 and 2.7 (Argyrou, et al., 2018).

$$\text{Anode: } 2Na \leftrightarrows 2\text{Na}^+ + 2\text{e}^- \tag{2.6}$$

$$\text{Cathode: } NiCl_2 + 2e^- \leftrightarrows \text{Ni} + 2\text{Cl}^- \tag{2.7}$$

The cell voltage, 2.58 V, in a ZEBRA battery is higher than the cell voltage of a NaS battery (Argyrou, et al., 2018).

A downside to the ZEBRA battery is that to start up the battery after it has turned solid (frozen), it takes 12-15 hours to heat it up. The main advantage the ZEBRA battery has over the NaS battery is safety. If the solid electrolyte breaks, molten sodium will at first react with $NaAlCl_4$ and form two non-hazardous materials. At the operating temperature of the ZEBRA battery, aluminum is in the solid state, and so aluminum forms a physical wall, and thus no other reactions take place after that. Due to this, the ZEBRA battery is considered safer than the NaS battery (Gallo, et al., 2016).

Flow Batteries (Redox Flow Batteries)

A flow battery consists of two main parts that are connected through pumps: the battery stack, where chemical energy is converted to electricity, and the external tanks, where electrolytes are stored and delivered to the battery stack through the pumps. The battery stack usually consists of one pair of electrodes, bipolar plates and current collectors on both sides of a membrane. The membrane blocks the electrolytes from mixing while functioning as a charge-carrier conductor (Zhang, et al., 2018).

Flow batteries are also known as Redox Flow Batteries (RFB). This is because the principle behind the energy conversions in the batteries is the reversible electrochemical reactions of two redox couples, for example, A^{2+}/A^{+} and C^{2+}/C^{3+} as shown in Equation 2.8 (Zhang, et al., 2018).

$$A^{2+} + C^{2+} \underset{\text{Charge}}{\overset{\text{Discharge}}{\leftrightarrows}} \mathrm{A}^{+} + \mathrm{C}^{3+} \qquad 2.8$$

In conventional batteries, the electrochemical reactants are stored in the actual electrodes, while in RFBs, the reactants are stored in electrolytic solutions in external tanks, and the electrolytes are pumped from these tanks to the battery stack in order to convert energy. This gives RFBs an advantage over conventional batteries; the electrodes have a longer lifetime as they do not have to undergo complex redox reactions, mechanical strains and structural changes. Also, the decoupling of storage and reaction adds flexibility as the total energy stored is determined by the concentration and volume of electrolytes instead of being limited by the electrodes. The power rating depends on the cell size, the total area of the electrodes, and the reaction rates at the anode and cathode. It is also easy to refill and replace the electrolyte. One disadvantage of RFBs to conventional batteries is that their design is more complicated due to the pumps pumping the electrolyte, which is often very corrosive. Another disadvantage is that the design of RFBs gives them a lower volumetric energy density and specific mass compared to conventional batteries (Menictas, et al., 2015; Zhang, et al., 2018).

RFBs can be divided into four types based on the electrolyte composition (water or organic solvent) and the redox-active materials (metal compounds or organic species). There are aqueous metal-based, non-aqueous organometallic, aqueous organic and nonaqueous organic RFBs. Aqueous metal-based redox batteries are the most developed systems so far. Figure 19 shows a timeline of major developments in RFB technologies. The first three kinds of RFBs developed, Zinc-Bromium (Zn-Br), Iron-Chromium (Fe-Cr) and Vanadium (V) Redox will be briefly presented in the next chapters (Zhang, et al., 2018).

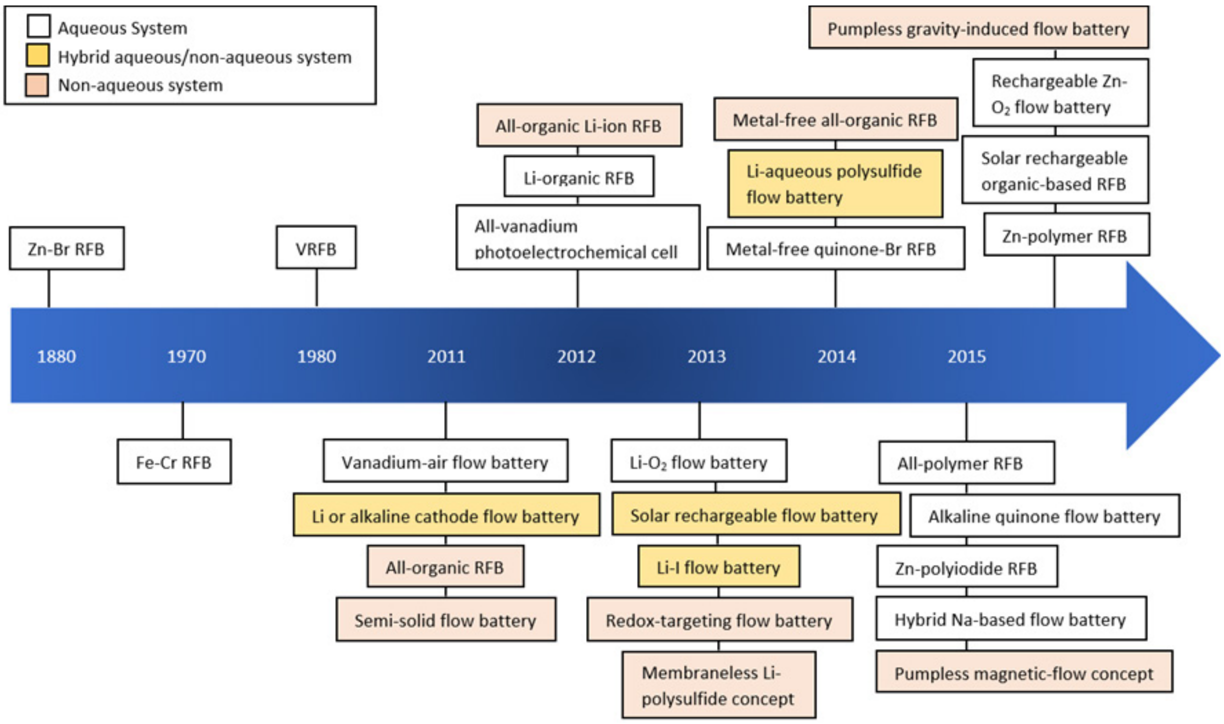


FIGURE 19. Timeline for development of different types of redox flow batteries (Zhang, et al., 2018).

Iron-Chromium Flow Batteries (ICB)

The first RFB prototype that was successful was the iron-chromium flow battery (ICB) developed by NASA (Zhang, et al., 2018). The ICB uses iron as the active material at the cathode and chromium as active material at the anode. Usually, hydrochloric acid (HCl) is added to the electrolyte in order to dissolve the chloride salts of iron and chromium. The redox reactions taking place in the battery stack can be seen in Equation 2.9. The theoretical voltage is 1.18 V (Zhang, et al., 2018).

$$Fe^{3+} + Cr^{2+} \underset{\text{Discharge}}{\overset{\text{Charge}}{\leftrightarrows}} \mathrm{Fe}^{2+} + \mathrm{Cr}^{3+} \qquad 2.9$$

This prototype had a problem with the active materials crossing over which caused the capacity to decrease. This was solved by developing mixed electrolytes that contain both positive and negative electrolytes. Another solution proposed to this was to use the same element with different states on both sides of the RFB (Zhang, et al., 2018).

The ICB has two other significant problems that are caused by the Cr^{3+}/$Cr2^{+}$ couple. The first problem is the low redox potential, which makes hydrogen evolution a major side reaction that happens during charging, and this lowers the coulombic efficiency and limits the depth of charge. The other problem is the slow kinetics of the Cr^{3+}/Cr^{2+} couple. As a result, loading of catalysts is needed as well as higher operating temperatures to boost the cell performances (Zhang, et al., 2018).

Zinc-Bromine Flow Batteries (ZBB)

The ZBB is considered a mature technology. In 1991, 1 MWh and 4 MWh prototypes of ZBBs were built, and currently, 500 kWh ZBBs are in the early stages of commercialization. The redox couple is zinc and bromine (Menictas, et al., 2015).

The reactions for charging and discharging the ZBB are shown in Equation 2.10 (Soloveichik, 2011). When charging, metallic zinc is deposited on the negative electrode and elemental bromine is deposited on the positive electrode, the bromine combines with other agents to form a polybromide (Gallo, et al., 2016).

$$Zn + Br_3^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\leftrightarrows}} \mathrm{ZnBr_2} + \mathrm{Br^-} \quad \mathrm{E^0} = 1.85\ \mathrm{V} \tag{2.10}$$

The problem with the development of ZBBs is that bromine is very corrosive and toxic, zinc dendrite and hydrogen gas are formed during operation, the high cost of electrodes, short cycle life and lower energy efficiency. But because of its low cost, high energy density (75-85 Wh/kg) and minimal electrode polarization, the ZBB has been considered for load leveling applications (Soloveichik, 2011; Zhang, et al., 2018).

Vanadium Redox Flow Batteries (VFB)

The VFBs look the most promising and are the most well-established among RFBs. The redox couples are vanadium and the electrolytes are mild sulfuric acid solutions. VFBs use four oxidation states of vanadium (V(V)/V(IV) and V(III)/V(II) couples) to undergo the reaction given in Equation 2.11. The theoretical voltage is 1.26 V. H^+ ions are exchanged between the two electrolyte tanks through an ion-exchange membrane. Derivatives of VFBs have been developed where the V(V)/V(IV) couple on the cathode side was replaced by another couple, such as iron (Menictas, et al., 2015; Zhang, et al., 2018).

$$VO^{2+} + V^{3+} + H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\leftrightarrows}} \mathrm{VO_2^+} + \mathrm{V^{2+}} + 2\mathrm{H^+} \tag{2.11}$$

In Figure 20, a VFB is shown, with the anode and analyte tank on the left side and the cathode and the cathalyte tank on the right side.

An advantage of VFBs is the fact that vanadium ions are used in both electrolytes. This should remove the risk of cross-contamination which other RFBs have, like ICBs. But despite the same element being used on both sides, cross-contamination is still an issue in VFBs. The cross-contamination causes constant decay of capacity as volume changes in the electrolyte tanks and the four vanadium species have different migration and diffusion rates across the membrane. The capacity losses can be restored through hydraulic pressure management and periodic remixing. Another problem in VFBs is gas evolution. With high overpotentials, hydrogen can be generated at the anode, or oxygen can be generated at the cathode. Other obstacles for VFBs are the high corrosiveness of the V(V) species and strong acids, and the costs of vanadium precursors and membranes are quite high (Zhang, et al., 2018).

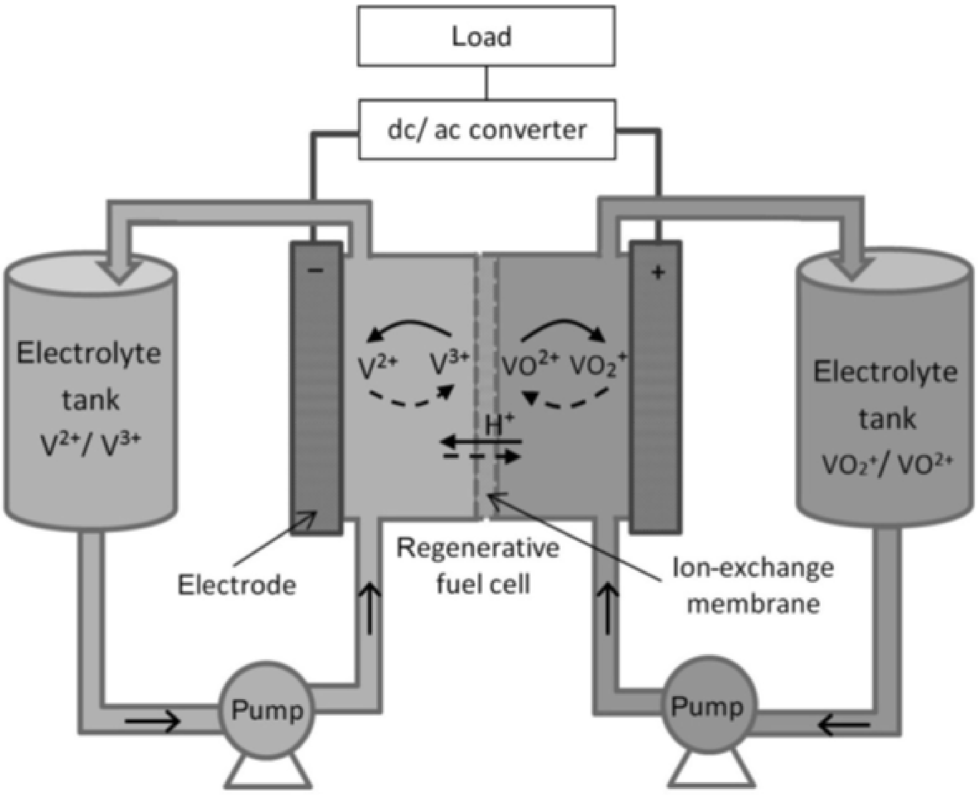


Figure 20. A Vanadium Redox Flow Battery (Menictas, et al., 2015).

Electrical Energy Storage

Superconducting Magnetic Energy Storage (SMES)

The main parts of SMES are a superconducting coil, a refrigeration and vacuum system, and a power conversion system. Figure 21 shows the components in a SMES system (Argyrou, et al., 2018). SMES operates by inducing a Direct Current into the coil of a superconducting wire, creating a magnetic field in which the electrical energy is stored. The superconducting coil is cryogenically cooled in a vacuum enclosure to a temperature below the superconducting critical temperature of the material used for the superconducting coil (Gallo, et al., 2016). Normally, when a current passes through a coil, the electrical energy will be given off as heat because of the resistance of the wire. But when the coil is made of superconducting material and it is maintained below the superconducting critical temperature, there is no resistance and so the electrical energy is stored with almost no losses. The energy stored in a SMES can be calculated using the formula:

$$E = LI^2 / 2 \qquad 2.12$$

where L is the inductance of the coil and I is the current going through the coil (Argyrou, et al., 2018). The electrical energy stored in the SMES system can be discharged back to the Alternating Current (AC) system through a power converter module (Luo, et al., 2015).

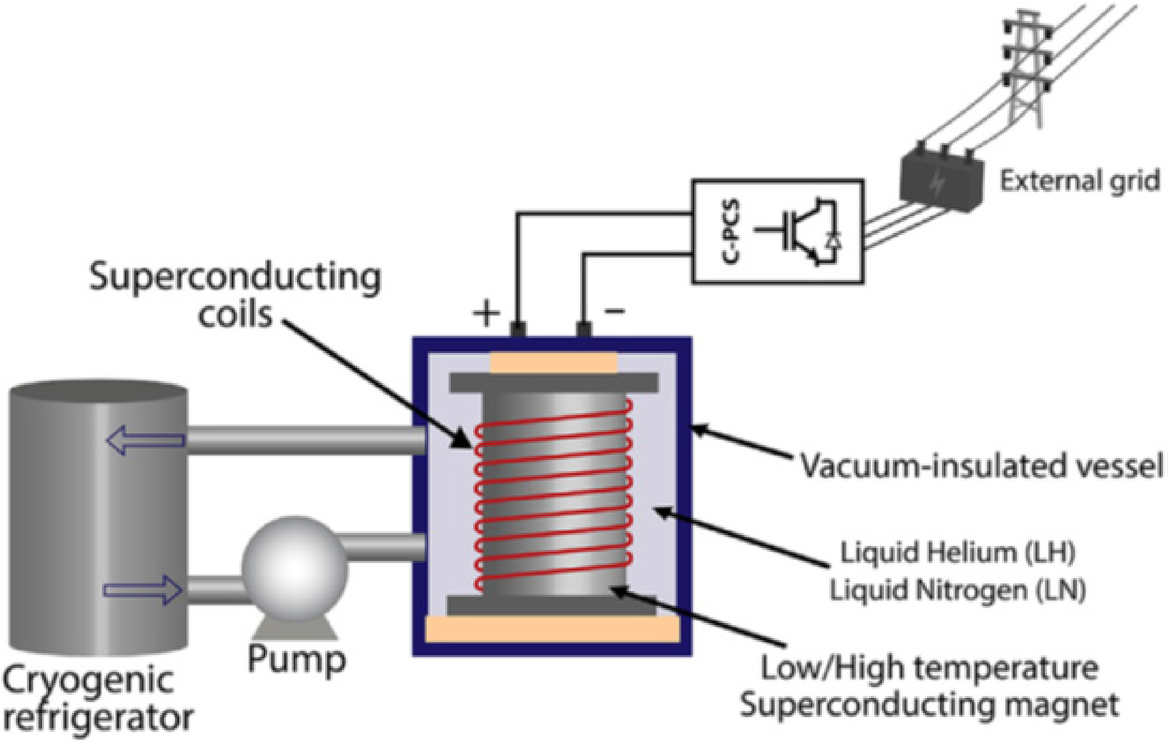


FIGURE 21. A SMES system (Argyrou, et al., 2018).

Superconducting coils can be divided into two categories: Low Temperature Superconducting (LTS) coils, which have an operating temperature of around 5 K, and High Temperature Superconducting (HTS) coils, which have an operating temperature of around 70 K. HTS-SMES is still in the development stage while LTS-SMES is more mature and is applied commercially. So far SMES systems with a power rating in the range of 0.1-10 MW have been applied commercially. A material commonly used for the superconducting coil is Niobium-Titanium, which has a superconducting critical temperature of 9.2 K (Luo, et al., 2015).

SMESs have a long cycle life, ranging from tens of thousands to hundreds of thousands of cycles (Gallo, et al., 2016). SMESs have a high power density of up to 4 MW/m^3, a high cycle efficiency in the range of 95-98%, a long lifetime of up to about 30 years, a fast response time (in milliseconds) and a fast full discharge time of less than 1 minute (Luo, et al., 2015). Unlike batteries, SMES devices can be fully discharged with very little degradation. The downsides of SMES are the high capital cost of up to 10,000 $/kWh or 7200 $/kW, a high daily self-discharge rate of 10-15%, the sensitivity of the coil to temperature variations which can cause energy losses and a negative environmental impact from the strong magnetic field formed during operation (Luo, et al., 2015).

Electrochemical Capacitors

Electrochemical capacitors are also known as supercapacitors, ultracapacitors or double-layer capacitors. In conventional capacitors, charges are stored on parallel plates separated by a solid dielectric. In electrochemical capacitors, a liquid electrolyte solution is instead used between two solid conductors (Burheim, 2017). In Figure 22, the operation of a group of supercapacitor cells connected in parallel or series is shown (Díaz-González, et al., 2012).

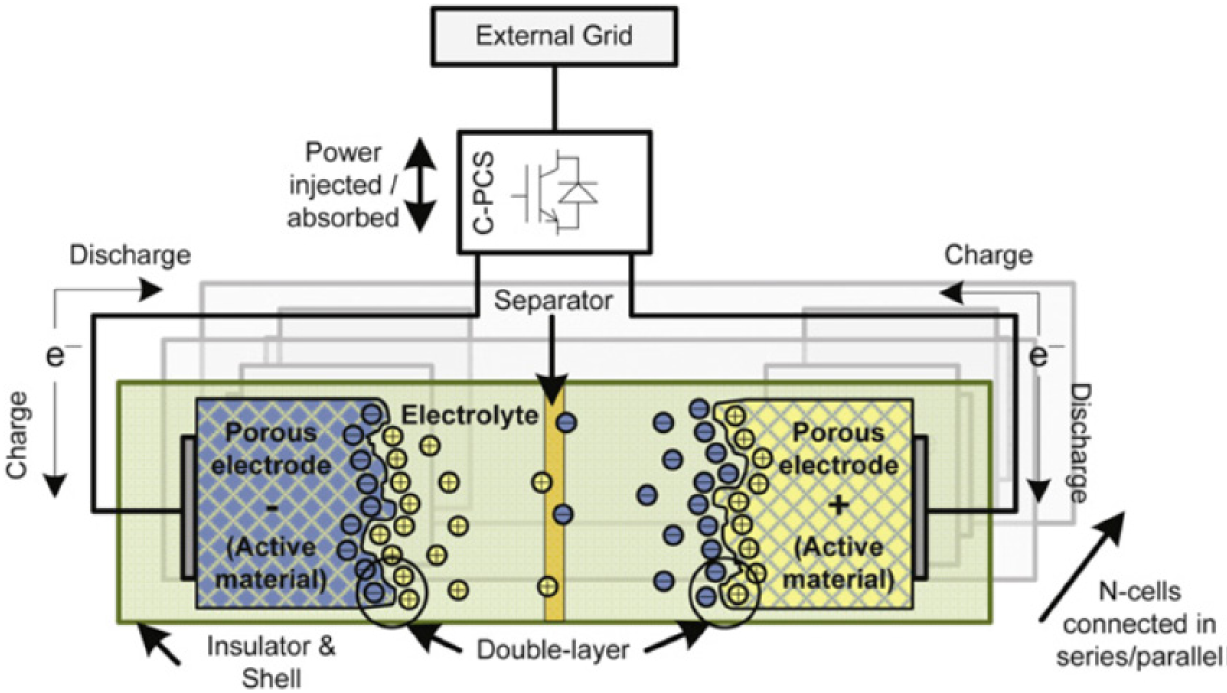


FIGURE 22. The operation of supercapacitor cells (Díaz-González, et al., 2012).

Due to the use of a liquid electrolyte solution, electrochemical capacitors have a much higher capacitance and a higher power density (500-10,000 W/kg) with regard to both mass and volume (Burheim, 2017; Gallo, et al., 2016). Although they are a form of electrochemical storage, their functioning does not involve redox reactions and hence there is no friction for charge transfer (Burheim, 2017). Due to this, electrochemical capacitors can handle huge loads in extremely short periods (tens to hundreds of milliseconds with high efficiency (85-95%) (Aneke & Wang, 2016; Gallo, et al., 2016). As the electrodes are not chemically degraded as in batteries, supercapacitors can be cycled more than 500,000 times and they have a lifetime of 12 years (Zhou, et al., 2013).

The downside of having no redox reactions is that electrochemical capacitors have a low energy density (5 Wh/kg). Another downside to electrochemical capacitors is that self-discharge occurs in a matter of hours or days. Also when designing a supercapacitor, an aging model should be made as the lifetime of a supercapacitor is affected by the variation of voltage and temperatures (Zhou, et al., 2013).

Due to their capability of rapid charging and discharging, superconductors are used in Hybrid Electric Vehicles (HEV) for storing energy from electrical braking and for delivering accelerating power. By combining the battery of a HEV and a supercapacitor, the higher energy capacity of the battery and the higher power density of the supercapacitor are combined. The supercapacitor extends the lifetime of the battery in the HEV as the depth of charge and discharge of the battery are reduced, and the size of the battery can be decreased as the peak loads of the battery are reduced. Supercapacitors can also be used to absorb short-term high power fluctuations generated from renewable energy sources (Zhou, et al., 2013).

Mechanical Energy Storage

Pumped Hydro-Power Storage (PHS)

Pumped Hydro Storage is an old and well-established method to store energy and electricity. It was commercialized already in the 1890s and in 2017 it was the market leader covering 96 % of the global electricity storage capacity (IRENA, 2017, p. 14). In a PHS system, there is a higher and a lower water reservoir, and the water is pumped up during the low demand (low price) period and used as a traditional hydropower plant in times of high electricity demand/price (Figure 23). Typically, the pump (water upwards) and turbine (water downwards) are combined in a reversible electric generator/motor system.

