TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

COMPARATIVE ANALYSIS OF ENERGY STORAGE TECHNOLOGIES FROM THE PERSPECTIVE OF ESTONIAN SECURITY OF SUPPLY

ENERGIA SALVESTUSE TEHNOLOOGIATE VÕRDLEV ANALÜÜS EESTI VARUSTUSKINDLUSE SEISUKOHAST

BACHELOR THESIS

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Tallinn, 2021

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ABSTRACT

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Abstract:

With the penetration of renewable energy into the grid, energy system will change completely. It would no longer be centralized system, but the system with a lot of energy suppliers. These changes will lead to new challenges for the energy system such as the stable operation of the energy system. Energy storage technology can contribute to many of the challenges of the new energy system and offer solutions.

The aim of the thesis is to investigate how the existing technologies of energy storage are applicable for improvement of the electric grid in Estonia, i.a. through enhancing system reliability and efficiency. There are different storage technologies, their application areas as well as the prices of different technologies compared and described in the thesis. The paper examines the current state of the Baltic energy system and analyzes the narrow points in the system that can be solved with the help of energy storage devices. The EU Renewable Energy Directive is also addressed in terms of storage technology.

Keywords: energy storage, renewable energy, pump hydro energy storage, battery energy storage, hydrogen energy storage, frequency regulation.

LÕPUTÖÖ LÜHIKOKKUVÕTE

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Töö juhendaja(d): Karl Kull, Oleksandr Matiushkin	
Sisu kirjeldus: Taastuvenergia osakaalu kasvuga energiasüsteemis tekib täiest uus olukord energia turul, mis ei ole enam tsentraliseeritud ja kus osaleb palju erinevaid energia pakkujaid. Need muutused toovad energiasüsteemile kaasa uusi väljakutseid, nagu energiasüsteemi stabiilne toimimine ja varustuse kindlus. Mitmete energiasüsteemi väljakutsete lahendamisele võivad kaasa aidata erinevad energia salvestuste tehnoloogiad. Töö eesmärk on uurida, kuidas energia salvestuse tehnoloogiaid võib kasutada Eesti energiasüsteemi parandamiseks läbi töökindluse ja efektiivsuse tõstmiseks. Töös käsitletakse erinevaid salvestuste tehnoloogiaid ja nende rakenduse valdkondi ja võrreldakse omavahel erinevate tehnoloogiate hindasid. Töös uuritakse Balti riikide energiasüsteemi hetkeseisu ja analüüsitakse süsteemi kitsaskohti, mida saab lahendada energia salvestuse seadmete abil. Samuti käsitletakse salvestuste tehnoloogiat EL Taastuvenergia direktiivi vaatenurgast.	
Märksõnad: energia salvesti, taastuv energia, hüdroakumulatsioonijaam, patarei energiasalvestid, vesinik-energiasalvesti, sageduse reguleerimine	

THESIS TASK

Thesis title:	**Comparative Analysis of Energy Storage Technologies from the Perspective of Estonian security of supply** **Energia salvestuse tehnoloogiate võrdlev analüüs Eesti varustuskindluse seisukohast**
Student:	**Mihhail Korb**
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Type of the work:	**Bachelor**
Supervisor of the thesis:	**Karl Kull**
Co-supervisor of the thesis: (company, position and contact)	**Oleksandr Matiushkin**
Validity period of the thesis task:	**18 may 2021**
Submission deadline of the thesis:	**18 may 2021**

Student (signature)	Supervisor (signature)	Head of programme (signature)

Co-supervisor (signature)

1. Relevance of the topic

The scope of practical application of the energy storage technologies has been increasing each year. Nowadays, the contemporary energy storages are obtaining a crucial role for the development of the electric grids. The traditionally storage devices were used for accumulation of relatively insignificant amounts of electricity as well as for providing uninterruptible power supply in low-power loads.

Prospectively, the energy storage devices would contribute to distributed generation and to more efficient management of the electric grids. Besides, a growing use of the energy storage would create new opportunities for renewable energy generation. Since production and consumption of the renewable energy are often not synchronized by time, a well-developed energy storage technology would serve as a proper tool to get better performance, ensuring the systems security of supply and get a clear spectrum of the grid currents. So, elaboration of the modern energy storage technologies is a prerequisite for further growth of renewables in the world energy balance.

2. Goal of the thesis

The goal of thesis is to investigate how the existing technologies of energy storage are applicable for improvement of the electric grid in Estonia, i.a. through enhancing system reliability and efficiency.

3. Research tasks:

Corresponding tasks include:

- To scrutinize in comparative perspective the existing energy storage technologies.
- To evaluate the implementation costs of selected technologies and their economic models.
- To identify the most effective energy storage solutions for Estonian power system and estimate their feasibility in Estonian context.
- To study how energy storage solutions could affect to power system, including the issues of security of supply, efficiency and growing role of renewables.