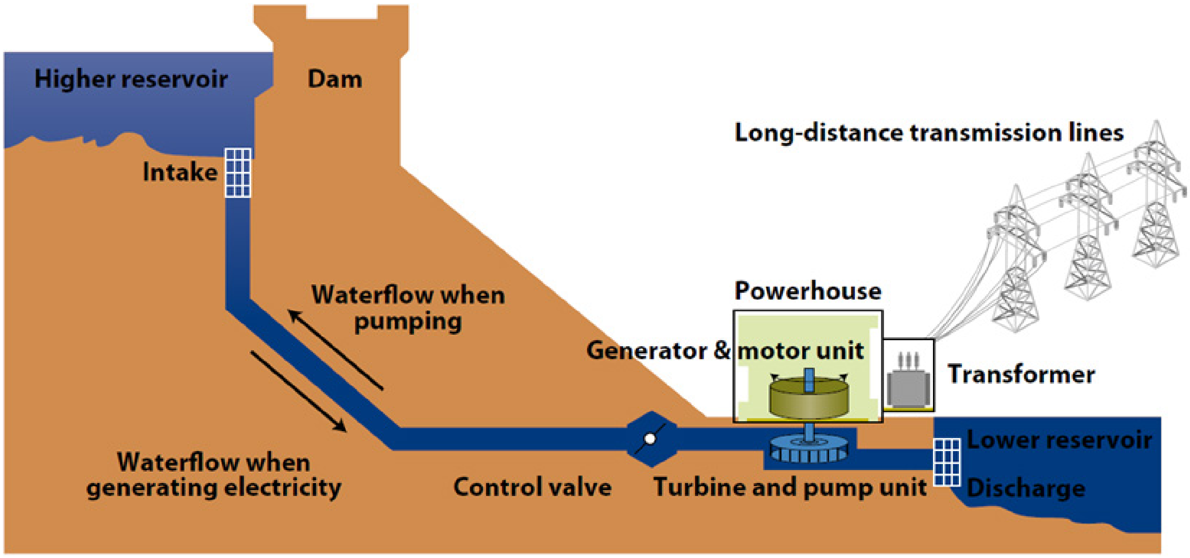


FIGURE 23. A typical PHS system (Luo, et al., 2015).

Like with traditional hydropower the PHS energy storage capacity depends on the volume of the upper reservoir and the height difference between reservoirs. In PHS systems usually at least one of the water reservoirs is already existing in the form of a lake or a river. To reach an adequate height difference between the reservoirs, elevated terrain is usually required. The PHS systems usually use freshwater as fluid, but there has also been at least one case (Okinawa, Japan 30 MW) where the Pacific Ocean has been used as the lower reservoir (IRENA, 2017, p. 51). In these kinds of solutions, the high salt density of the oceans is causing challenges (corrosion, more maintenance) which to a high degree could be avoided in the Baltic Sea due to the very low salt density of the seawater.

The round-trip efficiency for PHS plants is rather high (70 - 84 %) and the estimated lifetime rather long between 40 to 60 years. For PHS systems the storage time/capacity is usually from some hours to some days. Also, the discharge rate (max 2 % per day) of PHS systems is very low and competitive compared to many other storage options (IRENA, 2017, p. 51). A PHS plant is a net consumer of electricity due to the electrical and hydraulic losses when water is pumped up. A traditional hydropower plant can convert up to 90 % of the energy content of the flowing water into electricity, which means that a PHS plant also has some losses when producing electricity like a traditional hydropower plant. Although there are these losses both upwards and downwards a modern PHS plant usually reaches a higher roundtrip efficiency than 80 %.

FIGURE 24. A pumped hydro storage power plant in Thailand (Shutterstock, 2021).

Figure 24 is a picture of one PHS and such a plant has many advantages as a subsidiary energy supply resource. The round trip and costs efficacies are the best ones of all energy storage systems (Table 3).

Table 3. Pumped Hydro-Power Storage strengths and qualities.

PUMPED HYDRO POWER STORAGE (PHS) STRENGTHS/QUALITIES
Provides energy balance and stability for the intermittent production (wind, solar)
Very high round-trip efficiency (over 80 %)
Capability to reserve large quantities of energy
Low discharging rate
Best cost efficiency of all ESS technologies (often less than 100 €/MWh)
Can provide critical ancillary grid services (e.g. network frequency control)
Have a rather short ramp-up time (1-5 minutes)
Have reactive power and black start capability and can function as spinning reserve
Ability to balance excess generation and quickly provide pick up load

The number of variable-speed PHS is increasing because this solution improves even further the efficacy of the system (an analogy with the evolution from fixed speed to variable speed wind turbines). There are even more advanced applications of PHS where the water is pumped into a cylinder and a piston loaded with heavy rocks is either moving down (discharge) or up (pumping water to the cylinder and charging).

The economical profitability of a PHS plant depends heavily on the electricity market price fluctuations. If the diurnal or weekly price differences between the peak and off-peak market prices are extensive, the profitability of a PHS plant can increase dramatically. Also, the frequency and price cycle density can to a great extent influence the profitability of a PHS plant. This, of course, applies to all energy storage systems, but is especially relevant for PHS plants, because PHS plants are the only current energy storage technology that has reached true economic viability in the electricity market.

Traditionally PHS solutions need mountains or hills to reach the adequate fall height of running water. This technology can also be utilized in flat terrain if there is an underground water reservoir like an abandoned mine that can be used as the lower reservoir. In the best-case scenario, an existing lake or larger pond can be used as the upper reservoir. Globally there are many prospective projects to convert old mines to PHS power plants (Underground Pumped Storage Hydropower UPSH). One case is the old Prosper-Haniel coalmine in Germany with a depth of 600 meters and a planned power of 200 MW (Figure 25). In Finland extensive technical and economic studies have been conducted to convert Pyhäsalmi mine to a PHS plant. According to the feasibility study, even a 400 MW storage would be possible in this mine, but the most profitable solution would be a 75 MW plant with a capacity of 530 MWh. This mine has an exceptional depth of over 1,400 meters (Pyhäjärven Callio, 2021) and one-third of the incomes are estimated to come from the capacity markets of securing the grid frequency (Lampila, 2018). However, it looks unlikely that this PHS solution of utilizing an abandoned mine would be used soon in the region of Ostrobothnia.

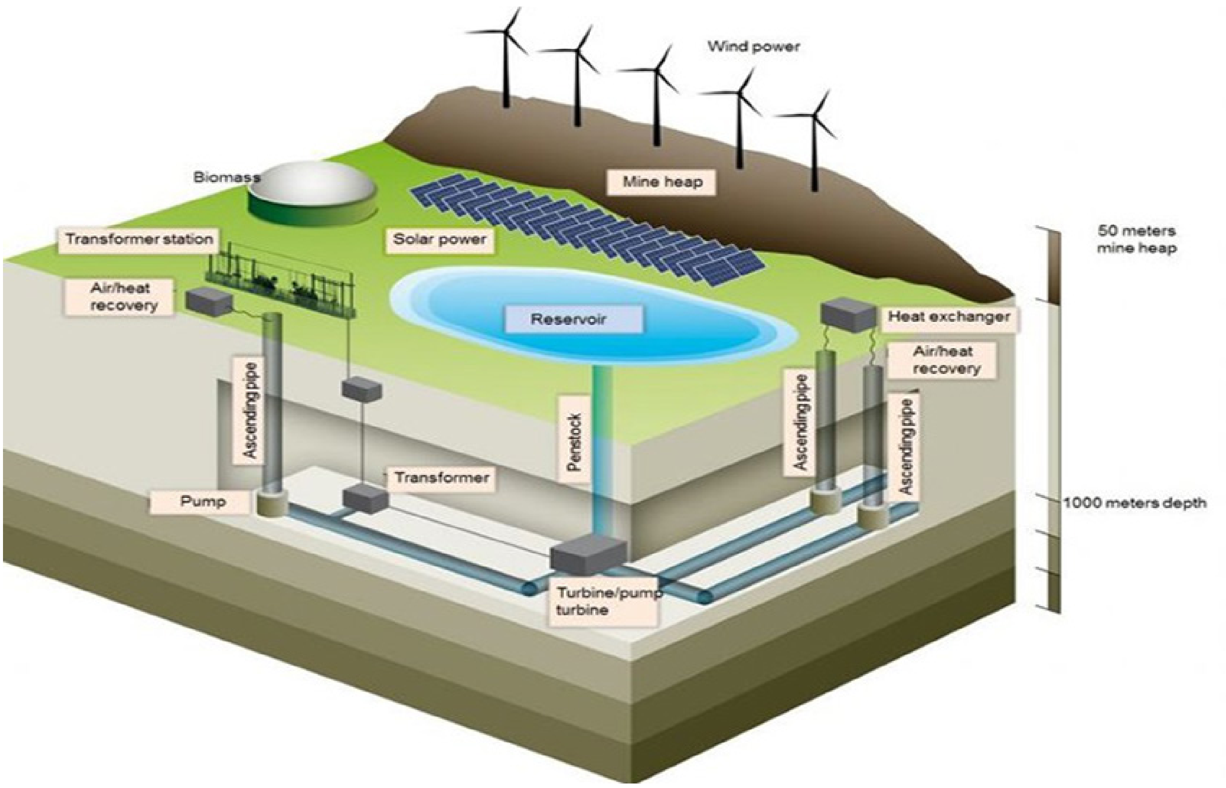


FIGURE 25. A draft to convert a German coal mine to a PHS plant (University of Duisburg-Essen, 2017).

Compressed Air Energy Storage (CAES)

Already for more than half a century, compressed air has been utilized on a small scale for special purposes (e.g. mine locomotives) as an energy storage. The challenge with compressed air as an energy storage is the heat that is created during the compression process. In traditional solutions, the created heat is wasted and these systems are called diabatic Compressed Air Energy Storages (dCAES). When the excessive heat of the compression process is stored, the efficacy of the system increases dramatically and these systems are called adiabatic Compressed Air Energy Storages (aCAES). Both the heat creation during the compression and cooling down during the expansion (discharging) are vital issues when compressed air is used as an energy storage.

The first commercial-scale CAES plant was built in 1978 in Huntorf in Germany and it had a power output of 290 MW, and the second one with 110 MW was commissioned in 1991 in McIntosh, Alabama, USA. To store large amounts of compressed air a cavern (in Huntorf 310 000 m^3) is usually used because a manmade metal vessel for the energy storage would be too expensive. When storing large amounts of compressed air underground there are many requirements on the cave. Old salt mines have many positive features for this purpose, but they also have some challenges like the heat exchange between air and the surrounding salt (Crotogino, et al., 2001, p. 1). When metal vessels are used for the storage, the humidity of the air is a challenge due to the risk of corrosion. The CAES plants are used in combination with gas turbines and they operate as traditional gas power plants with the differentiation that the needed compressed air is not produced simultaneously but instead stored when low-cost electricity has been available. In traditional gas turbines, 2/3 of the used energy is needed to compress the combustion air, which is provided in a CAES plant by the storage unit.

Figure 26 displays the main components of the CAES plant in Huntorf Germany; (1) compressor train, (2) motor-generator unit, (3) gas turbine and (4) underground compressed air storage.

The Huntorf plant has now been in operation for over 40 years and it has mainly served as a reserve power plant as a minute reserve or peak shaving in the evening when no more pumped hydro capacity is available (Crotogino, et al., 2001, pp. 3-4).

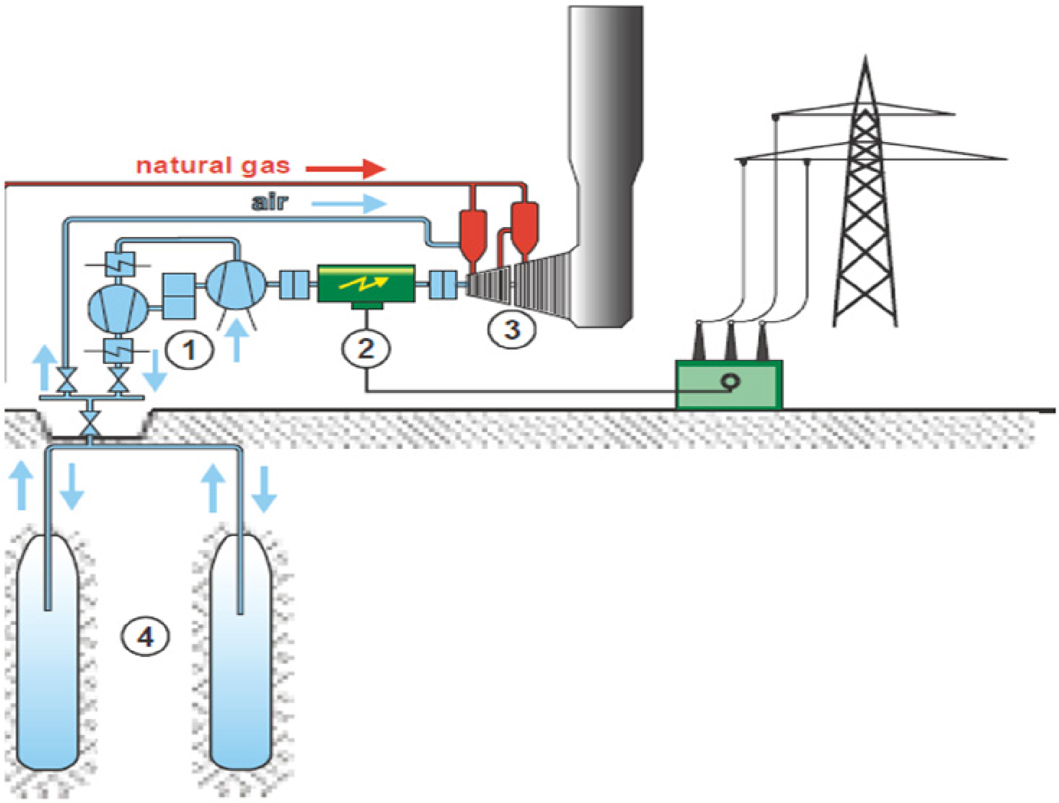


FIGURE 26. Components of the Huntorf Germany CAES plant (Crotogino, et al., 2001, p. 1).

Diabatic Compressed Air Energy Storage (dCAES)

In the dCAES, the heat created during compression is considered as waste. The heat is removed from the warmed-up air by different kinds of intercoolers before the final storage. If the temperature of the stored air is low, there will be a need to preheat the compressed air prior to the expansion in the turbine or generator. The reheating of the compressed air reduces the efficiency of the system and, if the heat process is done with fossil fuels, this is an environmental issue. In dCAES, the round-trip efficiency is often rather low, an efficiency of 42% has been reported for Huntorf and 54% for McIntosh (RWE Power AG, 2017).

(Advanced)/Adiabatic Compressed Air Energy Storage (aCAES)

A thermal energy storage system is used to store the heat of the compression process in an aCAES system. The stored heat is used to warm up the compressed air prior to the expansion process through the turbine. This method dramatically increases the round-trip efficiency (over 70%) of the CAES system because there is no need to use additional fuels to preheat the expanding air. In a CAES system, the electrical motor compresses air when cheap electricity is available and the heat created by the compression is stored before it is reused to warm up the compressed air from the cavern/vessel (Figure 27).

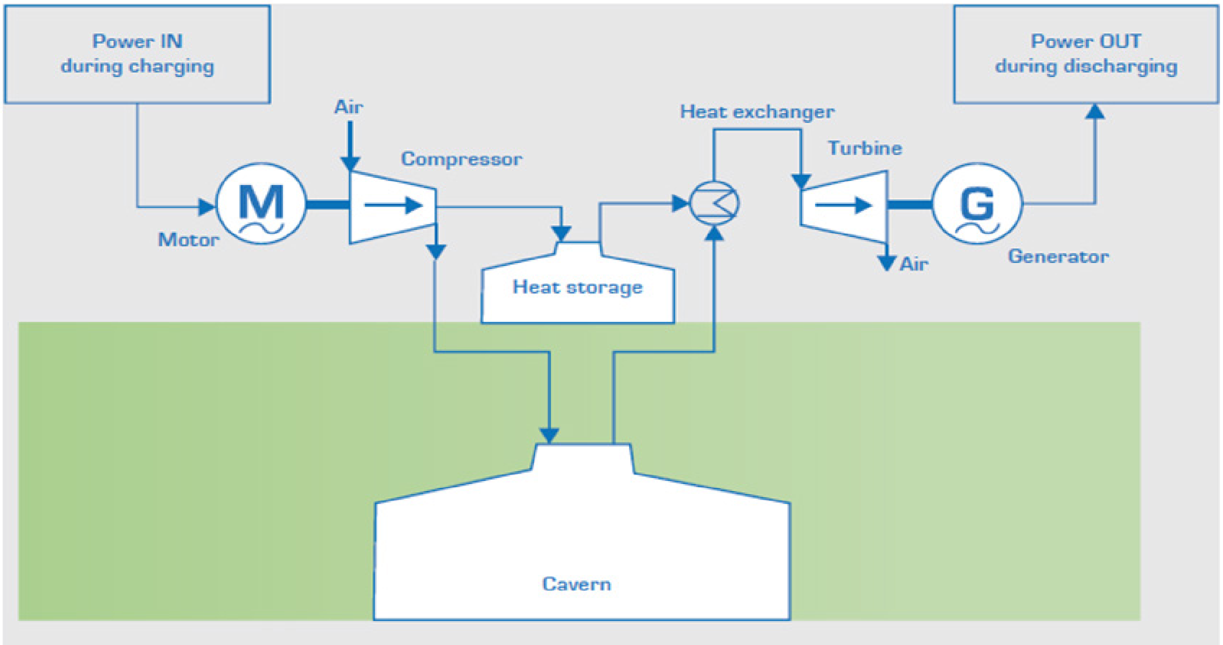


FIGURE 27. Operation principles of an aCAES system (EASE, 2018).

An issue for all CAES systems is how adjustable the volume of the air storage is. If the volume of the air tank/cave is fixed, the air pressure will be fluctuating, which causes some technical challenges in the process. One solution to solve this problem is to use large air backs which are covered by a fluid. This kind of solution has been tested in some aCAES R&D projects, however, there is not yet any commercial site with this solution. An aCAES plant can compress the air up to over 70 bars and the compressor discharge pressure can exceed 600 °C (EASE, 2018).

In an aCAES plant, there is a TES which can consist of ceramic, concrete or natural rock materials. A TES system is normally divided into (Pelay, et al., 2017):

- Sensible heat thermal energy storage
- Latent heat thermal energy storage by using Phase Change Materials (PCM) (using a Heat Transfer Fluid (HTF) and a heat exchanger)
- Thermo-chemical storage

TES systems can also be divided into active and passive systems. In an active direct system, a single HTF is used for both heat transfer and storage. In an active indirect system, a second medium for storing the heat is used: first, the HTF is heated and then it flows to a heat exchanger where it transmits its heat to the storage material.

In passive TES systems, the storage medium does not circulate through the system, the HTF transfers the heat to and from a fixed storage (Pelay, et al., 2017).

Adiabatic CAES power plants are at the moment in the research and development state and the first power plant was to be commissioned in spring 2018. The extreme heat (over 600 °C) and very high pressure (up to 100 bar) are creating technical challenges concerning especially the durability of different components. The largest aCAES case is in Germany (ADELE/360MWh capacity) but there are also projects in Switzerland (the SNF project) and the US. The most advanced technology is the isothermal CAES where the thermal exchange is very carefully managed and steered both during the charging and discharging phases. This isothermal method will most likely not make any commercial breakthrough in the near future.

Isothermal CAES (iCAES)

In iCAES, the aim is to prevent the increase in temperature in the compressors during compression and the decrease in temperature in the expansion devices when discharging. So far, all methods for iCAES use piston machinery because it allows a comparably slow compression and expansion process, giving enough time for heat exchange processes inside the machinery itself. One method for iCAES is by compressing and expanding the air very slowly. Another method is to spray water inside the piston to absorb the heat generated during compression. This water is then stored, and during discharge, this water is sprayed to maintain the temperature. Another method is to use a pre-mixed foam to absorb the heat (Budt, et al., 2016; Gallo, et al., 2016).

Table 4 shows a comparison of dCAES, aCAES and iCAES. The advantages iCAES would have over traditional dCAES and aCAES are higher efficiency, smaller capital costs and removing the need to store the heat of compression (Heidari, et al., 2017). In addition, fossil fuels are not required to reheat the air during expansion (Matos, et al., 2019).

TABLE 4. Comparison of dCAES, aCAES and iCAES (Budt, et al., 2016)

	DIABATIC	ADIABATIC	ISOTHERMAL
Cycle efficiency (AC to AC)	Today: 0.54 Goal: 0.6	Today: – Goal: 0.7	Today: 0.38 Goal: 0.8
Energy density (per m^3 of CAES)	2-15 kWh/m^3	0.5-20 kWh/m^3	1-25 kWh/m^3
Start-up time	10-15 min	5-15 min	<1 min
Power range	5MW-1GW	1MW-1GW	5kW-1GW
Development status	Application/ Demonstration	Research/ Demonstration	Research/ Demonstration

Flywheels

Flywheels belong to the category of electromechanical energy storage systems. A flywheel stores energy in the form of kinetic energy by rotating a mass (a rotor). In Figure 28, the components of a flywheel are shown. When a flywheel is charged, a motor is using electrical energy to spin the rotor. The motor is connected to the rotor through a shaft. When the flywheel is being discharged, the same motor acts as a generator instead, converting the kinetic energy back to electricity, decelerating the rotor. The interior space of a flywheel is either vacuum or filled with a low friction gas to reduce wind shear (Díaz-González, et al., 2012). The energy stored in a flywheel is dependent on the square of the rotating speed and the moment of inertia of the spinning mass (Aneke & Wang, 2016; Gallo, et al., 2016).

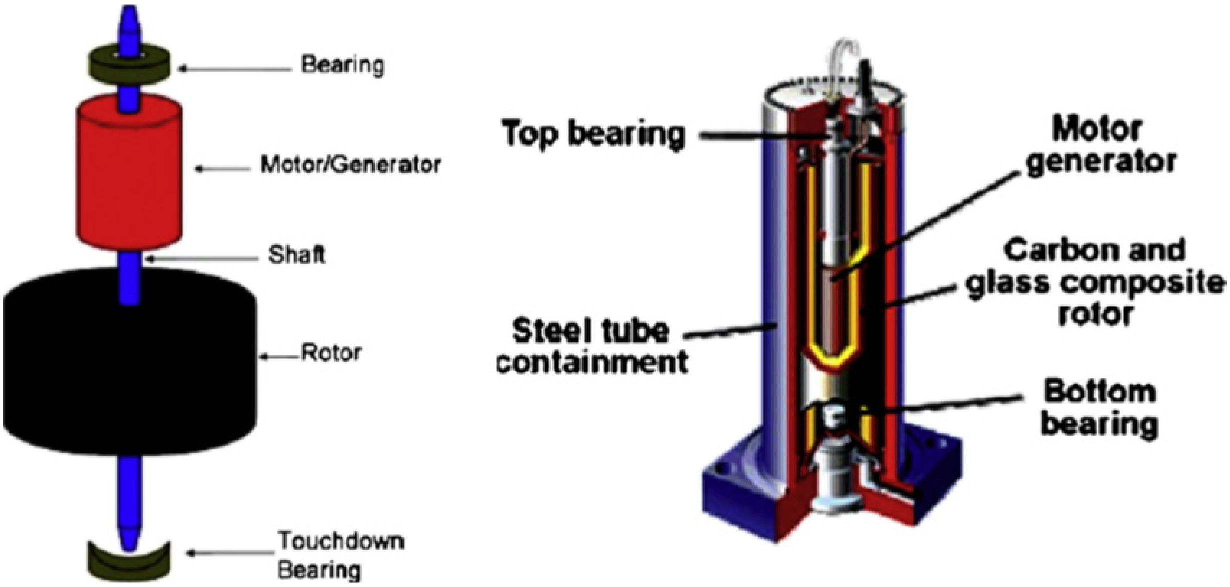


FIGURE 28. The structure of a flywheel (Aneke & Wang, 2016).

Flywheels can be divided into low-speed flywheels, which have rotational speeds of less than 10,000 rpm, and high-speed flywheels, which have a rotational speed greater than 10,000 rpm. The low-speed flywheels use rotors made of steel. The rotor in high-speed flywheels is made of composite material, such as graphite or carbon-fiber (Díaz-González, et al., 2012). The magnetic bearings on the top and bottom which support the rotor are made of different materials in low-speed and high-speed flywheels. In low-speed flywheels, conventional bearings are used. In high-speed flywheels, low friction magnetic bearings such as superconducting magnetic bearings are used. The motor-generator equipment is also more robust in high-speed flywheels. Due to the difference in materials used, low-speed flywheels can be up to 5 times cheaper than high-speed flywheels (Gallo, et al., 2016; Zhou, et al., 2013).

The energy stored in a flywheel is related to the moment of inertia, J, and the angular velocity, ω, as seen in Equation 2.13 (Mousavi G, et al., 2017).

$$E = \frac{1}{2} J \omega^2 \quad (2.13)$$

The energy density, EV, of a flywheel by volume is determined by the product of a shape factor, K, and the maximum stress of the flywheel, σ_(θ.u) as seen in Equation 2.14. (Mousavi G, et al., 2017).

$$E_v = K \times \sigma_{\theta.u} \quad (2.14)$$

The energy density of a flywheel by mass is the energy density by volume divided by the mass density of the rotor, ρ, as seen in Equation 2.15 (Mousavi G, et al., 2017).

$$E_m = \frac{K \times \sigma_{\theta.u}}{\rho} \qquad 2.15$$

With Equations 2.14 and 2.15, it is possible to conclude that when designing a flywheel, the choice of material is critical. The material has to be of high strength in order to stand the stress, but the material should at the same time be lightweight (Díaz-González, et al., 2012). The energy density of low-speed flywheels is 5-30 Wh/kg, while the energy density of high-speed flywheels can be up to 100 Wh/kg (Zhou, et al., 2013).

Commonly, the power rating of flywheels is on the scale of hundreds of kW, and in modular units, the power rating has reached some MW. Flywheels have a high efficiency of 75-85%, a long life cycle (up to 20 years or 100 000 cycles), the response time is fast (milliseconds to a second), no significant adverse impact on the environment (Gallo, et al., 2016), low maintenance costs, no effect from the depth of discharge, a wide operating temperature and can stand harsh conditions (Aneke & Wang, 2016). However, flywheels have a high self-discharge (55-100 %/day) rate due to friction losses (Gallo, et al., 2016). Because of this, flywheels are not suitable for long-term energy storage. Suitable applications of flywheels include Uninterruptible Power Supplies, smoothing power fluctuations through frequency regulation and facilitating the integration of intermittent renewable energy. The most common application is to have the flywheel function as a ride-through when switching between different power sources (Zakeri & Syri, 2015).

Thermal Energy Storage

Thermal energy storage can be divided into subcategories by many different criteria like sensible/latent heat or active/passive systems. Latent TES systems are based on phase change materials, which can charge or release great amounts of energy when their physical state is changing e.g. from solid state to liquid. These latent TES systems are mostly still under the R&D stage and all large-scale commercial TES are based on sensible heat, where storage is based on the varying temperature. There are some promising new technologies like Pumped Heat Electrical Storage (PHES), which uses heat pumps to store electrical energy as thermal energy and heat engines to convert heat back to electricity (Frate, et al., 2017). Thermal energy can be stored either in a man-made vessel or into the ground or soil. Underground thermal energy storage systems (UTES), like the borehole thermal energy storage, can offer in the future great opportunities in terms of heating and cooling.

Pumped Heat Electrical Storage (PHES)

PHES is a technology where electrical energy is stored as thermal energy. It uses heat pumps to store electrical energy as thermal energy and heat engines to convert heat back to electricity (Frate, et al., 2017). A low cost and long cycle life make it among the promising technologies that are in the developing phase for large-scale energy storage (Benato & Stoppato, 2018).

The working principle of PHES is simple. It shuffles heat between two tanks containing mineral gravel by means of a working gas, usually an inert gas. In the charging mode, gas is pressurized to around 12 bars, which heats it up to 500 °C. The hot gases enter the top of the tank and flow down slowly heating the mineral gravel in the tank and cooling itself down. At the bottom of the tank, the gases are at ambient temperature but with high pressure. At this point the gases are expanded back to ambient pressure which cools the gases to around negative 160 °C. The gases then enter the second tank cooling the mineral gravel in the second tank and warming itself up before exiting the tank at the top at ambient temperature and pressure. When energy is needed the process is reversed. Inert gases at ambient temperature and pressure enters the cold tank, warming the mineral gravel and becoming itself cold. It leaves the bottom of the tank at negative 160 °C and enters the compressor. The gases are then compressed to 12 bars, heating back to ambient temperature. The gases then enter the bottom of the hot tank. It flows up, cooling the mineral gravel and being warmed to 500 °C. The hot pressurized gas then enters the expander where its energy is used to drive generator. The round-trip AC to AC efficiency is claimed to be around 75-80%. PHES has the advantages of relatively high energy densities, no geographical constraints and a small installation footprint when compared with PHS and CAES (Long, et al., 2018). In Figure 29, the main components of the PHES system can be seen.

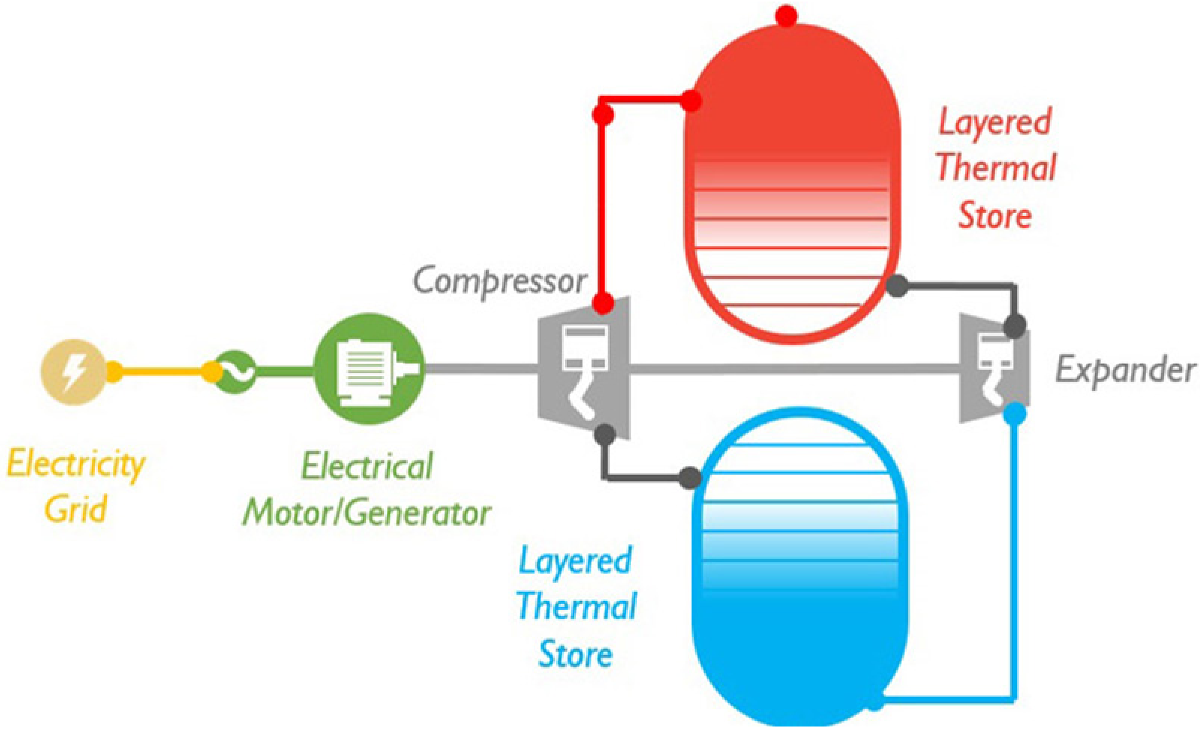


FIGURE 29. Main components of PHES (Tim, 2019).

Liquid Air Energy Storage (LAES)

Liquid Air Energy Storage is the storage of energy by liquefying air at -195 °C and storing it in a tank (Antonelli, et al., 2016). LAES is also known as Cryogenic Energy Storage (Aneke & Wang, 2016). As mentioned earlier, CAES is limited to geographically suitable locations which enable the storage of large amounts of compressed air, because producing steel tanks to store the compressed air in would cost too much. However, liquid air is much easier to store due to its high energy density and low pressure. The volume of liquid air has 1/700 the volume of gaseous air. A LAES plant can be up to 12 times smaller than a conventional CAES plant. The efficiency of LAES is in the range of 40-85%, depending on the processes used. The efficiency is high if waste heat is used during the discharge cycle. LAES has a storage capacity rating for several hours of operation, a response time of about 10 minutes and a long lifetime of 20-40 years. The downsides of LAES are the costs of the liquefaction process and that waste heat is needed to improve the efficiency (Gallo, et al., 2016). Cryogenic fluids like liquid air can be stored for several months in low pressure insulated tanks; the losses can be as low as 0.05% volume/day. LAES is an interesting technology to power utilities because the components of LAES are common in power plants and industrial air separation plants. Due to this, the technology of the components is mature, the maintenance requirements are well understood, and the components can be scaled to be compatible with plant sizes from 10's to 100's MW (Morgan, et al., 2015).

There are three stages in the LAES cycle. First, electrical energy is used to liquefy air. After the air is liquefied, the energy from the liquid air can be recovered through a Rankine cycle, where the liquid air is the working fluid. Liquid air is taken from the tank and compressed, and then heated using thermal energy from the environment. The air is then expanded through a turbine, producing mechanical work which can be used to turn a generator, feeding electricity to the grid. The efficiency of the cycle can be tremendously improved by storing the cold thermal energy that is released when discharging, and re-using this energy to reduce the work needed for liquefying air in the charging phase (Morgan, et al., 2015).

Hydration and dehydration of salts for thermal energy storage

Erlund and Zevenhoven (2018) have studied TES through hydration/dehydration of magnesium carbonates mixed with silica gels. Thermal energy is stored by heating up and thus dehydrating a magnesium carbonate and silica gel mixture. This energy can be released at a later point by hydrating the mixture. These chemical sorption reactions have a higher energy density and need lower temperatures compared to water storage tanks used for thermal storage. The temperatures required for chemical sorption systems are in the range of 50-150 °C (Erlund & Zevenhoven, 2018).

Different materials can be used for chemical sorption thermal energy storage. In the study by Erlund & Zevenhoven (2018), nesquehonite (NQ), which is what magnesite ($MgCO_3$) and water vapor forms, is used in combination with a silica gel (SG). NQ has the potential to be a cheap resource in the future as it can be produced in a carbon capture and storage mineralization process (Erlund & Zevenhoven, 2018).

A concept for using NQ and SG in a chemical sorption TES system is illustrated in Figure 30, with the discharge of heat occurring with the help of a heat pump on the left and storing of heat from solar collectors on the right. Temperatures of 50-65 °C are possible for the dehydration of NQ, forming $MgCO_3$. For hydrating MgCO3, which discharges heat, temperatures of 5-25 °C can be used. When heat is stored, NQ and SG are dehydrated in the reactor, releasing sizeable amounts of water, resulting in humid air which is partially condensed in a heat exchanger. The condensed water is gathered in a water tank, and the air that remains is sent back to the reactor as seen in Figure 30. Excess heat from condensation can be used for re-heating the reactor and for heating a hot water tank.

When heat is discharged, a water tank located underground uses ground heat for evaporating water, which is used for hydrating $MgCO_3$ and SG in the reactor. To use the ground heat at 5 °C for evaporating the water for hydration, the humid air must be pressurized to a few bars to obtain an adequate relative humidity (RH) for complete hydration. The reactor has an operating temperature of 15-25 °C, so a heat pump is needed to raise the temperature to around 35 °C to make it compatible with a modern house heating system. A normal ground heat pump would have a temperature rise from 5 °C to 35 °C, which is almost double the temperature rise of this system. Due to this, the Coefficient of Performance of this system would almost be double of the normal ground heat pump (Erlund & Zevenhoven, 2018).

In Figure 30, the temperature and RH for two different cases are shown. In case 1, the reactor temperature is 20 °C giving a RH of 36%, which is not sufficient for maximum hydration. In case 2, a compressor is used to raise the temperature to 50 °C by using two-stage compression, or 82 °C by using one-stage compression. In the heat exchanger, the air is cooled to 5 °C before the evaporator by the air leaving the evaporator. At the same time, the air leaving the evaporator is heated to 82 °C or 50 °C. The air then passes through the turbine, where the pressure is decreased to 1 bar and the temperature is reduced to 20 °C. The energy is used as work in the compressor. Due to this, less external electricity is required. This is the case for case 2 when maximum hydration is achieved. Case 1 is at the start of hydration. Pressuring the evaporator is needed to evaporate water when the ground temperature is 5 °C. In other studies in locations with ground heat temperature at 10 °C, pressuring of the evaporator was not needed (Erlund & Zevenhoven, 2018).

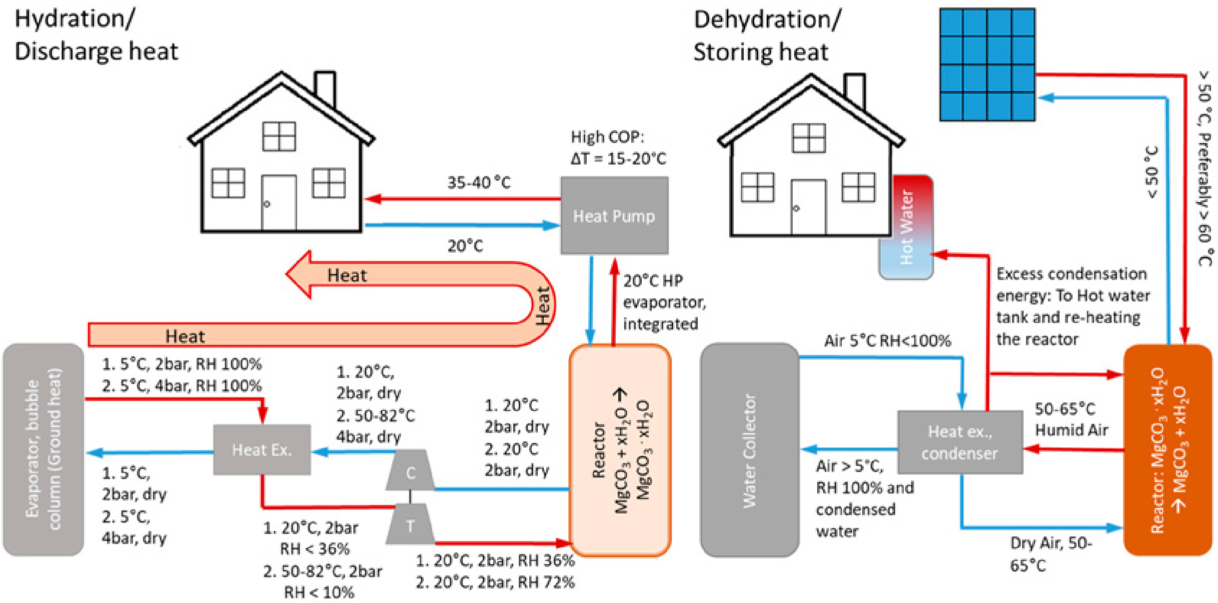


FIGURE 30. Scheme showing the heat storage process coupled with a ground-source heat pump heating system (Erlund & Zevenhoven, 2018). C = Compressor, T = Turbine.

The system can work with air at a low RH in the beginning, and proceed to a higher RH later to complete the hydration. Working at a lower RH is more energy efficient. The thermal storage capacity for mixed NQ and SG is 0.32 MJ/kg at 40% RH and 0.68 MJ/kg at 75% RH (Erlund & Zevenhoven, 2018).

Phase Change Materials (PCM)

PCMs store latent heat, which is the heat stored when a material changes phases. The stored energy can be charged or discharged when the material changes phases and this takes place at almost constant temperature. The amount of energy stored by a PCM is determined also by the sensible heat, which depends on the operating temperature range of the latent heat storage system. In general, latent heat storage has a higher energy density than sensible heat storage. Solid-liquid PCMs are the main type of PCM used for latent heat storage because systems based on solid-gas or liquid-gas transitions would be impractical because they require large volumes for the gas phase, and solid-solid PCMs tend to have a lower energy storage density and a slower transition rate than solid-liquid PCMs. The advantages of solid-liquid PCMs include a small volume change (about 10% or smaller) (Sharma, et al., 2009), easy handling, compactness and high thermal energy density (Zhang, et al., 2018).

Solid-liquid PCMs can be divided into three categories: organic, inorganic and eutectic mixture PCMs. To use PCMs in latent heat storage systems, they should have a range of thermal, physical, kinetic and chemical properties that make them suitable for latent heat storage. The material should also be economically feasible for use in a latent heat storage system. While many PCMs with a suitable melting temperature for a certain operating temperature can be found, they will lack many of the properties required for use in a latent heat storage system and thus require modifications (Sharma, et al., 2009).

Chemical Energy Storage/Synthetic fuels

The classification for chemical energy storage varies from literature to literature. In some literature, batteries fall under the category of chemical energy storage and in others, they fall under their own category of electrochemical. The common way to harvest solar and wind energy is by converting them to electricity through the use of photovoltaic cells and wind turbines (Maggio, et al., 2019), which means that as the share of wind and solar grow, electricity will be the main product from these sources. Producing synthetic gases improves the usability of these renewable energy systems as supply and demand do not always match. From Figure 10, synthetic fuels have a favourable discharge time and storage capacity to thrust the growth of renewable energy sources to dominate over fossil fuels. Methods that can be used to produce synthetic fuels are the electrolysis of water to produce hydrogen, methanation of CO_2 or CO & H_2 to produce CH_4 and gasification of biomass to produce either hydrogen or methane.

Hydrogen Gas and Synthetic Natural Gas

Hydrogen occurs naturally in nature but is bound to other elements and exists as compounds such as hydrocarbons, carbon hydrates and water. Hydrogen can be released from these compounds by various methods such as with electricity in the electrolysis of water, thermal energy in gasification of biomass, to mention a few.

Electrolysis produces high purity H_2 in the range of 99.98-99.999% depending on the technology (see Table 6) (Dincer & Acar, 2015; Maggio, et al., 2019). The electrolysis of water happens in the presence of a catalyst and regardless of the technology, Equation 2.16 describes the reaction that produces hydrogen. The difference comes in operating temperatures, output efficiencies and purity of the hydrogen produced.

$$H_2O + electric\ work \rightarrow H_2 + \frac{1}{2}O_2 \qquad 2.16$$

Where: H_2O is water that is to be split, *electric work* is the energy required to break the H_2O, H_2 is the hydrogen that is produced and O_2 is a by-product of the reaction.

Table 5 shows the relationship between the different technologies. Even though the Solid Oxide Electrolyzer Cell (SOEC) seems like it could be a market leader, it is in the R&D stage compared to the alkaline electrolyze which is a mature technology.

TABLE 5. Hydrogen production technologies & their properties (Dincer & Acar, 2015).

SPECIFICATION	UNIT	ALKALINE	POLYMER ELECTROLYTE MEMBRANE	SOEC
Technology maturity	-	State of the art	Demonstration	R&D
Cell temperature	°C	60-80	50-80	900-1000
Cell pressure	Bar	<30	<30	<30
Current density	A/cm^2	0.2-0.4	0.6-2.0	0.3-1.0
Cell voltage	V	1.8-2.4	1.8-2.2	0.95-1.3
Voltage efficiency	%	62-82	67-82	81-86
Specific system energy consumption	kWh/Nm^3	4.7.0	4.5-7.5	2.5-3.5
Hydrogen production	Nm^3/hr	<760	<30	-
Stack lifetime	hr	<90,000	<20,000	<40,000
System lifetime	yr	20-30	10-30	-
Hydrogen purity	%	99.98	99,999	-
Cold start-up time	min	15	<15	>60

Synthetic natural gas can be produced through the methanation of hydrogen and carbon dioxide/carbon monoxide through the Sabatier reaction shown in Equations 2.17 and 2.18. The storage challenges for hydrogen, limited applications, high reactiveness and lower energy density by volume compared to methane (Müller, et al., 2013) make methanation a better option for storing the converted energy.

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad \Delta H = -165\text{kJ}/mol \tag{2.17}$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad \Delta H = -206kJ/mol \tag{2.18}$$

Storage Technologies- Materials-based hydrogen and methane Storage

Hydrogen and methane can be stored in all three states of matter: gas, liquid and solid. Compared to other energy carriers, even though hydrogen has a high energy density by weight as shown in Table 6 it has a very low energy density by volume. For hydrogen to effectively compete with other energy carriers/ sources, it must be packed as compactly as possible to increase its volumetric density (Züttel, 2003). Below is a figure of the technologies used in the storage of hydrogen and methane, both mature and research-stage technologies. The biggest challenge with hydrogen storage is the molecular size.

Like hydrogen, methane faces challenges in storage as methods of storing it in a safe, convenient and cheaper manner still need to be devised (Zhou, 2010). The current known and mature technologies (compression and liquefaction) do not solve the main storage challenges completely.

TABLE 6. Comparison of energy densities by weight and volume of various energy carriers/sources (Burheim, 2017).

TECHNOLOGY	ENERGY DENSITY BY WEIGHT (KWH/KG)	ENERGY DENSITY BY VOLUME (MWH/M³)
Li-ion battery	0.19	0.56
CAES	0.14	0.012
Hydrogen (1bar)	33	0.0027
Hydroelectric, pumped,400m	0.0011	0.0011
Hydrogen, 700bar	33	1.6
Hydrogen Liquid	33	2
Liquid Natural Gas	15	6.1
Gasoline	13	9
Diesel	13	10
Jet-A-fuel	13	10

Of the three states of matter, gas and liquid storage have been practiced for a long time and will not be looked into in this report. The potential lies within solid state storage where challenges with volumetric energy densities can be overcome. From Figure 31, a pictorial comparison of the storage technologies is shown with water as a reference and material-based storage technologies show superiority over the physical storage technologies.

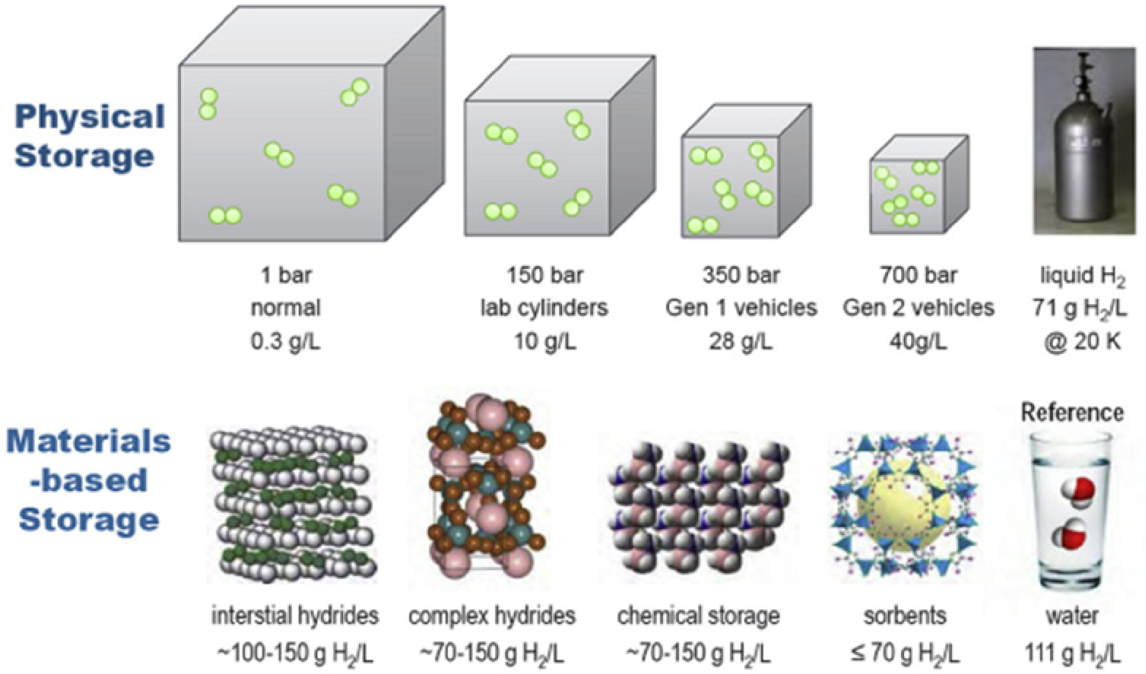


Figure 31. Comparison of hydrogen storage technologies (Ren, et al., 2017).