4. Basic data

The basic data include the statistics of Estonian energy system – consumption, load, production of renewables, price levels, etc. Technical characteristics and data about known samples of energy storage technologies implementation. Academic surveys and online sources.

5. Research methods

Secondary data survey and literature review; meta-analysis methods for statistical data; analysis of technical documentation, comparison, economic modelling.

6. Graphical material

The work primarily includes schemes of different energy storage technologies, tables, equations and block schemes in theory part.

7. Thesis structure

1. Energy storage technology

2. Chalanges of Baltic Energy Systems

3. Energy storage application in the energy system

8. References

The work primarily includes thematic literature in the form of books and research articles, equipment operating reports, interviews with experts engaged into energy storage technology development and investment in Estonia.

9. Thesis consultants

Priit Siitam, Energiaalv Pakri OÜ, CEO

10. Work stages and schedule

Literature review (1 December 2020);

Writing the theoretical part (February 1, 2021);

Analysis of existing storage objects (January 1, 2021);

Completion of the first version of the work (March 1);

Corrections (Mai 1).

TABLE OF CONTENTS

INTRODUCTION

The Estonia energy system, as well as the energy systems of the other Baltic States, are facing major changes that may indicate complex challenges. First of all, in 2025, Estonia, together with the other Baltic States, will exit the synchronously operating interconnected system IPS / UPS. Apart from the Baltic States, the system includes Russia and Belarus and other Eastern countries. For a long time, the Baltic States were referred to as an "energy island" in Europe, as it is underlined in the European Energy Security Strategy. The change is taking place with the aim of integrating the Baltic States into the European synchronous area. To achieve this, the Baltic States are building better interconnections and increasing the volume of connections with other European countries, such as Poland.

Another big change is more global. EU countries have agreed that in the near future, EU countries will renounce the use of energy production sources with high CO2 emissions. This means that more energy will be produced from renewable energy sources such as wind and solar power. Several European countries have also decided to renounce nuclear energy. Unfortunately, these changes have a negative impact on the stability of energy supply. While reducing CO2 emissions in the coming years, several energy units at Narva Power Plants will be closed, [1] which in turn will have a negative impact on energy supply but may also negatively affect the frequency retention capacity in Estonia.

The third challenge of the energy system is related to consumption growth. If we extrapolate the figures of energy consumption from previous years to the future, then Elering forecasts an increase in the volume of consumption. [1] Although, considering global changing trends such as the replacement of manpower by technology in production, increase in the use of electric cars, growing volume of heat production from electricity, it can be claimed that the electric energy consumption growth will be even faster than current forecasts predict it.

Both wind and solar power are not stable, even though predictable energy sources. In their absence, the system must have sufficient active and reactive power to keep the system running. There are two main solutions for this: either building a nuclear power plant or a gas-fired power plant. [2] There is a 250 MW Kiisa gas reserve power plant in Estonia. There is an active discussion about the possible construction of the Nuclear Power Plant by 2029. Both have major disadvantages. In the case of a nuclear power plant, stable consumption for the entire load is required. It is clearly difficult for a small reactor nuclear plant to compete on price with large nuclear power plants in the region. In addition, nuclear power generation can in no way be considered a safe way of power generation, and there are clearly problems with the disposal of radioactive material. Gas-fired power plants have a fast start-up response, but the price of the energy they produce is expensive and they still produce CO2 emissions. There is an over way to solve green energy challenges - energy storage.

The introduction of energy storage technology is a clear response to the growing volume of renewable energy production in the Energy system. In 2020, 43% of the energy produced in Estonia was produced from renewable sources. Already in the coming years, the volume of Estonian renewable energy production may exceed the total energy consumed per day. There is already 329 MW of wind energy capacity and 128 MW of solar energy capacity today in Estonia. In 2021, it is planned to organize underbidding for another 450 GW of renewable energy capacity and in 2023 for another 650 GW capacity. [3] In addition, the development of renewable energy technologies already allows for economically viable projects that can be set up without subsidies. These changes lead to a situation where the production of renewable energy at a certain point in time can significantly exceed the consumption and, on the contrary, only a reserve of energy has to be taken into account at a certain point in time. In order to make these situations less, energy storage technology must be introduced.