Hydrogen sorption stores hydrogen in solid state where it is either stored on the surface of a solid in adsorption or through absorption where it is stored within a solid. Storage of H_2 by sorption has a higher density than compression and can improve the performance of hydrogen-fueled vehicles. The drawback comes with the heat management system that would increase the weight of the metal hydride (Møller, et al., 2017). One of the metals used in absorption and one of the growing materials of interest is magnesium due to its availability. Magnesium is cheaper than some other metals that can also be used but are more difficult to extract hence being more expensive.

Physical adsorption- Physisorption

According to Ren, et al. (2017), this technology uses porous materials such as porous carbon structures, zeolites and Metal-Organic Frameworks (MOFs) where hydrogen or methane is physically adsorbed on the surface pores of a material. However, according to Makal, et al. (2012), the use of activated carbons and zeolites for gas storage is limited by the difficulty in tuning pore shapes and sizes, and the limited number of structures, low surface areas and hydrophilicity respectively. Ren, et al. (2017) further state that storage capacity is affected by factors such as surface area, pore volume, working pressure and temperature. The low binding energy (4-10kJ.mol^{-1}) makes this reversible and has fast adsorption-desorption kinetics (Ren, et al., 2017; Panella, et al., 2006). According to tests carried out by Panella, et al. (2006), optimal storage or high capacity storage in this technology occurs at a cryogenic temperature of ~-196˚C as also stated by Ren, et. al. (2017). However, saturation pressures vary from technology to technology. The main challenge with this technology is that storing hydrogen at cryogenic temperatures will require liquid nitrogen, and that would pose engineering challenges (Ren, et al., 2017).

Makal, et al. (2012) have looked into methane storage in advanced materials and conclude, based on data collected, that the adsorption and storage of methane and hydrogen on porous material is the same.

MOFs are not the only promising technology, porous organic polymers also show high porosity and attractive potential for material-based gas storage and separation applications (Makal, et al., 2012).

Chemical adsorption- chemisorption

Chemical adsorption storage, also classified as metal hydrides, occurs at an elevated pressure which results in an exothermic reaction. In comparison to physisorption, the H_2 bonds strongly (almost irreversible) to the adsorbent and requires pressure reduction and high temperatures of more than 300˚C (Ren, et al., 2017) to release the stored gas depending on the adsorbent used. At this stage in research, using this technology will reduce system efficiency.

Even though material-based energy storage gives promising possibilities for the storage of hydrogen and methane, there are still challenges and boundaries to be overcome. The positive aspect is that there are vast materials that can be used, which broadens the scope. Even though some literature mentions the similarities in adsorption of methane and hydrogen, their molecular composition makes the behavior not the case for all adsorbents especially in MOFs with linkers also known as IsoReticular MOFs. Chemisorption has high potential with high energy densities that can be achieved but there is need to still improve the thermodynamic and kinetic properties of this technology (Ren, et al., 2017).

3. EVALUATING ECONOMICS OF ENERGY STORAGE

Traditionally energy technology investments have been viewed by the three following approaches and these are expressed in Figure 32.

- An energy production method should have a high degree of reliability and supply security and thus be capable to provide a certain amount of capacity (kW/MW) at a given moment. This objective can be evaluated by the investment cost of deployment of the production capacity (Levelised Cost of Capacity: LCOC).
- The energy investment also has to be cost-efficient and in the area of energy production, this is measured by LCOE. Derived from this measurement the profitability of the ESS can be measured by the LCOS.
- The third method to evaluate the energy in investment is the environmental approach and this can be evaluated by the LCA method.

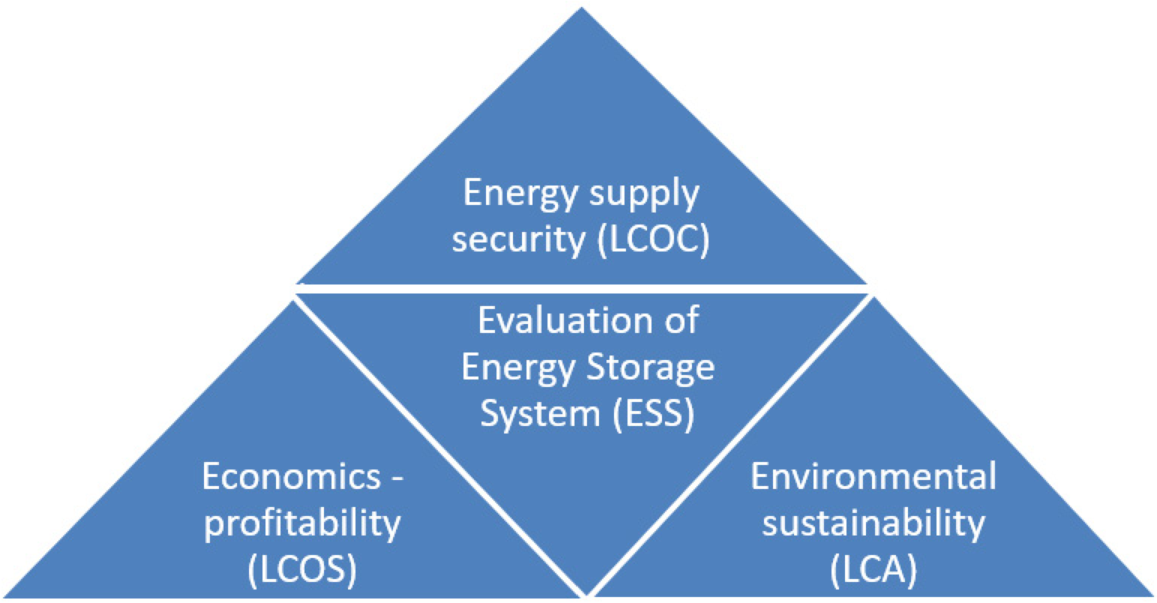


Figure 32. Criteria for energy storage system investments.

Levelized Cost of Energy (LCOE)

The most commonly used economic energy storage measurement is the LCOS. This is based on the formula of LCOE, and in order to understand the LCOS the LCOE is first presented. The LCOE calculations have many issues and the same challenges also apply to a great extent to LCOS evaluations. Due to the difficulties with the LCOE calculation, it is rather profoundly explained here. LCOE can be calculated by using a single formula or more detailed by using a full cash-flow analysis for the whole life length of the investment (Ecofys, 2014b, p. 1).

It is often stated that the LCOE is a standard methodology, but in fact, there are differences in how this measurement tool is implemented and used. There are different versions of the LCOE formula and different players do not use it in the same way. LCOE as a measurement is ambiguous and has also faced criticism and can easily lead to flawed results if not used skillfully (Joskow, 2011). Some sources, e.g. (E-nable Online Services GmbH, 2016) have called the LCOE "the holy grail of confusion". When calculating LCOE there are different approaches and there are confusions at least with the following issues;

- How should the initial investment cost be taken care of (deviation into annuities for the future years or aggregated as a single input)?
- How should the interest of the foreign capital be dealt with (is this included in the annuities or embedded in the discount rate)?
- How does the return on equity influence LCOE (the amount, price of own capital and variations of equity capital in the project through the lifetime)?
- How should taxation issues and subsidies be considered?
- How should depreciation (lower value of the plant in the future) and degradation (lower production of the plant in the future) be handled?

LCOE is also known as Levelized Energy Cost and this measurement is widely used to evaluate the costs and competitiveness of different energy production forms. This means that LCOE is often more interesting to policymakers than to investors, who prefer to use Internal Rate of Return (IRR) and Return on Equity (ROE). The LCOE formula calculates the total annual production costs, which consist of the investment and Operation & Maintenance (O&M) cost, and divides this sum with the annual energy production. The future production costs are discounted by a discount rate to the current moment and, thus we gain a figure which takes the whole lifecycle of the investment into account. Ecofys (2014b, p. 5) points out that it can be expensive and cumbersome to gain good high-quality data for the LCOE calculations. LCOE provides the Net Present Value (NPV) of the lifetime cost per electricity unit (€/MWh) with the following formula (Ecofys, 2014b):

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + OM_t + F_t}{(1+DR)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+DR)^t}} \tag{3.1}$$

where *LCOE* is the levelized cost of electricity, I_t is the investment expenditures in the year *t*, OM_t is the operations and maintenance expenditures in the year *t*, F_t is the fuel expenditures in the year *t*, E_t is the electricity generation in year *t*, *DR* is the discount rate and n is the economic lifetime of the power plant.

I t = Investment expenditures in the year *t*

Often the initial energy production investment is not discounted by the discount rate, because the main and initial investment is taking place at the current moment. There have also been applications where the initial investment has been divided over future years by an annuity method. In some LCOE calculations, it has not been evident whether the analysis has been dealing more with the cash flow or with the profitability and grid parity cost of the energy production method. The energy production facility usually needs some technical updates and refurbishing. Both these reinvestments and the initial investment are discounted into the current moment by the discount rate. The LCOE formula excludes the financing costs during the construction time and these have to be added to the calculation when the construction time of the power plant is rather long (e.g. offshore wind or nuclear).

OM t= Operations and maintenance expenditures in the year *t*

O&M costs are usually divided into *variable* and *fixed* operation and maintenance costs. Variable costs are directly depending on the produced amount of electricity. For example, a wind turbine owner can pay the turbine manufacturer for the technical maintenance per produced megawatt-hour, or the land lease contract with the landlords can be based on the incomes of the sold wind electricity. Fixed costs instead do not fluctuate according to the production, and they are also there when the power plant is not in operation. Other costs, such as insurance and some grid connection costs, are often fixed and are not depending on the amount of energy produced.

F t= Fuel expenditures in the year *t*

Fuel expenditures are variable costs that fluctuate according to production. For some energy-producing forms (coal, gas), the fuel expenditures can be rather high and for some others, these are calculated as zero (wind, solar, hydro). For energy production forms with low or zero fuel cost it is typical that the initial investment costs are high (renewables and nuclear).

E t= Electricity generation in the year *t*

The average Annual Estimated Production (AEP) is the measure to evaluate the future electricity production. This number can be calculated as a rough estimate with the estimated Capacity Factor or by doing a more specific analysis of the production *losses* and *uncertainties* and thus gain a P50 –value. The capacity factor estimate is created by estimating the annual production (full load hours) and dividing this by the annual number of hours in one year (8760 h). Considering the AEP, it is often forgotten that the production usually decreases in the long run due to the increased downtime (technical failures) and aging of components. For example, for a wind turbine, the annual decrease of the production can be 1 – 1,5 % which already in the middle life of the turbine leads to significantly lower production. To reach a more correct LCOE, a technology-specific annual degradation rate (%) should be used. To calculate the AEP profoundly and correctly is as such a science of its own. Different losses (downtime, transmission losses, etc.) are easily underestimated, or in the worst case, totally ignored when estimating the annual energy production. Different uncertainty factors should also be taken into account when the production evaluation is done, and when considering e.g. wind power, these losses and uncertainties can detract the annual production by 15-25 %.

DR = Discount Rate

There has been some confusion about the discount rate in the LCOE formula (Sklar-Chik, et al., 2016) and especially the parallel and synonymous use of the terms ´discount rate` and `interest rate` has caused some misunderstandings. Confusion is also caused by two different types of LCOE. *Real LCOE* removes effects of inflation associated with O&M and fuel costs and is usually preferred by government/

policymakers. *Nominal LCOE* incorporates assumptions regarding inflation and is preferred by developers/ project owners. When we detract the inflation rate (e.g 2 %) from the nominal discount rate (e.g. 8%) we get the real discount rate.

In the LCOE calculations typically a Weighted Average Cost of Capital is applied which includes both the foreign and the own capital. The discount rate is quite commonly estimated to be 8 % (WEC, 2016, p. 19) and this covers both the foreign and own invested capital. This estimate of the discount rate is quite case sensitive because it is influenced by many factors, for example:

- The interest rate of the foreign capital can fluctuate (except loans with fixed interest rates).
- The investors' demand for the return on the equity can vary in the long run.
- The proportion of foreign capital and equity (own capital) can vary to a large extent case by case. Usually the amount of the own capital increases and when the loans are paid back to the financial institution. How the capital is divided between own and foreign finance during the lifetime of the investment has to be somehow evaluated.

n = Lifetime of the system

The lifetime of the system can be estimated either *technically* or *economically.* If the energy production facility requires many updates and reinvestments in the future, the technical lifetime can be much longer than the economically feasible lifetime. Usually, the calculations are based on estimates of the economically feasible lifetime of the energy production form. This evaluation can be rather challenging, and it can have a huge impact on the results of LCOE. Another question is how profoundly the refurbishment calculations to upgrade the old power plant are done and how reliable these estimates are.

Levelised Cost of Storage – LCOS

The proverb "ignorance is bliss" can be applied both for the LCOE and LCOS calculations, and the risk to make flaws with LCOS calculations is even higher than with the LCOE calculations. Besides this, WEC (2016) emphasises that a narrow focus only on LCOS alone can bring misleading results. It is important to first define the business model under consideration and how the storage plant is planned to be operated. When evaluating the energy storage systems according to (WEC, 2016), the following notions should be made:

- **Situational factors.** The economic analysis is very case-specific, and the context and situational factors can have a huge impact on the results.
- **Changes in the storage costs.** Some storage technologies can be considered mature and some immature. Especially the storage cost of some immature technologies will be significantly improved in the next couple of years.
- **Different evaluation criteria.** Operation markets influence the economy and there can be a large difference between the intrinsic (producer) and extrinsic (society/system) value.
- **Difficulties in valuation.** For example, the flexibility of the energy storage system, can be very difficult to evaluate in financial terms.
- **Security of power supply.** The increase or absence of power quality and reliability is hard to express in economic terms.

- **Load balancing.** The energy storage can decrease the need for other grid investments and thus bring economic benefits, which are difficult to value.

The LCOS method has faced much criticism and for example WEC (2016) is pointing out the *arbitrariness* and *incompleteness* of LCOS. Sahlén & Swenman (2017) have studied the energy storage investment logics in the Swedish context by interviewing different decision-makers and stakeholders. The result showed that precise LCOS calculations played only a minor role when doing energy storage investment decisions. Green and other soft values often steered the investment decisions and interest to test new technology was also considered as one of the main drivers behind the decisions to invest in energy storage. Many players also considered that the power capacity (supply security) is more important than energy (economical profitability) in the field of energy storage. The following formula to calculate LCOS looks quite similar to the previous formula of LCOE (Sahlén & Swenman, 2017):

$$LCOS = \frac{CAPEX + \sum_{t=1}^{t=n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{W_{ut}}{(1+i)^t}} \qquad 3.2$$

where CAPEX is the investment cost (€), At is the annual cost at year *t* (€), W_{ut} is the annual energy production (kWh), *n* is the technical lifetime and *i* is the discount rate/interest rate.

The biggest difference compared to LCOE is how the annual cost at year (At) is calculated and how the storage losses are taken into account in the calculation. The At is calculated as (Sahlén & Swenman, 2017):

$$A_t = OPEX_t + CAPEX_{re,t} + C_{el} \times W_{in} - R_t \qquad 3.3$$

where $OPEX_t$ is the operation and maintenance cost in year *t*, $CAPEX_{re,t}$ is the reinvestment to storage components in year *t*, C_{el} is the average electricity price in year *t*, W_{in} is the annual stored energy (kWh) and R_t is the residual value in year *t*.

Sklar-Chik et al. (2016) have criticized LCOE because it ignores time effects associated with matching production to demand. This criticism is even more valid and justified concerning the LCOS because of:

- Dispatchability; the ability of a generating system to come online, go offline, or ramp up or down, quickly as the demand swings.
- The extent to which the availability profile matches or conflicts with the market demand profile.

The arbitrariness of LCOE is a widely accepted standpoint and, because LCOS is even more complicated as a calculation method, the flaws and concerns about LCOS calculations are not analyzed here in depth. In Figure 33 the pumped hydropower storage (PSP) and CAES show the lowest cost reduction from 2015 to 2030, because these technologies have a high current maturity level (WEC, 2016).

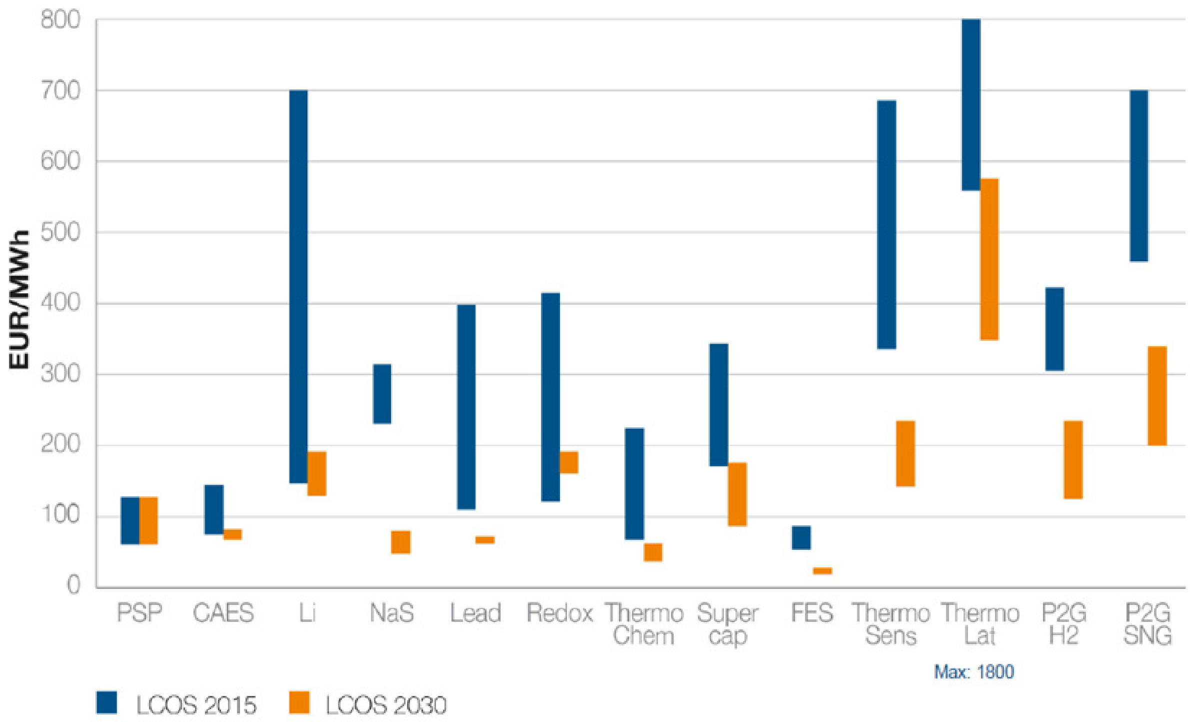


FIGURE 33. Comparison of LCOS for 2015 and 2030 (WEC, 2016).

According to the WEC (2016), the most significant cost reduction will be among NaS batteries, and pumped hydropower storage will not at all increase its economic competitiveness until 2030 (Figure 34). Despite this, NaS batteries have shown a decreasing deployment rate since 2014.

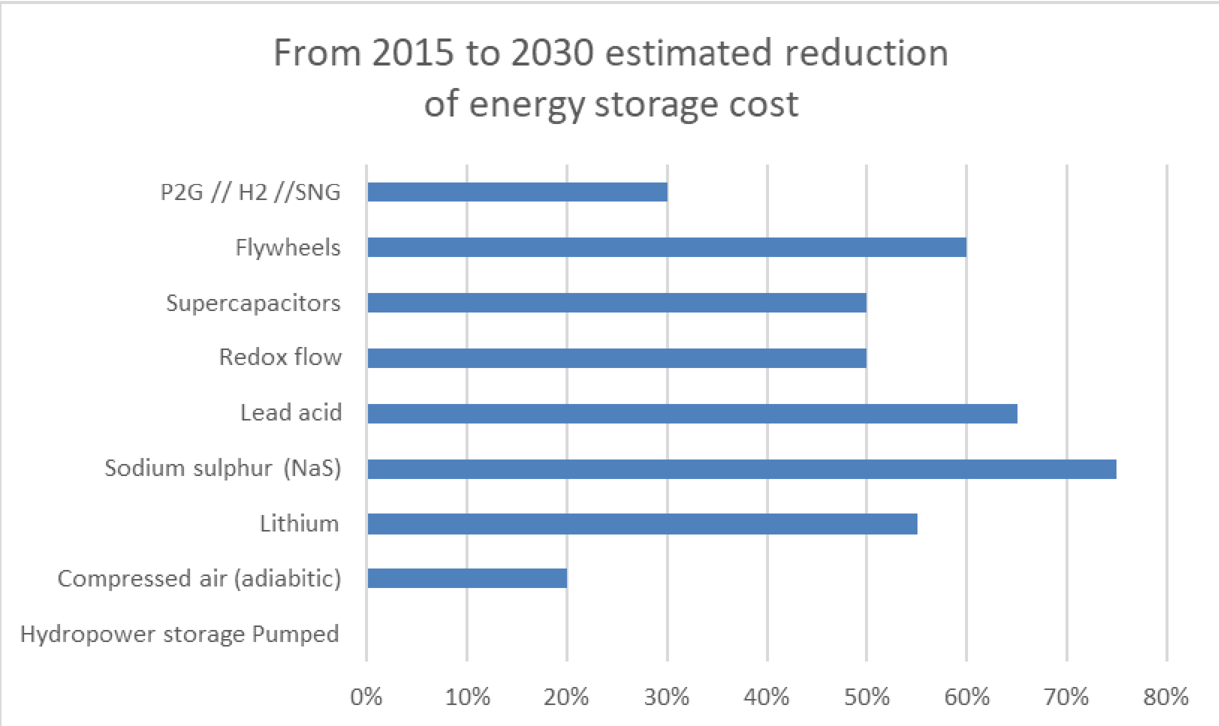


FIGURE 34. Estimation of the cost reduction of different storage technologies globally (WEC, 2016).

IRENA (2017, p. 24) points out that there are challenges concerning battery energy storage. The charge/discharge regime of an electric vehicle battery is relatively simple and does not require very advanced and expensive battery management. In most stationary battery energy storage solutions, the intensified cycle of charging/discharging cause higher investment costs and a lower technical lifetime of the storage. Although the battery type might be exactly the same (vehicle/stationary storage) the different usage can make a difference and cause confusion when calculating the LCOS. According to IRENA (2017, p. 28), the global **electricity** storage (excluding thermal storage) capacity will grow to up to 1 000 GW by 2030 and the majority of this can be electric vehicles (600 GW). Pumped hydro storage will be downgraded to second place (from the current 96 % to 35 % share of ESS) and stationary battery storages will take third place with 175 GW.

Jülch (2016) has estimated the LCOS variations of different technologies, as can be seen in Figure 35.

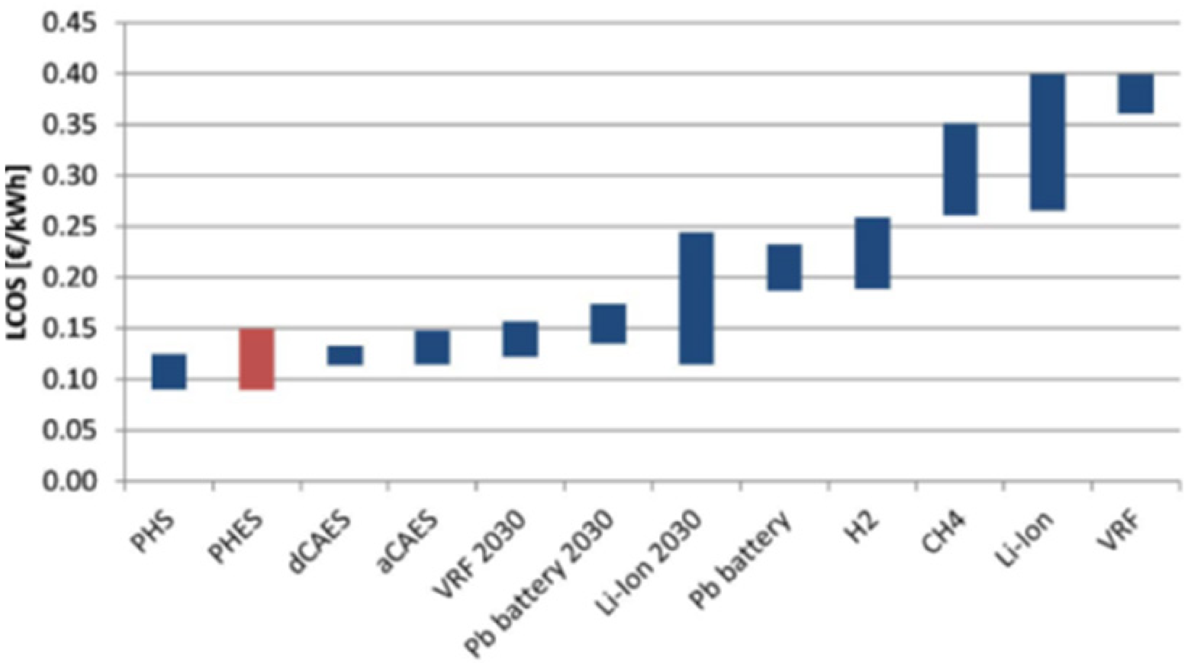


FIGURE 35. Comparison of LCOS of different technologies (Jülch, 2016).

The different energy storage technologies can also be evaluated with the needed investment costs (Figure 36), but this is a narrower approach than using the LCOS.

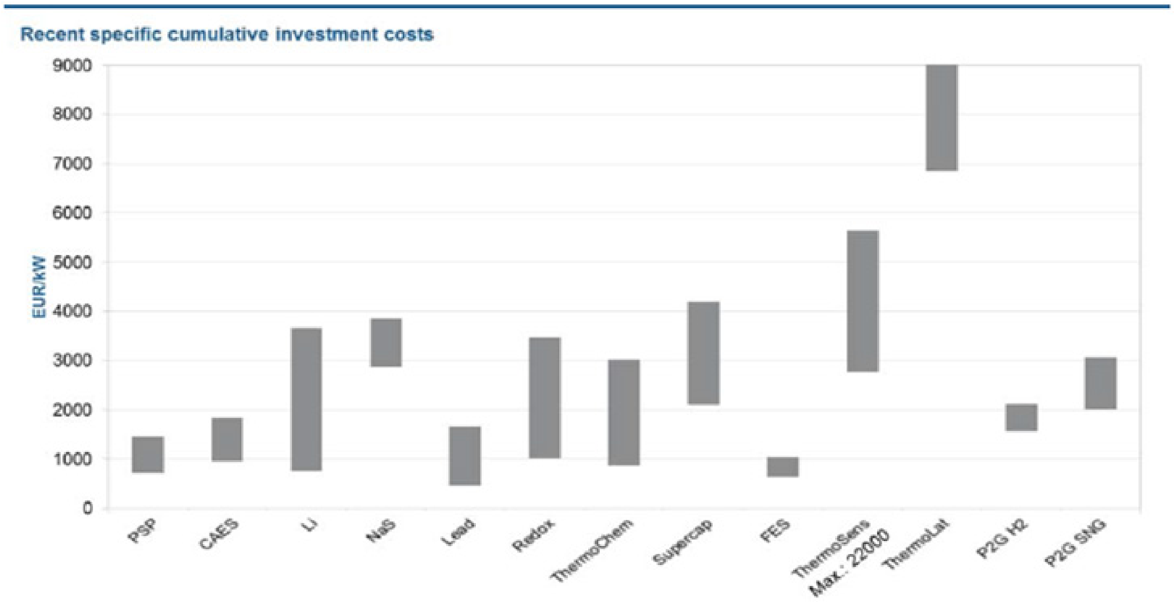


FIGURE 36. Investment costs (€/kW) for different technologies in 2015 (WEC, 2016).

Life Cycle Assessment – LCA and external costs of energy storage

The LCA is a standardized method to evaluate the ecological impact of a product (system) on its environment. This internationally accepted method has its roots in the 1970s and 1980s fields of chemistry. In 1993 the Society of Environmental Toxicology and Chemistry launched their guidelines for LCA, and in the same year, the process started to create an ISO 14040/14044 standard to measure the environmental influence of a product. The LCA method covers the whole life cycle of a product from "cradle to grave" including extraction of raw materials, production phase, usage of the product and the disposal/recycling of the product. Each step of the life cycle is carefully evaluated and assessed and also the impact of the transportations between each step is carefully evaluated (Klöpffer & Grahl, 2014).

In the LCA method is embedded an `Open System` theory approach and a focal thing is to evaluate the interaction between the product producing system and its environment with the input-process-output –chain of events (see Figure 37). The LCA method is as well closely related to the Company Social Responsibility approach which aims to enhance the company´s operation from a social and ecological point of view.

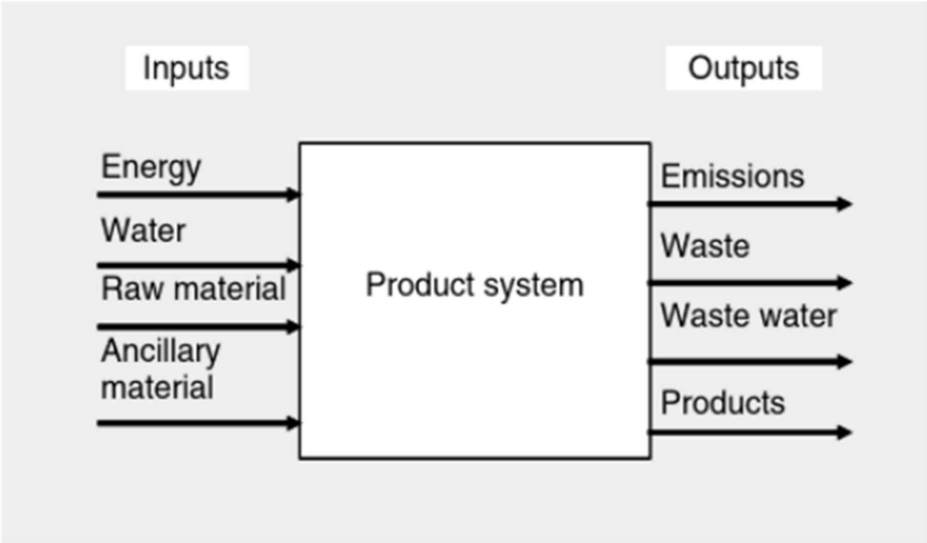


FIGURE 37. Inputs and outputs of a product(ion) system (Klöpffer & Grahl, 2014, p. 11).

In the LCA method, Cumulative Energy Demand is calculated for each product (system) and there are precisely defined methods to calculate the environmental impact of each energy production form (fossil fuels, renewables, nuclear, etc.). All energy production forms have some kind of environmental impact and even renewables cause some greenhouse gas emissions. For example, the production of a wind turbine and the construction of the turbine´s concrete foundation cause quite rich CO_2 emissions, and it is evaluated that it takes 4-6 months for a wind turbine to compensate for the carbon dioxide emissions of the preproduction phase.

Considering energy storage, a substantial amount of research and studies dealing with the LCA of different kinds of battery technologies has been carried out. Although it is evident that different kinds of batteries use environmentally critical raw materials and chemicals, also other kinds of energy and electricity storage methods have an environmental impact. For example, pumped hydropower storage can have a large environmental impact if the upper or lower water reservoir has to be constructed from scratch, and large areas of land will be covered by the stored water.

The external energy production costs are often calculated with the assistance of the LCA method. The external energy production costs are paid by the society through a deteriorated living environment and the health status of people. For example, the usage of hard coal in energy production causes many kinds of health issues for the local inhabitants and it is also a big source of greenhouse gases. The European Union has funded studies conducted by Ecofys (2014a) about the external energy production costs in Europe and the fossil fuels (coal and oil) cause huge indirect external costs in terms of health issues, premature death and a polluted living environment. (Figure 38)

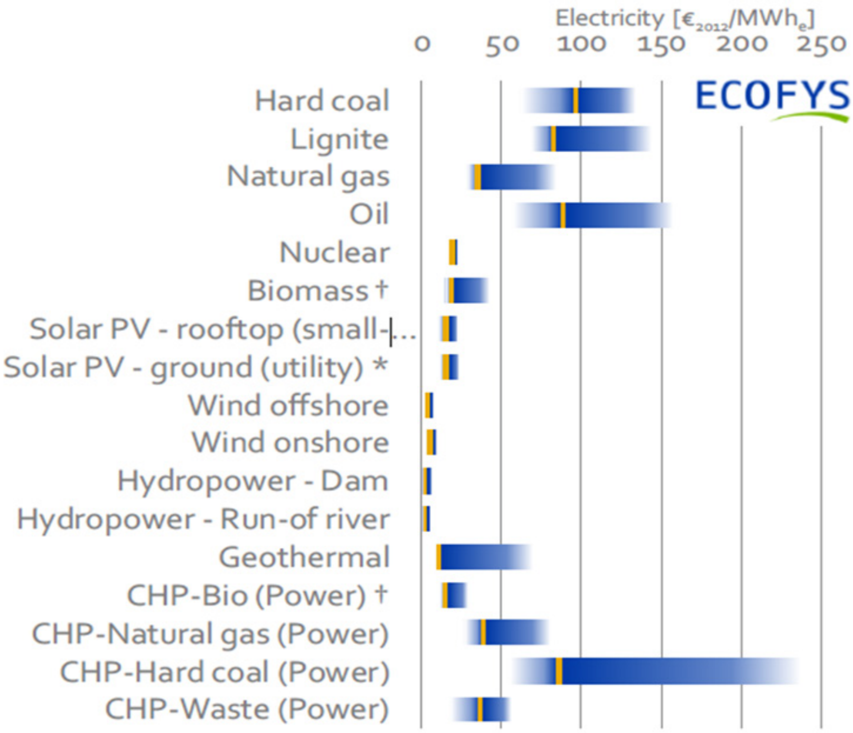


FIGURE 38. External cost ranges per technology for electricity technologies (blue bars), EU28 weighted averages (orange lines) (in €2012/MWhe) (Ecofys, 2014a).

The external cost of energy storage is a rarely studied subject, however, based on the external costs of energy production, the following questions can be made about the external costs of the energy storage:

- What is the impact of the energy storage method on climate change? Are there any CO_2 emissions or e.g. methane slips from the storage?
- Does the manufacturing and usage of the energy storage lead to a depletion of natural resources?
- Are there any particulate matter formations from the energy storage?
- Is there any toxicity or radiation for humans or risk for this?
- Does the energy storage occupy agricultural or populated land?
- Does the energy storage cause damage to the flora and/or fauna (e.g. eutrophication)?

Other parameters for profitability evaluation

Internal Rate of Return (IRR)

Within energy production investment the Internal Rate of Return is a much-used method to evaluate the profitability of the power plant investment. In this method, the future estimated net cash inflows are discounted to the current moment (the event of the financial closure). Thus, the formula for IRR is the same as for calculating the NPV. The IRR-figure tells the profitability of investment by providing a discount rate where all future net cash flows minus the initial investment is equal to zero. The formula for IRR is (Investopedia, 2019):

$$IRR = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 = 0 \qquad 3.4$$

where C_t is the net cash inflow during the period t, C_0 is the total initial investment costs, r is the discount rate and t is the nuamber of time periods.

In practice the IRR calculation is not a very simple method, one needs either a good excel or a web-based calculator to solve the IRR of the energy investment. One can also interpolate different discount rates and thus find which of them provides a figure closest to zero when calculating the NPV. IRR is every now and then considered the "economic rate of return" because it gives the interest rate (discount rate) that the investment is offering. In the IRR calculations, external factors like inflation or the cost of capital are ignored, and the higher the rate obtained, the better and more profitable is the investment. IRR is also a close relative of Revenue of Investment (ROI), but IRR tells the average annual growth and ROI the total growth for the whole life length of the investment.

Concerning energy storage investments IRR can be used with some limitations depending on the case. In some cases, the energy storage investment can be made heavily relying on reasons to secure the power supply and the grid frequency - in this kind of setting the economic calculations can have secondary importance. If the energy storage is supposed to operate on the capacity (primary, secondary or tertiary) and/or on the electricity markets (day-ahead and/or intraday markets) the future incomes can be estimated and thus the IRR-calculation for the storage investment can be conducted.

The payback time of the investment

Calculating the payback time of the investment is probably the simplest method to evaluate the energy production or storage investment. In this method, you get the time when the initial investment cost has been recovered by the net incomes (annual incomes – annual operation and maintenance costs). In this method, the inflation and capital cost are ignored, and due to the simplicity of the method, the payback time method can be the first step before evaluating the investment e.g. with the IRR-method. The shorter the payback time is the more competitive and lucrative is the storage investment.

Capital requirements

Concerning different energy production forms, there are huge differences in capital requirements. Some technologies (e.g. nuclear power plant) require high initial investments but have rather low O&M costs, and some other technologies have low capital requirements and rather high O&M-costs (e.g. gas turbines). The same high variety applies also to the capital requirements of the energy storage technologies. In Figure 39, capital requirements and technology risks of different storage methods are evaluated by the IEA (2014) and WEC (2016). In the figure, it can be seen that Pumped Storage Hydropower (PSH) and some types of thermal storage have reached the commercialization phase. Li-ion and NaS batteries, molten salt, flywheel and CAES are on their way to the commercialization phase and hydrogen, synthetic natural gas and supercapacitors are laying furthest in the future.

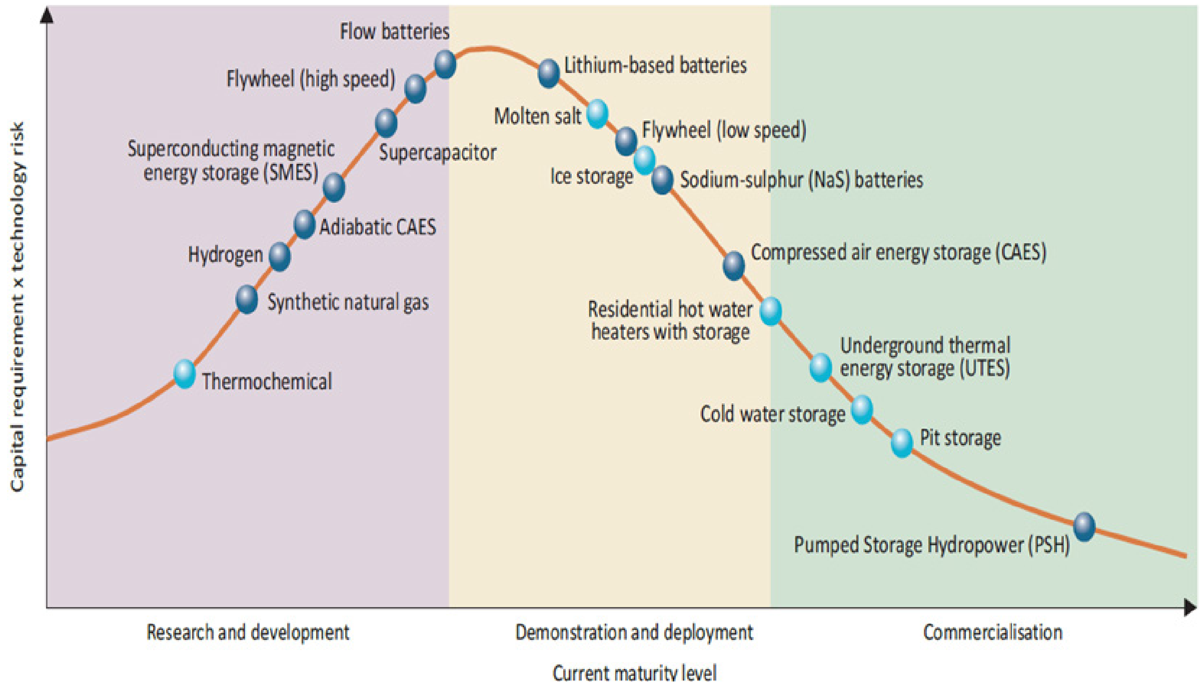


FIGURE 39. The maturity level of energy storage technologies evaluated by capital requirement and technology risk (IEA, 2014; WEC, 2016).

Hydrogen economy

In recent years power-to-gas (PtG/P2G) solutions have gained much publicity and created a debate as to when this kind of technology will reach the economic viability to solve the dilemma of the intermittent electricity production of wind and solar power. The main interest has been towards the hydrogen economy and also towards converting the hydrogen to methane with CO_2 or with another coal source. When hydrogen is converted to methane it can be fed into the existing natural gas pipelines or stored in the existing gas storages. In some countries, hydrogen can even be fed with some limitations to the natural gas grid (Newton, 2014). Gas storages offer many advantages compared to any other kind of energy storage. Gas can be stored for a long period with minor losses and the gas storages can also be extensive in size. In Germany for example the current (2018) gas storage capacity is 230 TWh and the PHS capacity is 6.7 GWh (Dena, 2019). Thus, in Germany, the size of the gas storage capacity is over 30,000 times bigger than the PHS storage capacity.

The International Energy Agency states that there have been at least three false starts in the past for the hydrogen economy (IEA, 2019, pp. 13, 19). The first-time hydrogen gained much attention was in the middle of the 1970s during the oil crisis and it was estimated that the production of hydrogen with coal and nuclear electricity could be one key element to solve the oil crisis. The second wave of hydrogen came in the 1990s when the climate change discussion began and hydrogen was seen as one solution to capture carbon by using it for methane production. By the early 2000s hydrogen was boosted for the third time and many car manufacturers planned to launch their hydrogen-driven cars. Unfortunately, also this third hydrogen wave went down and some car manufacturers withdrew from the hydrogen/fuel cell car concept. Although we are currently living in the fourth hydrogen boom, the main problem still remains how to produce hydrogen from renewables at a feasible cost.

IEA (2019, p. 14) estimates that the cost of hydrogen production from renewables might fall by 30 % by 2030. If this price drop will be sufficient to boost the hydrogen economy will depend on many external factors like how other energy storage options will develop their price competitiveness. There are estimates that many battery solutions (various types of lithium batteries, sodium sulphur battery and redox-flow vanadium battery) will continue the rapid improvement of their cost competitiveness (IRENA, 2017). Also, different kinds of thermal storages are all the time gaining more and more economic viability and some materials even have the capability to store energy at high temperatures (e.g. molten salt) so that it can be converted to electricity by using a conventional steam turbine. The total round-trip efficiency for hydrogen storage is rather low when the wind and solar electricity is first converted into hydrogen with electrolysis and then converted back to electricity after shipping and storing the hydrogen. The most efficient way to convert hydrogen to electricity is to use modern fuel cell technology and according to IEA (2019, p. 33) the round-trip efficiency can, in this case, be lower than 30 %.

The hydrogen market has grown more than threefold since 1975 and in practice, all demanded hydrogen is at the moment produced by fossil fuels (natural gas 76 % and coal 23%) (IEA, 2019, p. 37). Thus, hydrogen production is a huge source of CO_2-emissions (830 million tonnes/year) which is equivalent to the CO_2-emissions of the UK and Indonesia combined. One-third of the global hydrogen supply is produced as a “by-product” of something else and this kind of hydrogen requires usually dehydrating and cleaning process to reach the required purity (IEA, 2019, p. 31). Hydrogen can be produced with electrolysis from renewable electricity but this corresponds to only some per milles of the total amount of produced hydrogen (Figure 40).

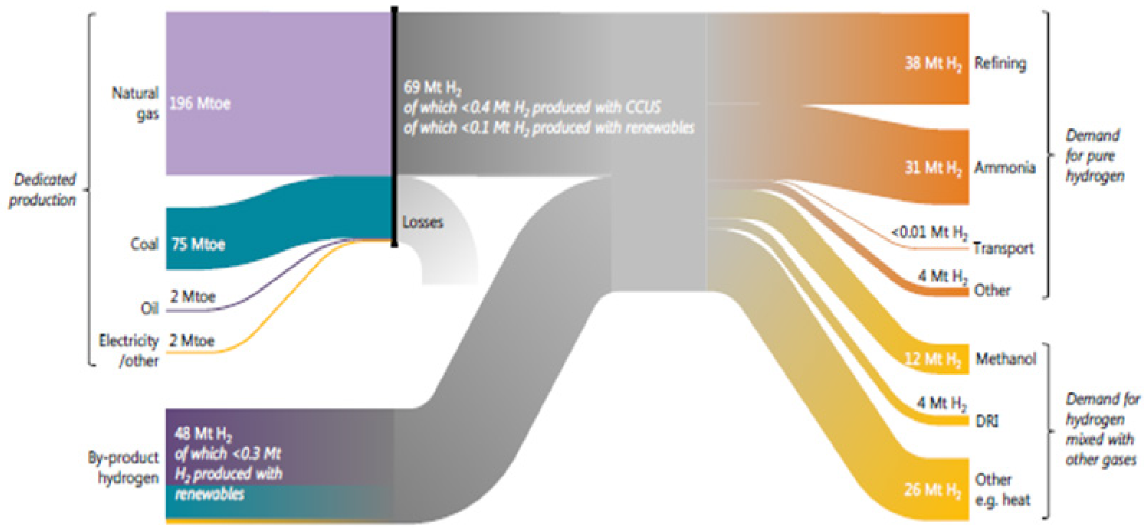


FIGURE 40. Current hydrogen value chain (IEA, 2019, p. 32).

To handle and store large amounts of hydrogen is always a challenge due to its chemical structure. The hydrogen molecules are much smaller than e.g. the molecules of natural gas, and the small size of hydrogen molecules enables the gas to penetrate and diffuse many materials, like for instance some types of iron and steel pipes and vessels. This dilemma is solved by many car manufacturers by using composite materials with hydrogen storage tanks that minimize the hydrogen slip. Hydrogen is usually stored in a pressurized form (up to 700 bars) or liquefied, and to store large amounts of hydrogen many smaller tank vessels are usually needed and used. Different hydrogen storage issues, such as hydrogen slip with metal tanks, make it lucrative to further convert the produced hydrogen to methane gas. This makes of course sense only if the hydrogen is produced with renewables (the main part of hydrogen is currently produced out of natural gas, so there is no sense to convert the material back to the original state.) Hydrogen is highly flammable which also encourages to produce methane out of the renewables produced hydrogen.