As the volume of renewable energy in the energy system increases, there are a number of challenges that needs to be addressed. Nuclear power, coal, and natural gas are all highly centralized sources of power, meaning they rely on relatively few high output power plants. Wind and solar, on the other hand, offer a decentralized model, in which smaller generating stations, spread across a large area, work together to provide power. This means finding solutions to new energy system challenges such as frequency retention capacity, compensating for reactive energy, ensuring the reliability of the network. It will certainly become more difficult to predict energy production, backup and emergency energy sources shall have a greater impact. Energy storage solutions are able to help solve many of the challenges of the new energy system. There is also a belief that in case of successful resolution of these challenges, it is possible to create a new, more stable and secure energy system, where large number of energy suppliers is involved. [4]

Storage technology solves a number of energy transmission problems. Electrical storage devices are used to meet several requirements to ensure the electrical network and to solve the problems as: load management, spinning reserve, system stability and voltage regulation, transmission grid ja deferral of system and plant upgrading, renewable energy integration, endure applications like emergency back-up, demand side management ja peak shaving. [5] Energy storage technology is not a new part of the energy system, the first storages were built as early as 1880. [4] The role of energy storages in the energy system is clearly changing. Energy storage have not yet been widely used, and many technologies have only been developed on an experimental basis, however, it is clear that storage technology shall take an important role in the energy system in the future, and many interesting discoveries in the development of storage technology lie ahead. Several energy storage technology projects are also being developed in Estonia. Eesti Energia is planning a project with a capacity of 50 MW in Ida-Virumaa. One storage project, which is much more powerful with 500 MW capacity, is also under development by a private investor in Paldiski.

The aim of thesis is a feasibility study of the existing technologies of energy storage in the world and in Estonia. Corresponding tasks include: estimate to investigate how energy storage solutions would affect to power system, including development of the local isolated networks, improving the system stability and more effective uses of energy resources, i.a. renewables; analyze To analyze technical and economic features of the available energy storage technologies: to study the potential of the energy storage projects in Estonia and the implication of their implementation for the power system.

The energy system is inevitably changing. Old energy production methods are being replaced by new renewable energy sources. This is accompanied by the new energy challenges that cannot be resolved without a variety of storage technologies. The aim of this work is to determine the suitability of different storage technologies for the energy system to address the various bottlenecks in the new renewable energy system. An additional goal is to gather the most up-to-date information about the costs of storage technology and to study which technologies are most suitable for one or another situation in the energy system.

1. ENERGY STOREGE TECHNOLOGY

1.1. Future of Renewable Energy Sources (RES)

At the Paris climate conference (UNFCCC COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. The deal has been ratified by over 180 countries. The EU has been a key player in reaching this agreement, which aims at keeping temperature increase to well below 2°C above pre-industrial levels and pursue efforts to keep it to 1.5°C. The EU's nationally determined contribution reflects its objective to reduce EU's greenhouse gas emissions by 40% by 2030 compared to 1990, and is consistent with the then-objective to reduce emissions by 80 to 95% by 2050. In December 2019, the European Commission has presented the "European Green Deal", a set of policy initiatives aiming at ensuring the EU becomes climate neutral by 2050. [6]
In line with the objective of reaching carbon neutrality by 2050, the European Commission's Long-Term Strategy describes a number of pathways that reach between 80% and 100% decarbonization levels. All of them have strong implications for the energy sector, and for the electricity sector in particular. Indeed, in every pathway, a high level of electrification is envisaged, supported by a large-scale deployment of RES. The European Union energy system still relies a lot on fossil energies, and is the main contributor to the overall greenhouse gases emissions with around 80% of the total emissions, the rest being caused by agriculture emissions, industrial processes and waste management. In order to reach zero emissions in 2050, the whole energy system will have to be radically transformed, with an important effort on energy efficiency and a switch from fossil fuels to renewable energy sources. [6] All pathways have in common that they require a more flexible energy system, in order to integrate variable RES technologies (mostly solar PV, and onshore and offshore wind power) cost efficiently while maintaining adequate levels of security of supply. Energy storage is a key technology being able to provide flexibility to the power system, on all time-scales. [6]

The power plants that are connected to the electricity grid must provide basically three types of power services. *Base-load power* is the power that is always requested by the loads connected to the grid, and is normally around 30-40% of the highest power draw from the grid during a day. Coal-fired, nuclear, hydroelectric, or biomass are the technologies used as base-load power plants. Base-load power plants can take many hours or days to change their power output. *Load-following power* plants change production in order to match the varying power consumption demand above the base-load of the area they serve. Normally, natural gas steam turbine or hydroelectric power plants are used since they can provide fast changes in their power output. *Peaking power plants* inject power to the grid only in cases when there is an occasionally high demand for energy. Normally, natural gas steam turbine plants are used as pikers, often in a highly efficient combined cycle gas turbine configuration. By combining ESS to a high penetration of RES in the power generation mix and a new paradigm in energy management smart technologies, base-loading can be covered by technologies that do not resort to fossil fuel usage; entire regions with varying energy availability and demand needs can be interconnected with smart power backbones that can make energy flow consistent with supply-demand logic. For instance, replacing a 1 GW coal-fired power plant would need a cluster of 2,6 GW wind turbine, where higher capacity caters for the same base-loading capabilities of the coal-fired plant. [7]