Electrolysis accounts only for 2 % of the global hydrogen production and electrolysis is an extremely electricity-consuming way to produce hydrogen. According to IEA (2019, p. 37) the electricity demand for hydrogen production would be over 3,600 TWh if all hydrogen would be produced with electrolysis. This is more than the total electricity consumption of the whole European Union. The production of hydrogen with electrolysis from renewables has some extensive challenges. The first issue is that the annual number of surplus electricity production hours is very low even in countries such as Denmark and Germany, where the amount of installed wind power capacity is much higher than in Finland. The second main challenge with electrolysis technology is that it cannot fluctuate according to the variable surplus production. It requires 30-60 minutes to ramp up the (alkaline) electrolysis production and this is in most cases too long a time to utilize the surplus supply peaks of electricity production (Götz, et al., 2016).

There are three methods to produce hydrogen by electrolysis; using Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane Electrolysis Cells (PEMEC) or SOEC. Alkaline electrolysis is, out of these three, the only mature and commercial technology. PEMEC and SOEC electrolysis are more efficient, but these technologies are still in the development phase and are too expensive for any commercial use. PEMEC has many advantages compared to AEC electrolysis, like faster cold start, higher flexibility and higher purity of hydrogen. The number of PEMEC electrolysis installations has increased significantly in recent years, but these are mostly smaller units for laboratory or testbed purposes. When experts within hydrogen technology and economy were interviewed, the majority had the view that in 2030 the PEMEC electrolysis will outperform the AEC electrolysis (Schmidt, et al., 2017). According to IEA (2019, p. 45) the average size of new electrolysis installations was less than one MW in the years 2015-2019. The SOEC technology is highly exothermic and heat management is an issue with this technology. The estimates of hydrogen production costs (€/kgH2) vary much depending on the source, but IEA (2019, p. 48) estimates this to be 8-20 USD/ kgH2 at the moment and in 2030 approximately 5 USD/ kgH2. This latter figure is still so high that the future competitiveness of hydrogen production from electricity by electrolysis is covered with great uncertainty (Schmidt, et al., 2017). Götz et al. (2016) have summarized in their review that there are both technical and economic barriers that must be solved before PtG solutions can become commercially successful. In Table 7 the current and future status to use hydrogen as energy storage are summarized.

Table 7. Summary of using hydrogen as an energy storage.

HYDROGEN AS AN ENERGY STORAGE
• Gas storages enable storing huge amounts of energy for a longer time
• Power-to-Gas solutions are mainly in the development stage and there is huge uncertainty as to when they will reach economic viability.
• Hydrogen is a widely used gas in many industries and converting renewable electricity to hydrogen is the key challenge.
• Because the electrolysis process to convert water to hydrogen is too expensive at the moment, practically all hydrogen is currently produced by fossil fuels.
• Hydrogen can be produced out of water with the help of three different electrolysis methods. The only mature electrolysis technology with alkaline is inflexible and too expensive to compete with other hydrogen production forms.
• Hydrogen can be converted with a carbon source to methane, which makes the transfer and storage of the material much easier.
• There is a high uncertainty if hydrogen with utilizing electrolyses can in 2030 be a competitive solution to store green energy.

Cynthia Söderbacka and Ossi Koskinen

4. EMPIRICAL STUDY OF ENERGY STORAGE

Energy Storage Competence Outlook for the Vaasa Region

One of the main objectives of the Energy Storage in Our Future Low Carbon Society (Energilagring!) project is to promote energy storage competence growth in the Vaasa region in both the higher learning institutions and companies. In order to fully understand what is needed to achieve this, the status of the region on both the corporate and academic sides must be mapped. The main purpose for conducting the survey was to map out energy storage activities that give the energy storage outlook in the region. The higher learning institutions aim at serving the local industry, which is the largest energy cluster in the Nordic region, by implementing educational curriculums that support the activities and needs of the regional companies and global trends. The region has six higher learning institutions namely, Hanken School of Economics, Novia, VAMK, University of Helsinki (Legal Unit), University of Vaasa and ÅAU. With four higher learning institutions offering both engineering and business-related programs at both undergraduate and postgraduate levels, the survey also aimed at collecting background input data for the diversifications in energy storage focus areas within the learning institution for future use to avoid overlapping and to broaden the scope.

The survey that was conducted by sending out questionnaires to the stakeholders from the industry also aimed at finding out the companies views on investing in research in the Technobothnia Education and Research Center's energy storage demo environment and from the academic side, how an energy storage network that connects industry, education and research can be strengthened.

Method

The following methods were used to collect data for the survey from both the corporate and academic sides. Two separate questionnaires were sent out to the company representatives in the region and the higher learning institutions respectively and are attached as Appendices 2 and 3 respectively. The questionnaires were sent out to 30 companies and about 25 on the academic side of which, a total of 20 representatives responded, 10 from each sector. The data was collected from company representatives, with the aim of mapping out the needs, expertise and solutions available from each organization within the field of energy storage. The representatives responded in writing through an online form that was sent out to them.

For the higher learning institutions, the initial plan was to carry out face-to-face interviews. This was based on the experience from the data collected from the companies, where some responses would have required clarifications or in-depth descriptions. However, due to the Covid-19 global pandemic, only two participants were interviewed in that manner and opted to continue with the oral interviews set up via digital platforms such as Zoom and Microsoft Teams. The questionnaire was sent in advance before the meeting. For the academics, the aim was to map out what is available in terms of education and research, plans for the future and what the interviewees saw as a means to actually achieve regional competence growth in the field of energy storage. Table 8 shows the organisations from both industry and academia that the respondents represented and their roles. Most respondents, especially from the industry, had leading roles, meaning that they had influential positions to enact change. Even though some respondents from the academic sector had leading roles (departmental), they were not the main decision-makers and hence, the collected data does not give the full overview of the region's energy storage outlook.

TABLE 8. List of organisations that participated in the survey and respective roles of respondents.

NAME OF ORGANISATION	TYPE OF ORGANISATION	TYPE OF ACTIVITY	ROLE OF RESPONDENT	DATE INTER VIEWED
Vaasan Sähkö/ Vasa	Corporate	Electricity & Heat distribution	Leading role	17.6.2019
Wärtsilä	Corporate	Maritime Energy Solutions	Leading role	17.6.2019
Wärtsilä	Corporate	Maritime Energy Solutions	Leading role	17.6.2019
Geyser Batteries Oy	Corporate	Batteries/ superca-pacitors	Human Resources	17.6.2019
Stormossen Ab/ Oy	Corporate	Biogas production/ CBG filling station	Leading role	17.6.2019
EPV Energia Oy	Corporate	Heat & Electricity generation	Leading role	19.6.2019
The Switch	Corporate		Leading role	21.6.2019
Westenergy Oy Ab	Corporate	Heat generation	Leading role	28.6.2019
VASEK	Public Sector	Business Advisor	Leading role	5.7.2019
Danfoss Drives	Corporate		Leading role	16.9.2019
VAMK	University of Applied Scien-ces	Education/Research	Teacher/ Researcher	20.2.2020
University of Vaasa	University	Education/Research	Researcher	12.5.2020
University of Vaasa	University	Education/Research	Researcher	22.5.2020
University of Vaasa	University	Education/Research	Teacher/ Researcher	26.5.2020

NAME OF ORGANISATION	TYPE OF ORGANISATION	TYPE OF ACTIVITY	ROLE OF RESPONDENT	DATE INTER VIEWED
University of Vaasa	University	Education/Research	Teacher/ Researcher	28.8.2020
University of Vaasa	University	Education/Research	Teacher/ Researcher	04.9.2020
University of Vaasa	University	Education/Research	Teacher/ Researcher	10.9.2020
VAMK	University of Applied Scien-ces	Education/Research	Teacher	08.10.2020
Novia	University of Applied Scien-ces	Education/Research	Teacher/ Leading role	28.10.2020
Novia	University of Applied Scien-ces	Education/Research	Teacher	09.11.2020

Company needs, expertise and solutions

The companies contacted ranged from international companies competing on the global markets and local service providers as can be seen from Table 8. The following data is a collection from 10 respondents from Wärtsilä, Danfoss Drives, Vaasan Sähkö, Westenergy Oy, EPV Energia, Ab Stormossen Oy, VASEK, The Switch and Geyser Batteries Oy. From the data collected, most of the companies are interested or involved in applications of energy storage solutions, with some interested also in the materials for the technologies and recycling and re-use when it comes to the life cycle of respective energy storage technologies as can be seen from Figure 41. This figure represents all energy storage technologies that these organisations work with or are interested in.

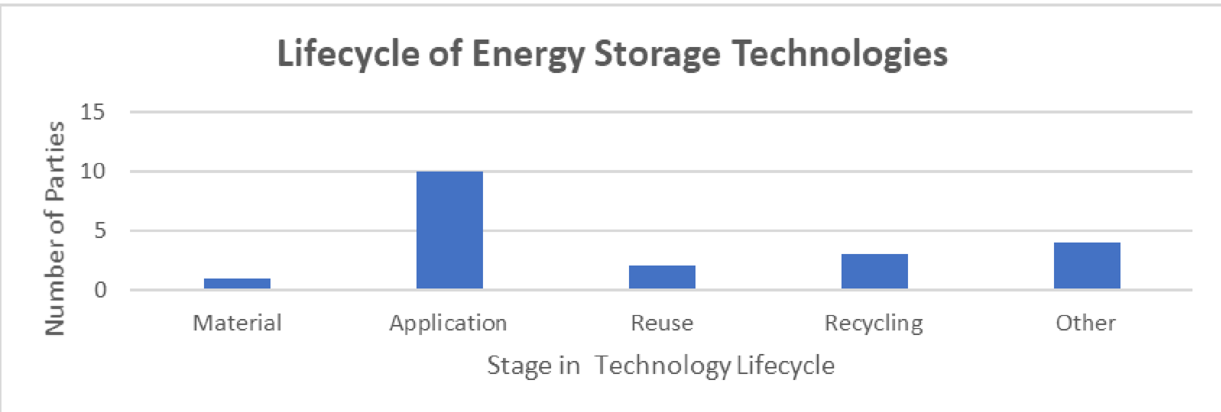


FIGURE 41. Company interest in the life cycle of the energy storage technologies.

It is understandable why "Application" is the most popular as most of these companies sell energy solutions such as battery energy storage for various applications. The most popular energy storage technology for the region is batteries and understandably so due to their wide range of applications and the current global trends that has seen an increased use of batteries especially Lithium-ion batteries. However, the companies are also looking at the future and not only limiting their interest to the lithium-ion batteries, but to all battery technologies that can yield high power and energy, and are cost-effective.

These companies are not only focusing on current trends but are also looking to the future and require a matching knowledge base within the region to continuously grow and maintain positions on the global market. Other energy storage technologies of interest are shown in Figure 42. From Figure 42, it can be seen that Pumped Hydro Energy Storage is not part of the technologies of interest even though it is currently a global market leader and most of the companies in the region sell products and solutions worldwide. An explanation for this can be attributed to the limitation of the number of respondents. With this in mind, it is a clear indication that the data collected is a partial picture of the status of the region.

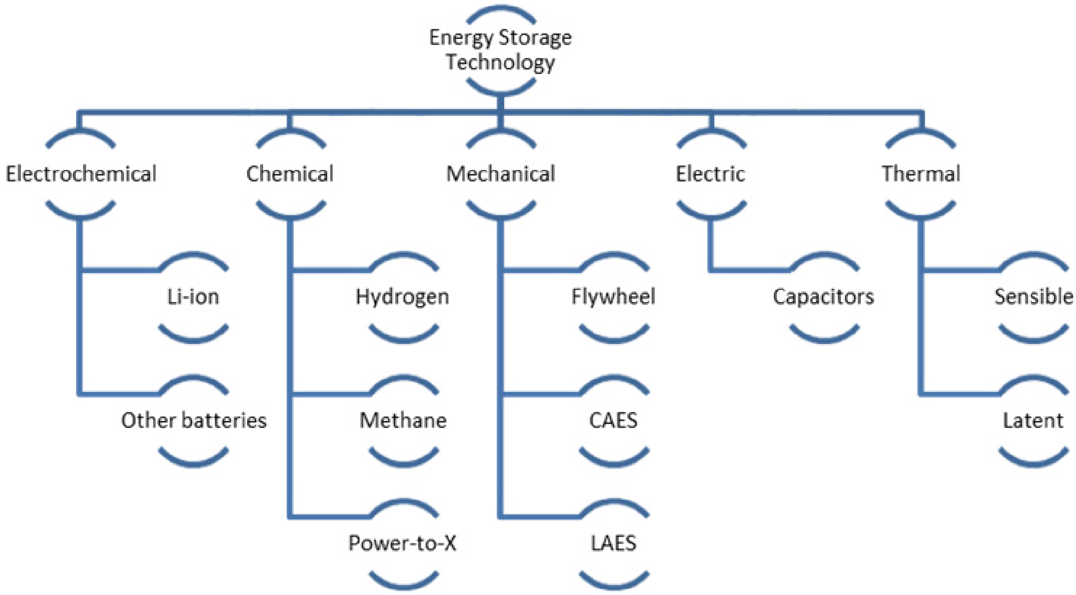


FIGURE 42. Energy storage technologies of interest for the Vaasa region.

Energy storage competence within the local universities

The presence of the energy cluster within the region creates a drive for the schools to provide education and research that is relevant to the region as they prepare to produce students suitable for the cluster. The survey initially aimed to map out the energy storage roadmap from the schools. Due to limitations with the number of participants for this survey and their positions, and the fact that energy storage is just becoming a focus area with the growth of renewable energy systems, the data collected painted the picture on what is currently being done. Long-term plans were not mapped because the main decision-makers were not interviewed. The interviewees from Novia, VAMK, the University of Vaasa and ÅAU (through project activities) highlight their projects, challenges and what they see as important competences for the students within the field of energy storage. A total of 10 university personnel were interviewed varying in roles between teaching and research.

Research and education

The schools have been working on joint energy storage projects such as the ongoing Energy Storage in Our Future Low Carbon Society (Energilagring!) project and Sitra Energy Storage project where a study package of 15 study points was created and offered to students in the region. The institutions involved in this Sitra project were Novia, VAMK, University of Oulu and University of Vaasa. The schools as individuals have continued to implement energy storage in their education for engineering students as modules in exiting courses or new courses especially battery technologies. But according to the majority view, what is being offered is a general overview of these technologies and energy storage education could be extended to other study fields outside engineering. This is because energy storage is multi-disciplinary like other energy or engineering sectors. One requires understanding the technical, environmental, legislative aspects and business models of energy storage. The respondents from the universities of applied sciences pointed out the need to close the loop and look into means to transfer research data to education. It is usual that research personnel are not involved in teaching and vice-versa, a picture that is changing within VAMK where they are working at having more teachers involved in research as well. For the universities, it is a partially different picture, especially for doctoral research. The involvement of teachers in research will help teachers to update their teaching materials and bring real-life problems for students to solve.

Energy storage demo environment in Technobothnia and living lab sites

The irregular tendencies of renewable resources especially with reference to solar and wind energy create an unstable energy supply posing a big challenge for the users and also maturity of technology and infrastructure. New systems have to be built but that is not always the solution. These renewable sources have to be integrated into the conventional systems and are expected to perform as reliably as conventional fuels have. The stability of the energy supply of these renewable resources can be guaranteed with the use of energy storage. But the solution is not that clear-cut, the systems will become more complex and the type of energy storage solution will depend on the need(s). That is why an energy storage demo environment has been built in Technobothnia Education & Research Center, showing different energy storage technologies. Input on what type of technologies would be of interest and relevant to the region was sought from representatives from both academia and the industry who are part of the steering group in the Energy Storage project. Some of the technologies to be implemented are discussed below. The aim is to implement the demo environment in teaching, giving students hands-on experience, playing ground for researchers and for demonstration purposes.

A Flywheel Energy Storage demo was developed using existing components from the laboratory and it can be rearranged and ready to use within 15 minutes. This demo is a first-generation flywheel energy storage, which stores energy in mechanical form by rotating the wheel in a certain direction and releases the stored energy by reversing the direction of rotation. The demo gets power from the grid and feeds back into a grid to demonstrate this technology and has a storage capacity of 8 Wh. The cycle lasts less than a minute but is long enough for students to observe what is going on and has an efficiency of ~50%. The flywheel demo shown in Figure 43 has already been implemented in education in VAMK from the autumn semester of 2019.

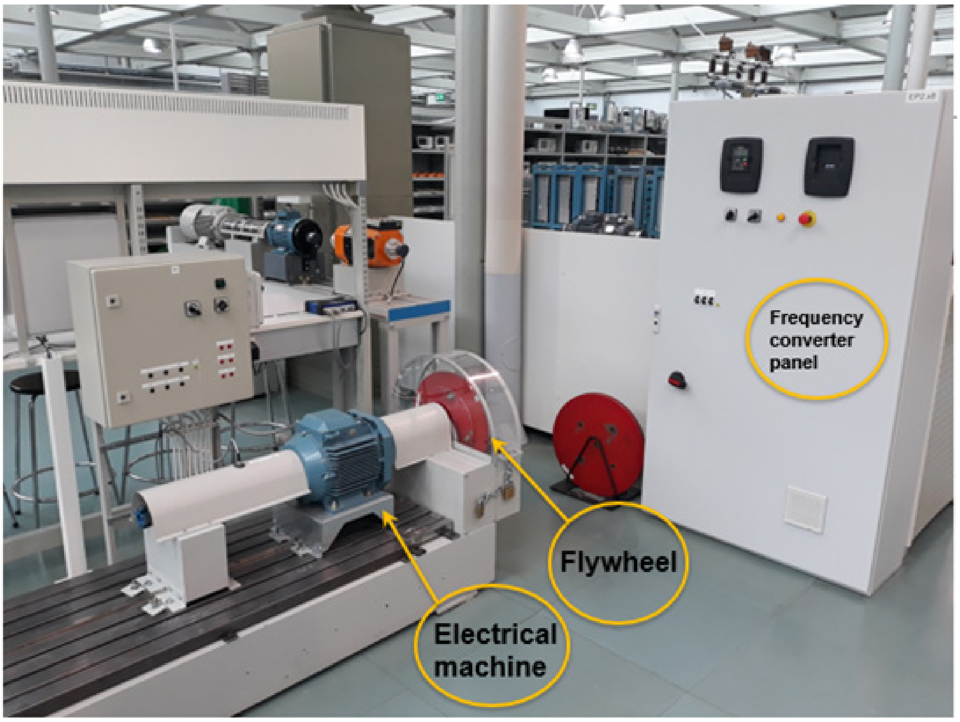


FIGURE 43. Flywheel Energy Storage demo [Picture by Jukka Hautala].

Compressed Air Energy Storage

This demo has been a work in progress for European Project Semester (EPS) students of Novia. CAES stores energy by compressing air and storing the pressurized air in a reservoir or storage tank during excess production. The stored air is reused to produce electricity using a gas turbine when there is low or no production. The biggest challenge is sizing the demo to lab-scale and still maintain good roundtrip efficiency and cost-efficiency. A roundtrip efficiency of about 6% has been calculated for the system without TES and about 30% with TES (store and reuse waste heat from the compression process) according to the first EPS team. The 3rd team is recalculating some of the parameters and improving the demo layout, with the hope to reduce pressure losses in the system. The heat storage part is a Do-It-Yourself heat exchanger. A turbine has also been 3-D printed and will be compared with the air motor in the system, to see which of the two gives better system efficiency. Turbines offer better efficiency than air motors in such applications but it was way over budget and that is how the idea to 3-D print a turbine came about. It remains to be seen if this turbine will handle the process especially without TES (can the material handle the cold air?).

Phase Change Materials (PCM) Energy Storage demo

The demo was made as part of a Master's thesis at ÅAU (Lieskoski, 2020). PCMs store energy in the form of heat (latent heat) when undergoing a phase change from solid to liquid. The demo shown in Figure 44 focuses on analysing thermophysical properties of PCMs using the T-history method. The research focused on PCM with low melting points of about ~50 ˚C such as hydrate salts and paraffins. With this method, the materials are heated to temperatures above their melting points and then cooled down during which the temperature is continuously measured. With these temperature measurements, latent heat and specific heat capacity can be calculated from which the amount of energy stored by that particular material can be calculated.

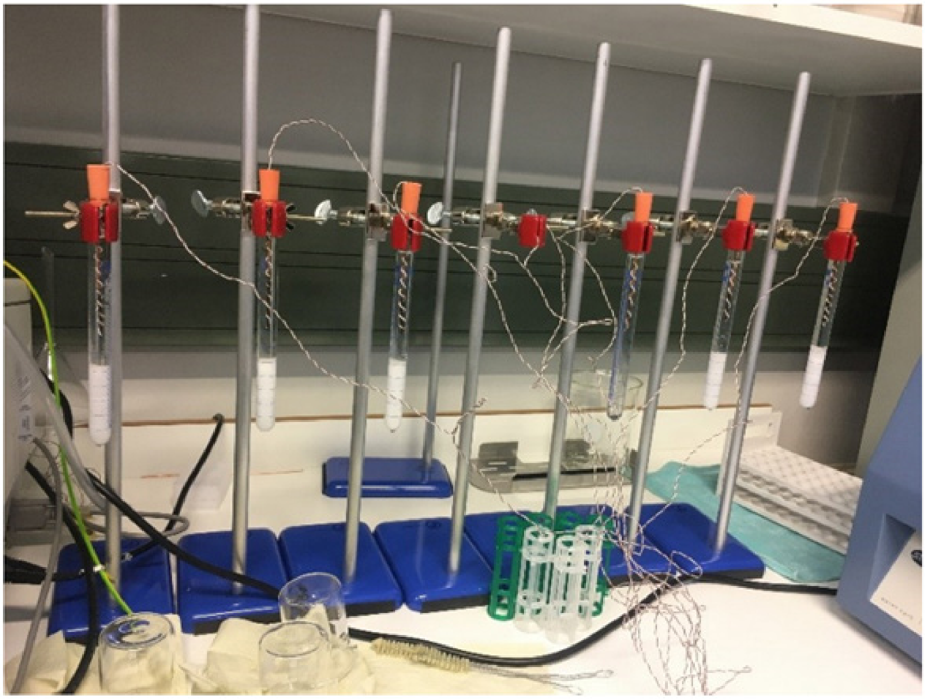


FIGURE 44. PCM demo set-up with sodium sulfate decahydrate samples at the start of the cooling process (Lieskoski, 2020).

Power-to-Gas is an important part of the renewable energy matrix, as it helps to optimize the use of energy from intermittent sources by converting the excess electrical energy to gas form for easier and longer storage. The first stage is the conversion of electrical energy to hydrogen through the electrolysis of water, simply put use excess electricity to split water into hydrogen and oxygen. The renewable hydrogen can be used in the usual hydrogen applications or is further reacted with carbon dioxide over a catalyst to produce methane and water. Novia and ÅAU started working on the Power-to-Gas demo shown in Figure 45 under the AIKO Gas CoE Project (1.1.2017-30.4.2019) to show the methanation of hydrogen and carbon dioxide. **VTT Finland** has been instrumental in the process as they provided free consultancy and a methanation reactor. Apart from the methanation process, this demo can also produce methane & hydrogen by Supercritical Water Gasification of biomass. No tests have been run yet.

FIGURE 45. PtG demo located in the R&R Laboratory built by ÅAU Lab Engineers.

Pumped Hydro Energy Storage demo

The aim is to design and construct a model of pumped hydroelectric energy storage for teaching purposes. The purpose was to design and build a small pumped hydro storage plant so that students can become familiar with this form of energy storage. Planning of the demo and the Francis turbine was constructed by an engineering student who wrote his Bachelor's thesis within the project for VAMK. The thesis reviews all the stages of both design and construction and examines how the design has been implemented in practice. The project was implemented with a view to its sustainability over the years, as well as possible changes in terms of efficiency and control.

A place for the demo was found in the construction laboratory and the fall height is over 9 meters. The water capacity of the upper and lower water reservoir is 1 000 litres each. In real life, the Francis turbine can also operate as a pump when storing water (energy) to the upper reservoir. There is still uncertainty if this demo turbine (Figure 46) can be used also as a pump or should a separate pump be utilized.

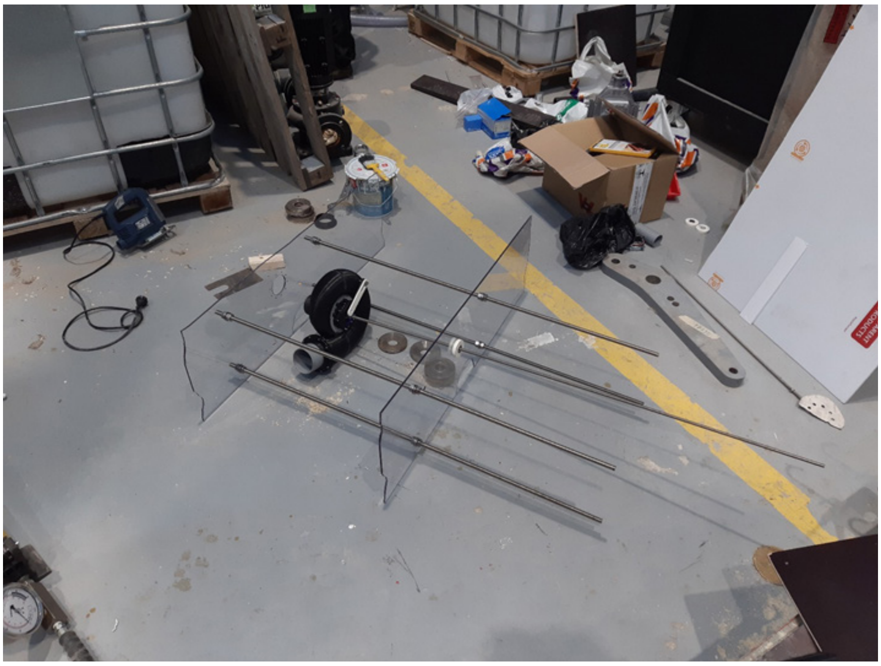


FIGURE 46. The Francis turbine to be placed in the lower water reservoir (tank).

Battery Energy Storage demo

The aim is to design and construct a battery energy storage demo for teaching purposes. Students can become familiar with the battery charging & discharging process and restrictions and will understand the need for cell balancing and battery management systems. The demo was planned and constructed by an engineering student as part of his Bachelor thesis within the project for VAMK (Figure 47). The process is monitored using the LabVIEW application (application still under development). The ongoing thesis reviews information regarding charging and discharging exercises.

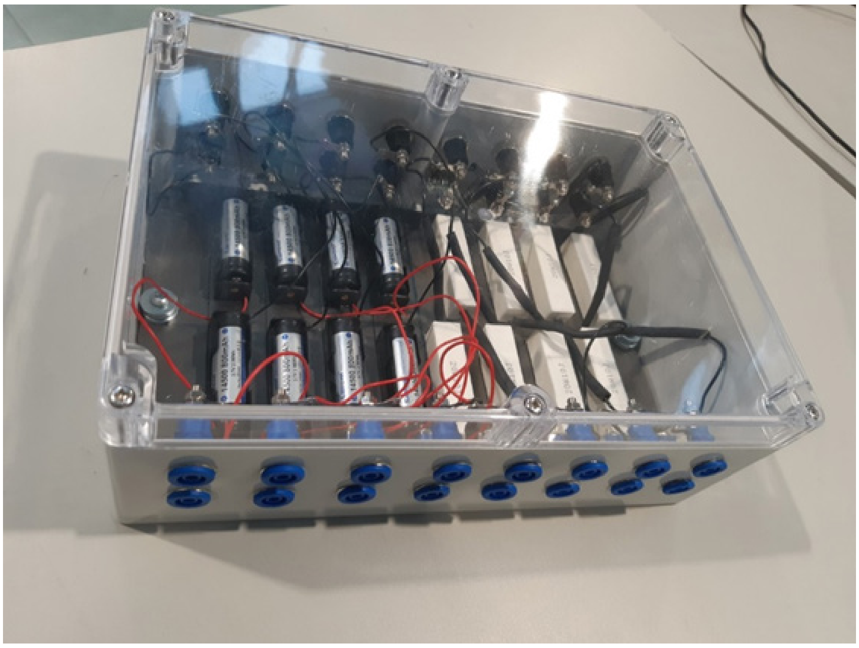


FIGURE 47. Battery energy storage demo.

Building a regional energy storage network

The region is already well known for continued cooperation between companies and schools. As energy storage is a new branch in the region, there is a need to create a joint platform for knowledge. The following are the views of the participants from academia on what they see as a way of developing an energy storage network in the region. These views do not represent organisations' or collective views but are individual views.

Mapping activities & looking for synergies

There are currently a number of research projects ongoing in the region on both the academic and industry side but information flow is limited. Identification of these activities and matching them would yield better results as the scope of research would widen or deepen.

Regional knowledge-sharing platforms

Creating a common energy storage platform for the players in the region to promote knowledge sharing and identification of partners to strengthen collaborations between the industry and schools. This platform can also be used for competence growth in education where students are presented with industrial problems during a course or creation of course modules with a certain number of study points with information flow from all sectors i.e. industry, research and education.

Activities that benefit all stakeholders (industries & schools)

For the network to grow and strengthen, the targeted parties should see a relevance and relate to the activities. A suggestion was to have some kind of committee with representatives from both sides of the stakeholders.

Develop Technobothnia Education & Research Center

Development of Technobothnia as it is a place that already exists and the local universities are partners. The companies could get more involved by partnering with the schools like is done in some projects. From the survey, it is clear that the industry is interested in working with learning institutions. In response to the question to the respondents from the industry on if their organisations would invest in the demo environment, the majority's response was a yes if the research is relevant.

Long term projects

Most projects with external funding have a length of 2 year's time, which is a short time as some projects have no continuation planned in advance due to limitations with funds and the project results are left unused as they are partial results. Working on longer-term projects with modules would enable the companies to join in for modules that are relevant to their line of work.

Company projects in education

As schools have more time for research, one suggestion to strengthen the energy storage network was for teachers and company representatives to work together by involving students in company research problems. The company would give tasks to students through the course material and the best solutions would be rewarded with summer jobs or thesis work. This would familiarize the students with the company activities earlier as well as help evolve teaching material in tune with the industry.

Competence outlook

As earlier stated, the survey aimed at mapping the energy storage competence regional outlook. Table 9 and Table 10 show results on the company needs, expertise, solutions, education and research that are ongoing or have been implemented in the region. It is evident that in both the industrial and academic sectors, energy storage technologies have already been applied.

Neither of the tables cover the full picture of what is going in the region especially with regard to the academic sector. Some of the known projects are not included as no personnel from such projects were interviewed nor the main decision-makers in the schools.

Table 9 shows the energy storage related know-how and solutions that are currently available in the region. The solutions here refer to either a pilot demo, actual demo or product sold and expertise to the knowledge.

In Table 9, it must be noted that all respondents had an understanding of renewable energy and energy storage and only those that are directly linked to energy storage are shown. The physical solutions located in the region are Automated Production Plant by Geyser Batteries which is scheduled to open in Vaasa, focusing on a new type of high power energy storage in supercapacitors and batteries. The Thermal Energy Storage by EPV Energia is located in Vaskiluoto in the old oil caves and was commissioned in September 2020. The heat storage has an expected storage capacity of 7000-9000 MWh and is currently considered the largest in Finland. The regenerative business models are included as the knowledge can be directly applied to energy storage. The energy storage demo environment in Technobothnia has been discussed in the chapters above.

The growth of renewable energy shares in the global energy matrix creates a need for more competence within the field of energy storage. Even though energy storage is not a new field, the current scenarios create a new approach to how energy storage is applied in energy systems. Table 10 shows the areas where the industry is in need of new knowledge and the research and education that is ongoing or has been made on the academic side. The table compares the needs of the industry and competence available in higher learning institutions.

Table 9. Energy storage expertise and solutions that are currently available in the Vaasa region.

INDUSTRY		ACADEMIC	
EXPERTISE/ SOLUTION	**ORGANISATION**	**EXPERTISE/ SOLUTION**	**ORGANISATION**
Automated Producti-on Plant *supercapacitors & batteries*	Geyser Batteries Oy	Energy storage demo environment	Technobothnia
Developing & Selling own Solutions	Wärtsilä	Battery properties simulations	University of Vaasa
Methane Storage	Stormossen	Battery Technologies	All
Heat Generation (E) -Westenergy-	Westenergy Oy	Energy Storage techno-logies, global trends and energy markets	University of Vaasa/ VAMK
Hybrid Solutions for Marine & Container based Battery Energy Storage	Danfoss Drives	Regenerative Business Models and Fleximar	University of Vaasa
DC-Hub with Batte-ries- (Marine systems)	The Switch	Sustainable automati-on- Renewable Energy	University of Vaasa
Thermal Energy Sto-rage	EPV Energia		

From Table 10, it can be seen that the industry is continuously growing and seeking new knowledge and broadening the scope. For example, the levelized cost of energy storage is of great interest as the cost of a solution is very important and affects its applicability. Li-ion batteries have been at the center of battery technology that has received much attention, but as is known with energy storage, it is not a one-size-fits-all and the industry sees the need to explore other battery options. There are Master's theses that have not been included in the table from ÅAU that can be accessed at the link given here https://blogs.abo.fi/energiteknik/alumner/.

TABLE 10. The energy storage competence that the companies need and ongoing research and education within the higher education institutions.

INDUSTRY	ACADEMIC	
COMPANY NEEDS	EDUCATION	RESEARCH
Minimising Levelised costs of storage	Sitra Project Energy Storage package-courses 15sp	Energy Storage Project-Economical aspect, Energy Markets, technology Overview (Project report)
Application in the Nordic markets Balancing wind power with energy storage	Battery Technology	Role of Battery Storage for Grid Applications- Li-ion (Doctoral Research)
Different Battery Technologies limitations with electric drives		Li-ion Battery Properties-Simulations (porosity, particle size, temperature) (Project research)
Viability of commercial applications in relation to local conditions		Geothermal Storage-Simulations (Project research)
High technological heat storage solutions		Adiabatic Compressed Air Energy Storage (EPS project)
Alternative (Non-Li-ion) Storage Solutions (Titanate batteries Supercapacitors)		Renewable Energy: Machine Learning, Data Analysis & AI (Project Research)
		Finnish -Balance Coordinators View of the Energy Storage Market. (BSc Thesis)
		Post Combustion-Waste-to-Energy Carbon Capture (Project research)

From Table 9 and Table 10, it is evident that the Vaasa region is working on growing its energy storage competence through various industry and academic research and educational activities. The growth can however be speeded up with more co-operations between the industry and academic sides with more than just thesis work, especially for the universities of applied sciences. The higher learning institutions usually come together and partner on research projects to combine expertise, though more can be done as observed through this survey, as sometimes there is little or no communication between the energy storage research projects between and/or within the learning institutions.

Energy Market actors

On the energy markets, there are several players, but in a simplified manner, it can be stated that there is usually an energy producer who sells its electricity production to a BRP which then operates both on the Nordic day-ahead (Spot market) and intra-day (Elbas) markets. This BRP uses the electricity production estimates for the producer's power plants and the BRP also carries the responsibility and risk, if the estimated production will not be met and there will be a too low or too high amount of the produced energy. The energy producer usually pays a compensation (1-3 €/MWh) to the BRP for operating on the energy markets and carrying the risk of the errors in the production estimates (applies especially for wind power).

As mentioned earlier it is hard, or even impossible, to do any energy storage business on the day-ahead or intraday electricity markets due to the rather low electricity prices and also rather low-price volatility. Albeit the electricity markets do not offer at the moment any business opportunities for energy storage, the capacity and reserve markets can offer some business opportunities for energy storage. In Finland, the system operator is Fingrid which collaborates actively with other Nordic Transmission System Operators in order to maintain the 50 Hz frequency in the grid (Fingrid, 2021). Fingrid has several products to ensure and maintain the right frequency of the grid on the fast response primary capacity markets and secondary capacity markets in Finland (Figure 48).

In Finland, the primary capacity market is called as Frequency Containment Reserve (FCR), which is in turn divided into two products of FCR-D (Frequency Containment Reserve for Disturbances) and FCR-N (Frequency Containment Reserve for Normal operation). The secondary capacity market in Finland is called Frequency Restoration Reserve (FRR) which is divided into automatic (aFRR) and manual (mFRR). The activation of the Frequency Restoration Reserve (FRR) requires more time and it realizes the FCR to its primary function to adjust the frequency anomaly of some seconds or minutes.

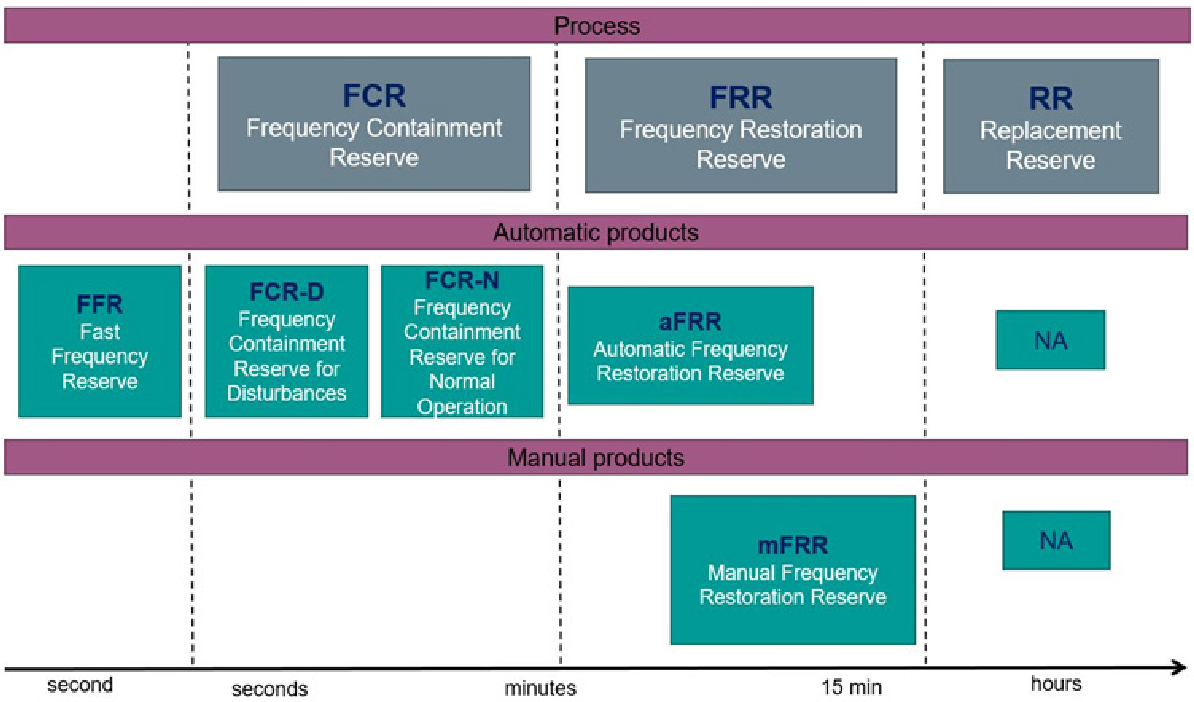


FIGURE 48. Capacity and balancing power markets in Finland (Fingrid, 2021).

In Finland there is approximately 300 MW of Frequency Containment Reserve for Disturbances and this reserve is activated in seconds, if there is a larger anomaly in frequency. The Frequency Containment Reserve for Normal operation is both in Finland and in the Nordics half of the capacity of the previously mentioned FCR-D and this reserve is in operation all the time. The capacity of aFRR in Finland is 70 MW and this reserve is also activated in a couple of minutes. The capacity of mFRR can be activated in 15 minutes and is activated only when needed (Fingrid, 2021). All capacity products operate on hourly markets and the price fluctuations can be very dramatic depending on the state of the system. In FCR markets you can also make an annual contract with Fingrid and then the compensation is paid for every hour the capacity is available (Table 11)

TABLE 11. Capacity market prices in Finland 2019 (Fingrid, 2019).

PRODUCT	ANNUAL MARKETS €/MW/H	HOURLY MARKETS
FCR-N	13,50 €/MW	10 - 450 €/ MW
FCR-D	2,4 €/MW	0 - 500 €/ MW
aFRR	-	0 - 44 €/ MW
mFRR	-	0 - 3000 €/ MW

Kielinen (2020) performed a study among the Finnish BRPs (total number of 51 players) and the survey was sent to 46 companies operating as BRPs between the electricity producer s and the electricity markets. There were only 9 respondents, but it can be assumed that the results anyhow present quite well the views of the Finnish operators in the electricity markets. The majority of the respondents had more than 500 MW in their portfolio and are thus large or medium-sized players. Out of the BRPs, 22 % already had some type of energy storage in their use, and 33 % announced that they do not possess yet any own energy storage capacity, but they have been discussing the need within their company. However, there was a strong consensus among the respondents (89 %) that they will need an own energy storage capacity in the future.

The survey confirmed the assumption that wind power is the main driver for BRPs to invest in energy storage capacity (Kielinen, 2020). Almost half of the companies (45 %) considered that also the increasing number of solar power will in the future create a need for their own energy storage. When the companies were asked about the main storage technology in the future, hydrogen storage received surprisingly strong support. The companies had the view that there was a slightly larger need for electricity storage within the intraday markets (Elbas) than on day-ahead (Spot) markets. The case companies considered that the production deficit is a slightly bigger driver to invest in the own electricity storage than the case when the production exceeds the production estimate.

The Finnish BRPs had a clear view that there are bigger business opportunities for energy storage within the capacity and reserve markets than on the electricity markets. This result is totally in line with the results received in other countries (e.g. Sweden, Germany (Zakeri, et al., 2017)). Based on the study performed by Kielinen (2020) it can be stated that there is a clear need to own electricity storage capacity for the Finnish BRPs. It can also be assumed that the need among the BRPs is larger than among the electricity producers because it is the BRP who carries the final responsibility and is liable for the losses if the production estimate fails.

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5. CONCLUSIONS

Recommendation for the Technobothnia energy storage investment

The main objective of this project is to build, for educational and R&D purposes, energy storage demo environment(s) in the Technobothnia Education and Research Center. To fulfill this goal the fundamental key question is, what are the main energy storage technologies in the future? Energy storage is at the moment having a strong and swift global growth due to the increasing number of wind and solar power deployments. PHS has dominated the electricity storage market with a market share of over 96 % and an installed capacity of over 170 GW. PHS plants provide the most cost-efficient option for energy storage, but the cost of some battery and thermal storage technologies is now decreasing rapidly. There have been estimates IRENA (2017, p. 13) that energy storage will not be a “one-horse race” but instead a market of 2-4 main technologies, which are complementary and used for different purposes.

There are many factors influencing energy storage investments, but naturally, the largest drivers are the economical ones. The economics of an energy storage investment can be evaluated by LCOS, IRR, Return on Equity (ROE), payback time or by LCA methods. Anyhow there are factors concerning an energy storage investment that are hard or almost impossible to evaluate with monetary and financial measurements. One such key issue is the supply security of the power source. The electrical grid must maintain a specific frequency (50/60 Hz) to secure the sufficiency of power in all circumstances, and this is focal to avoid any small- or large-scale grid failure. For example, a flywheel solution has very high costs compared to many other technologies, but it can provide some important features to recover the grid frequency for some milliseconds or seconds. Thus, when energy storage technologies are discussed we must study the following questions.

- What is the primary objective of our investment? Do we aim **to do business** with the energy storage, or do we deploy it to enhance the **power supply**? Or are there some environmental and **green values** behind the investment?
- What is **the amount of energy** (kWh/J) we want to store? Which technology is best suited to store small or large amounts of energy in a cost-efficient way?
- What is the timeframe and **period of storage**? Do we need to store energy for a short time (minutes/hours) or do we need to store it for a longer time (months/years)?

Based on this study there are three main technologies that should be included in the Technobotnia demonstration environment. Albeit **pumped hydro** will lose its market share, it will remain one of the leading storage technologies during the next decade (e.g. IRENA 2017). Thus, it is recommendable that one of the demo sites in Technobothnia would be a pumped hydropower storage plant. This demo could provide students a profound understanding of how the amount of water flow and fall height influence the production. This demo could also demonstrate what the losses are in different stages of the storage and how to improve the round-trip efficiency of the system.

In the field of **battery technology**, lead-based batteries still had in 2011 almost as large a market share as lithium-ion batteries, but already in 2016 lithium-ion batteries were the dominant solution with 88% market share (Figure 49). The growth for lithium-ion battery solutions has been very strong both for large grid-scale storages and for behind-the-meter solutions. Both households and industrial electricity users have been investing to own battery storage (behind-the-meter) mainly due to their solar power production. Concerning the sodium NaS batteries there were estimates (e.g. Zaker & Syri (2015)) that this technology will the most cost-efficient one and one of the market leaders. In 2014 NaS batteries had a market share of 19%, but since then, they have not been able to compete with lithium-ion batteries (IEA, 2020). NaS batteries have been mainly deployed in Japan and there have been some technical issues (hazard of fire and high corrosiveness), which have slowed down the deployment of this technology. There are some experiments for low temperature (100 °C and below) NaS batteries but this technology is still covered by high uncertainty (Kumar, et al., 2017). Thus, the only recommendable battery technology for the Technobothnia laboratory is the **lithium-ion battery**. There are many types of lithium batteries and the lithium-ion batteries can also be divided into different subcategories (Kamali-Heidari, et al., 2018).

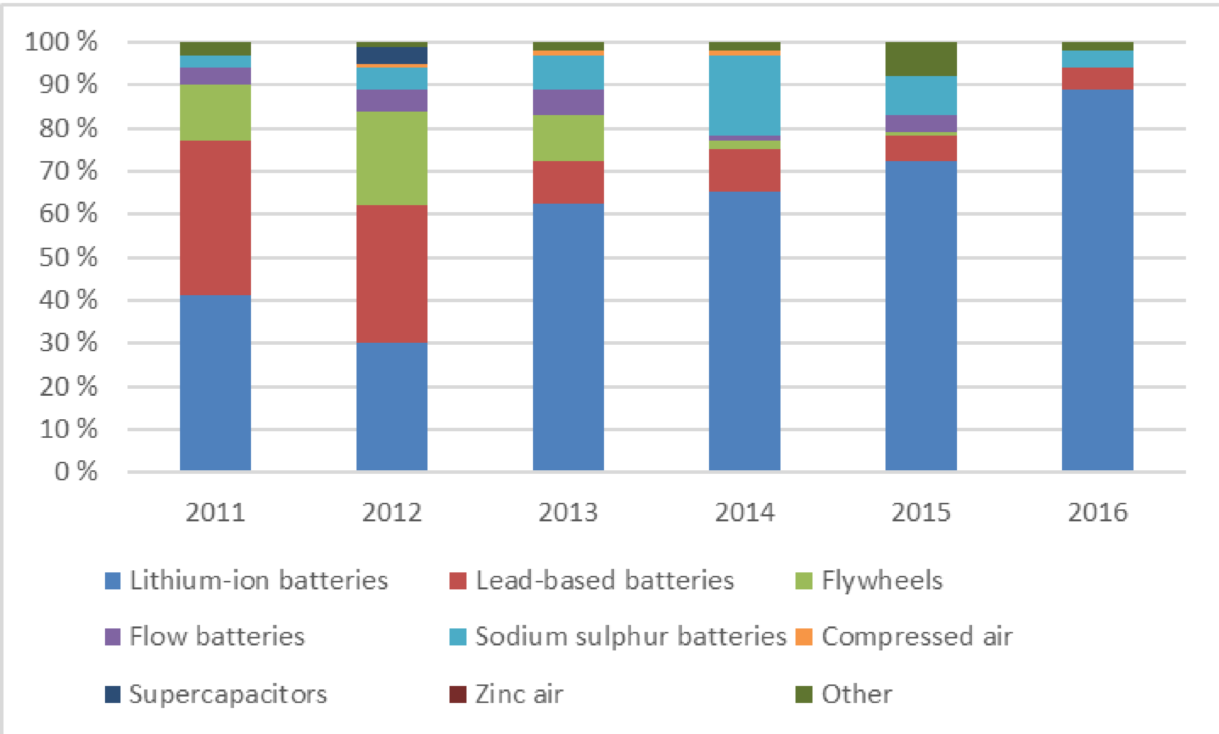

FIGURE 49. Technology mix in storage installations excluding pumped hydro, 2011-2016 (IEA, 2019).

The most promising TES-system at the moment is the **molten salt technology** which is applied in many concentrated solar power plants. With this concept, the stored heat can later be converted into superheated steam to power conventional steam turbines and generate electricity at night. IRENA (2017, p.15) estimated that this type of thermal storage will by 2030 be the second largest energy storage method globally, with a market share of 23 % (PHS 45% and Li-ion battery 21%). Thus, there is a clear need to have some type of thermal storage as one demonstration environment at Technobothnia.

Compressed Air Energy Storages can be divided into several subcategories, but the two main solutions are diabatic and adiabatic technologies. For decades there have been two operational diabatic Compressed Air Energy Storages combined with gas turbine power plants. When the air is compressed it will create heat and in an aCAES, the heat is stored to be used for heating the released cooled air. Albeit this thermal storage of aCAES can almost double the round-trip efficiency (up to 80 %), this technology has not yet become economically viable.

The cost of a flywheel solution is usually very high, but this technology can anyhow provide great assistance to maintain the correct frequency of the grid. This kind of supply security issue is very difficult to evaluate with economic terms and thus Flywheels and other minor technical solutions can have a future in the reserve and capacity markets (excluding the electricity markets).

Table 12 lists suggestions for the energy storage demonstration environment in Technobothnia based on this study.

TABLE 12. Summary of the suggested energy storage technologies for Technobothnia.

MAIN TECHNOLOGIES	ARGUMENTS/EXPLANATION
Pumped hydro	Current market leader and estimated to have a 45 % market share still in 2030.
Lithium Ion batteries	Mainly due to the continuous and heavy price drop both for stationary installation and for electrical vehicles rapidly growing market share.
Thermal energy storage	Variety of different kind of applications, estimated to be the 2nd largest energy storage method in 2030 (IRENA 2017). Molten salt solutions by concentrated solar power (CSP) plants one of the main drivers.
AUXILIARY TECHNOLOGIES	
Compressed Air Energy Storages (CAES)	When there is a free of charge store (e.g. salt cavern) for the compressed air, can CAES offer business opportunities in some circumstances.
Flywheel	Can provide fast support for grid and secure power supply.
Hydrogen production with electrolysis (P2G)	Current alkaline technology to convert water by electrolysis to hydrogen with renewable electricity is too expensive and slow. The new PEM electrolysis can be cost efficient in 2030 and capable to adjust itself to the variating wind and solar power production.

Suggestions for future studies

To be able to cope with the increased utilization of renewables, both globally and regionally, extended knowledge of energy storage technologies is needed. This report gives a comprehensive review of various energy storage technologies that are available on the market today. However, some technologies discussed are still in their early phase of development. Based on this review and the discussions with various key players, several demonstration environments were chosen to be built in Technobothnia Education and Research Center. These include PHS, Li-Ion batteries, TES (PCM), CAES, Flywheels and Power-to-gas (originally constructed within another project, AIKO GasCoE).

In the Vaasa region in Ostrobothnia, there are numerous educational institutions, universities and companies with a great interest in the energy sector. A confirmation of this was concluded in one of the empirical studies performed within this project. Here, two separate questionnaires were sent out to representatives in educational institutions and the industry respectively in order to map the energy storage competences and needs. One result of the survey suggested that both the coordination between different players and the information flow concerning the energy storage R&D activities could be improved. This is something to pay attention to. For a region to thrive and develop in a positive manner, cooperation across organization borders is necessary. With the various R&D activities going on, there is a need to close the loop so that there is a flow of research data available to all the key players, which are the industry, research personnel, and the teaching fraternity. Several suggestions of improvements have been put out by representatives of the Academia in the study. By creating a common energy storage platform and by identifying partners interested in the same field, the partnership between industry and the educational institutions could be strengthened. In addition, both long-term projects and company-projects would be beneficial in terms of strengthening the cooperation. One suggestion was that companies give research problems to the universities as part of course material, with the best solutions being rewarded with thesis work or summer jobs.

This development initiative (Energilagring!) is expected to finish at the end of 2021. One challenge with time-scheduled projects is that there is occasionally no additional money for continuing the work that has been initiated within the project. In order to overcome such challenges, new project ideas are more than welcome. In the second empirical study that was performed within the Energy storage project, the Finnish BRPs were interviewed in order to map their views on business opportunities within electricity storage. The study showed that there might be some challenges regarding business opportunities for energy storage in the electricity markets. From this as a starting point, a future study about the business opportunities both on capacity and electricity markets would be needed.

Several of the demo environments have already been finalized, but others are still in the constructing phase. The main goal of the demo environments is for them to be implemented in the engineering curricula of VAMK, Novia and ÅAU. To date, only the flywheels demo has been tested for educational purposes, however, in the future, several demos are planned to be utilized within different laboratory courses. Furthermore, another aim is that the demos would be open for research personnel and industrial partners to deepen their knowledge in energy storage technologies but there is still a need to sensitize the stakeholder on what is available and how this demo environment can be implemented into education.

Energy storage is a concept that has gained substantial interest as a research topic amongst researchers. At ÅAU, this energy storage project has been an inspiration source and a starting point for one ongoing Ph.D. thesis (two other ongoing research initiatives were identified before the project started, in an ÅAU unit in Turku). Within this topic, research is conducted on how energy storage can be used to integrate renewable energy in the transition to carbon-neutrality, both from a national and a regional perspective. Energy storage has been the focus of or included in several ÅAU M.Sc. theses during the lifetime of this project, but not financed by the project itself (see https://blogs.abo.fi/energiteknik/alumner/). In another area of research in ÅAU in Vaasa, outside the scope of this project, power-to-gas technologies are examined by looking at Process Integration for Novel Biorefinery Concepts and Biofuel Production.

Looking at the ongoing energy transition in general, traditional ways of storing fuels before utilized in various combustion processes seem to become increasingly unpopular. For example, seasonal storage of peat and coal fuels in heaps in the open air will gradually disappear, storage of fossil oil products in cisterns, car tanks and at gasoline stations seem to be less needed because of electrification. Furthermore, even the traditional ways of storing emergency fuel must probably be re-innovated. Both several new energy storage solutions (demos, pilots and commercial activities) and new capacity will probably be introduced in our local energy system in Vaasa in the future. It will be important for the local universities to be able to take part in such activities (through new projects and Ph.D. theses and the industry providing M.Sc. and B.Sc. theses for students) to finally be able to adjust and improve our education. To create new projects for building up a deeper understanding of the phenomena behind and the performance of local Living Lab storage activities, are ways to secure that new knowledge is transferred to education. New ways of reaching out to private consumers must presumably also be developed, in order to avoid dissatisfaction and unrealistic expectations regarding investment in new energy technology, which is expected to be paid off during its lifetime.

In summary, energy storage technologies are crucial in promoting a sustainable future. Consequently, understanding the phenomena behind the energy storage technologies is therefore imperative, and that issue is undertaken within this project and report.

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Appendices

Appendix 1. Electricity energy storage power capacity by technology type and primary-use case, mid-2017 (United States Department of Energy, 2017).

SERVICE/USE CASE 1	PUMPED HYDRO STORAGE	THERMAL STORAGE	ELECTRO CHEMICAL	ELECTRO MECHANICAL	GRAND TOTAL (GW)
Electric Energy Time Shift	149.94	0.14	0.15	0.11	150.34
Electric Supply Capacity	6.91	0.00	0.07	0.20	7.18
Black Start	5.92		0.04	0.32	6.29
Renewables Capacity Firming	3.20	2.39	0.10	0.00	5.68
Electric Supply Reserve Capacity – Spinning	2.00		0.18	0.01	2.18
Frequency Regulation		0.00	0.95	0.04	1.00
On-Site Power	0.14	0.00	0.00	0.86	1.00
Electric Bill Management	0.38	0.10	0.16	0.00	0.64
Renewables Energy Time Shift		0.48	0.05	0.00	0.64
Demand Response	0.42		0.01		0.43
Voltage Support	0.30		0.00	0.00	0.31
On-site Renewable Generation Shifting		0.21	0.02		0.23
Resiliency			0.03	0.01	0.04
Transport Services			0.04	0.00	0.04
Grid-Connected Commercial (Reliability & Quality)			0.02		0.02

SERVICE/USE CASE 1	PUMPED HYDRO STORAGE	THERMAL STORAGE	ELECTRO CHEMICAL	ELECTRO MECHANICAL	GRAND TOTAL (GW)
Microgrid Capability		0.00	0.01		0.02
Electric Bill Management with Renewables			0.02	0.00	0.02
Ramping			0.02	0.00	0.02
Distribution Upgrade Due to Solar			0.01		0.01
Stationary Transmission/Distribution Upgrade Deferral			0.01		0.01
Distribution Upgrade Due to Wind			0.00	0.01	0.01
Load Following (Tertiary Balancing)			0.00		0.00
Transmission Congestion Relief			0.00		0.00
Electric Supply Reserve Capacity – Non-Spinning			0.00		0.00
Transportable Transmission/Distribution Upgrade Deferral			0.00		0.00
Grid-Connected Residential (Reliability)			0.00		0.00
Transmission Support			0.00		0.00
Grand total (GW)	169.21	3.32	1.94	1.57	176.01

Appendix 2. Regional Energy Storage Competence - Questionnaire for the Industry

Energy Storage Technology- Company Needs

The Energy Storage in Our Future Low Carbon Society Project (1.5.2018-30.4.2020) is a partnership between Novia University of Applied Sciences, Vaasa University of Applied Sciences (VAMK) and Åbo Akademi University. The main objectives for the project is to create a demo environment for energy storage combined with a matching knowledge basis, create regional & international networks and cooperation opportunities within this area.

This is a survey to get an overview from the industry on the Energy Storage competence needs in the region. The data collected will be used as background input data in the planning "Diversification Plan" for Energy Storage Focus Areas among the Universities & Universities of Applied Sciences in the region in the future if there is a need. The aim is to eliminate repetitions and over-lapping of teaching material to cover a wider scope for competence building in the region.

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...

1. Name of organisation

Enter your answer

2. Contact person- include contact details

Enter your answer

3. Area of interest in energy storage technologies

- [ ] Materials
- [ ] Applications
- [ ] Reuse
- [ ] Recycling
- [ ] Other

4. Technology/ies of interest, eg. heat, batteries, flywheel etc. (can give more than one technology)

Enter your answer

5. What knowledge-gap in energy storage does your organisation need to be fill?

Enter your answer

6. Energy storage solutions & expertise ccurrently available within the organisation.

- [ ] Energy Storage Solutions
- [ ] Energy Storage Expertise

7. Give more information on your answers from question 6 specifying the kind of energy solutions (any pilots, demos?)and/ expertise.

Enter your answer

8. Would your organisation be interested to participate in investing in the energy storage demo environment in Technobothnia- either as a total solution, single components or other form if the demo is within your area of interest?

- ◯ Yes
- ◯ No
- ◯ Other

9. What kind of energy storage technology demo would be of interest to your organisation?

Enter your answer

10. Would your organisation be interested in using such demo environment in Technobothnia as stated in question 8 & 9?

- ◯ Yes
- ◯ No
- ◯ Other

11. Any other comments

Enter your answer

Submit

Appendix 3. Energy Storage Competence Roadmap - Academia

Regional Specific Studies- Ostrobothnia

Introduction

This survey is a data collection tool to get an overview from the academic side on Energy Storage competence now and in the future in the region with focus on Ostrobothnia. The data collected will be used as empirical data in the information package being prepared by the Energy Storage in our Future Low Carbon Society team(1.5.2018-31.12.2020) and as input/background data for a "Diversification Plan for Energy Storage Focus Areas" among the Universities & Universities of Applied Sciences in the region in the future if a need arises. The aim is to make energy storage resources from the schools that promote regional competence growth more accessible.

We would also like to create a "Regional Expert Catalogue" profiling energy experts in the region in one package.

I BACKGROUND INFORMATION

1. Name of learning Institution:

2. Level of education offered by the institution:

3. Faculty /Department:

4. Contact Person:

5. Position of Contact Person:

II GENERAL

1. Please describe your interest and focus within the field of energy storage.

2. How should research and training be connected to the energy cluster?

3. How to ensure the transfer of research data to education?

III. COMPETENCE MAP AND SKILLS DEVELOPMENT BY THEME

(SELECT THEME OF SPECIALITY)

TECHNOLOGY

1. Please describe how you see the current situation and future of different energy storage technologies?

2. What technical skills do you consider as most important and how these shall be developed in the area of energy storage?

3. Product development and Innovation activation: Does your institution have energy storage R & D activities? Demo environment, research, education, partners from industry?

ENERGY STORAGE ECONOMY, ENVIRONMENTAL ASPECTS AND LEGISLATION

1. What economical skills do you consider as most important and how these shall be developed in the area of energy storage?

2. What environmental know-how skills do you consider as most important and how these shall be developed in the area of energy storage?

3. What are the legislation research needs in the energy storage sector?

(IV) VISIONS

1. How should the energy storage network in the Vaasa region be built and strengthened? (roles of different actors, forms of cooperation, transmission of knowledge, innovation policy, networks)

2. How could the learning institutions in the region have diversification in energy storage focus areas?

3. What energy storage educational and R&D needs of the Vaasa energy cluster shall be covered in the future by the institution? (do you see gaps between the industry needs and what the universities are doing?)

4. What else do you want to highlight?

Appendix 4. Tables with the characteristics of various energy storage technologies and battery energy storage technologies.

TABLE 13. Characteristics of various energy storage technologies.

ENERGY STORAGE TECHNOLOGY	POWER RATING (MW)	ENERGY RATING (MWH)	DISCHARGE TIME	RESPONSE TIME	SELF-DISCHARGE RATE (%/DAY)	SUITABLE STORAGE DURATION	EFFICIENCY (%)	LIFETIME (YEARS)	LIFETIME (CYCLES AT 80% DEPTH OF DISCHARGE)	MAXIMUM DEPTH OF DISCHARGE (%)
Pumped Hydro Storage (PHS)	100-5000	1000+	1-24+ h	~3 min	0.005-0.02	h-month	65-85	30-60	N/A	95-100
Diabatic Compressed Air Energy Storage (D-CAES)	5-300	1000+	1-24+ h	~10 min	0.003-0.03	h-month	40-60	20-40	N/A	
Advanced Adiabatic Compressed Air Energy Storage (AA-CAES)	110 & 290		1-24+ h			h-month		20-40		
Adiabatic Compressed Air Energy Storage (A-CAES)	0.1-10 small 100+ large	1-10 small 100+ large	1-12 h small 1-24+ h large	min	0.5-1	h-month	75-95	20-30	N/A	
Isothermal Compressed Air Energy Storage (I-CAES)	0.1-10	1-10	1-12 h	<1 min	Very small	h-month	75-95	20-30	N/A	
Flywheel	0.01-10 0.1-20	0.01-5	s-min	ms-seconds	55-100	s-min	75-95	15-20	20,000-100,000	100
Superconducting Magnetic Energy Storage	0.01-10	10^{-4}-0.1	ms-min	ms	10-15	min-h	80-90	15-20	>100,000	100
Supercapacitors	0.001-10	10^{-6}-10^{-2}	ms-h	ms	20-40	s-h	85-95	10-20	>100,000	75

TABLE 14. Characteristics of various energy storage technologies (Table 13 continued).

ENERGY STORAGE TECHNOLOGY	POWER DEN SITY (W/l)	SPECIFIC POWER (W/kg)	ENERGY DENSITY (Wh/l)	SPECIFIC ENERGY (Wh/kg)	CAPITAL COST: POWER ($/kW)	CAPITAL COST: ENERGY ($/kWh)	TECHNOLO GY MATU RITY	ADVANTA GES	DISADVANTA GES	REFERENCES
Pumped Hydro Storage (PHS)	-	-	0.5-1.5	0.5-1.5	600-2000	5-100	Mature	Mature technology and high capacity	Suitable geo-graphical locati-on is required	(Argyrou, et al., 2018; Gallo, et al., 2016; Zhang, et al., 2018)
Diabatic Compres-sed Air Energy Storage (D-CAES)	-	-	3-12	30-60	400-800	2-50	Commercial	High capa-city	Suitable geo-graphical locati-on is required	(Wang, et al., 2017; Zhang, et al., 2018)
Advanced Adiabatic Compressed Air Energy Storage (AA-CAES)	-	-	2-6	-	-	-	-	High capa-city	Suitable geo-graphical locati-on is required	(Wang, et al., 2017; Zhang, et al., 2018)
Adiabatic Com-pressed Air Energy Storage (A-CAES)	-	-	3-12	30-60	-	40-80	R&D-De-monstration	High capa-city	Suitable geo-graphical locati-on is required	(Gallo, et al., 2016; Zhang, et al., 2018)
Isothermal Com-pressed Air Energy Storage (I-CAES)	-	-	3-12	30-60	500-1000	10-100	Pre-com-mercial	High capa-city	Suitable geo-graphical locati-on is required	(Gallo, et al., 2016; Zhang, et al., 2018)
Flywheel	1000-2000	400-1500	20-80	5-100	250-350	1000-5000	Commercial	High power density	High require-ments for the material of the flywheel and vacuum is required	(Gallo, et al., 2016; Zhang, et al., 2018)
Superconducting Magnetic Energy Storage	1000-4000	500-2000	0.2-2.5	0.5-5	200-350	1000-10,000	Demonstra-tion - Pre-commercial	High power density	Operates at low temperatures and the cost is high	(Argyrou, et al., 2018; Gallo, et al., 2016; Zhang, et al., 2018)
Supercapacitors	100,000	500-5000	10-30	2.5-50	100-360	300-2000	Demonstra-tion – Pre-Commercial	Long cycle life and high power density	Low energy density and the cost is high	(Argyrou, et al., 2018; Gallo, et al., 2016; Zhang, et al., 2018)

TABLE 15. Characteristics of various battery energy storage technologies.

ENERGY STORAGE TECHNOLOGY	POWER RATING (MW)	ENERGY RATING (MWH)	DISCHARGE TIME	RESPONSE TIME	SELF-DISCHARGE RATE (%/DAY)	SUITABLE STORAGE DURATION	EFFICIENCY (%)	LIFETIME (YEARS)	LIFETIME (CYCLES AT 80% DEPTH OF DISCHARGE)	MAXIMUM DEPTH OF DISCHARGE (%)
Lead-acid battery (PbA)	0.001-50	0.1-100	s-h	ms	0.033-0.3	min-day	70-90	5-15	400-1500	60-70
Nickel-Cadmium battery (Ni-Cd)	0.01-40	10^{-5}-1.5	s-h	ms	0.067-0.6	min-day	60-73	10-20	1000-1500	100
Nickel-Metal hydride battery (Ni-Mh)	0.01-1	10^{-5}-0.5	h	ms	0.4-1.2	min-day	70-75	5-10	800-1200	60-70
Lithium-ion battery (Li-ion)	0.1-50	10^{-5}-100	min-h	ms	0.1-0.3	min-day	85-95	5-15	2000-5000+	80-90
Sodium sulphur battery (NaS)	0.05-50	6-600	s-h	ms	0.05-20	s-h	70-90	10-15	4000-4500	90
Sodium Nickel Chloride (ZEBRA) battery	0.001-1	0.12-5	min-h	ms	15	s-h	85-90	15	4000-4500	75-85
Iron-Chromium Flow Battery (ICB)	1-100		4-8 h				72-75	10-15		
Zinc-Bromine (ZBB) Flow Battery	0.025-2	0.05-4	s-10 h	Ms	0.24	h-month	60-75	5-10	5000-10,000	100
Vanadium Redox (VFB) Flow battery	0.025-7	0.01-10	s-10 h	ms	0.2	h-month	60-85	10-15	10,000-13,000	100

TABLE 16. Characteristics of various battery energy storage technologies (Table 15 continued).

ENERGY STORAGE TECHNOLOGY	POWER DEN SITY (W/l)	SPECIFIC POWER (W/kg)	ENERGY DENSITY (Wh/l)	SPECIFIC ENERGY (Wh/kg)	CAPITAL COST: POWER ($/kW)	CAPITAL COST: ENERGY ($/kWh)	TECHNOLO GY MATU RITY	ADVANTAGES	DISADVANTA GES	REFERENCES
Lead-acid battery (PbA)	10-700	75-415	50-90	0.5-1.5	300-600	200-400	Mature	Mature technology and low cost	Short cycle life and environ-mental polluti-on by lead	(Argyrou, et al., 2018; Gallo, et al., 2016)
Nickel-Cadmium battery (Ni-Cd)	75-700	100-300	60-150	40-75	500-1500	800-1500	Commercial – Mature	Wide opera-ting tempera-ture, versatile sizing	Environmen-tal pollution by cadmium, limited applica-tions due to ban	(Argyrou, et al., 2018; Gallo, et al., 2016; Menic-tas, et al., 2015)
Nickel-Metal hydri-de battery (Ni-Mh)	500-3000	200-1500	140-300	45-80	600-1800	960-1800	Commercial – Mature	Compared to Ni-Cd: non-toxic (no cadmium), higher ener-gy density	Relatively low specific energy (compared to li-ion)	(Argyrou, et al., 2018; Gallo, et al., 2016)
Lithium-ion battery (Li-ion)	1300-10,000	150-2000	200-500	70-250	1200-4000	600-2500	Commercial	High power and energy density, high coulombic efficiency	Short life cycle and poor safety	(Argyrou, et al., 2018; Gallo, et al., 2016)
Sodium sulphur battery (NaS)	120-160	150-230	150-250	100-240	1000-3000	300-500	Commercial	High power and energy density		
Sodium Nickel Chloride (ZEBRA) battery	220-300	150-200	150-180	85-140	~ 400-1800	~ 500-1000	Commercial	High power and energy density		
Iron-Chromium Flow Battery (ICB)							Early stage of field deployment and demo trials	Flexible design and safety	Low energy density	(Parra, et al., 2017; Zakeri & Syri, 2015)

ENERGY STORAGE TECHNOLOGY	POWER DEN SITY (W/l)	SPECIFIC POWER (W/kg)	ENERGY DENSITY (Wh/l)	SPECIFIC ENERGY (Wh/kg)	CAPITAL COST: POWER ($/kW)	CAPITAL COST: ENERGY ($/kWh)	TECHNOLO GY MATU RITY	ADVANTAGES	DISADVANTA GES	REFERENCES
Zinc-Bromine (ZBB) Flow Battery	1-25	45	30-60	30-85	700-2500	150-1000	Pre-commercial	Flexible design and safety	Low energy density	(Argyrou, et al., 2018; Gallo, et al., 2016)
Vanadium Redox (VFB) Flow battery	0.5-2	166	16-33	10-35	600-1500	150-1000	Commercial	Flexible design and safety	Low energy density	(Argyrou, et al., 2018; Gallo, et al., 2016)