Total EU (with UK) installed electricity capacity in 2018 was 1037 GW. 44,5% of it was renewable energy sources share - totally 463,5 GW, wind 179 GW, hydro 155,6 GW and solar 117GW. [8] To achieve 2050 goals According to European Commission scenario variable renewable capacities (solar and wind) should rise to 672 GW in 2030 and to 2302 GW in 2050. Then, most of the power production in 2050 is coming from wind and solar capacities, for direct production of electricity but also for indirect electrification of end-uses. [6] There is no consensus on how much storage capacity would be required to achieve this on a mature national grid but it could be equivalent to around 10%-15%of available generating capacity. [14]

Indeed, the typical discharge time of batteries is measured in hours, the one of pumped hydro storage in a few hours to several days, and sector coupling has a discharge time allowing it to contribute to meeting seasonal flexibility needs. Therefore, an appropriate deployment of energy storage technologies is of primary importance for the transition towards an energy system that heavily relies on variable RES technologies to be a success. It is key to understand which of the technologies are the most likely to have an important role to play in the future, to detect the potential barriers to their development and finally to propose an updated regulatory framework and policy actions to allow the identified technologies to penetrate the market. [6] What kind technology investors choose time will show, but it’s better to create a competence in our own country.

1.2. Energy storage technology

The energy system operates on the principle of a balance between demand and power generation, which must be kept on the balance in real time. Right energy storage technology help to optimize energy system and reduce expenses. The principle of most storage devices is that electricity taken from the grid is converted into another type of energy. At the moment of use, the stored energy is taken and converted back into electricity and will be return to the grid. Due to the operation cycle of the storage device is not 100% efficient, the amount of electricity supplied to the network differs from the energy taken from the network by the loss of the storage system. Energy storage devices are used in many devices and processes Figure 1 describes the classification of different types of energy storage technology. [5]

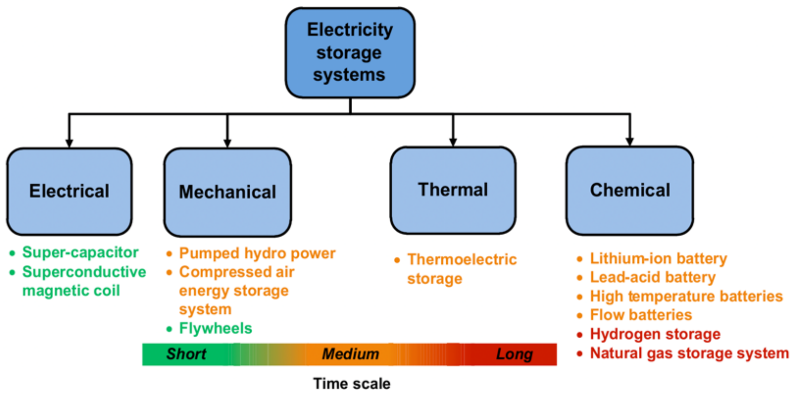

Figure 1. Classification of storage technologies [11]

There are different ways of classifying storage technologies. Here we use the classification shown in Figure 2. using the manner in which the energy is stored as the classification criterion. The focus is only on storage systems classified as 'electricity to electricity' storage systems. There are electrical, mechanical, thermal, and chemical storage systems. [11]

Depending on the way of energy storage, energy storage technologies also have different characteristics, so they are suitable for different applications. For example, Adolfo Gonzalez described the match of electrical storage technologies for different applications in the following Table 1 [5]

Energy Storage can be divided into three major categories according to the length of the operating cycle (charging and discharging cycle): short-term energy storage (seconds or minutes), long-term energy storage (minutes to hours) and ultra-long energy storage (several hours to days).

- Short-term response energy storage: Technologies with high power density (MW/m3 or MW/kg) and with the ability of short-time responses belongs, being usually applied to improve power quality, to maintain the voltage stability during transients (few seconds or minutes). [12]
- Medium- or long-term response energy storage: Long-term response energy storage technologies for power system applications can usually supply electrical energy for minutes to hours and are used for energy management, frequency regulation and grid congestion management. [12]
- Real very long-term response energy storage: Real long-term (days, weeks, or months) response energy storage technologies are usually applied to match demand over 24 hours or longer. The EES elements are classified [12]

Table 1. Based on the analysis of Fraunhofer ISE (*Institut für Solare Energiesysteme*), the following technologies are considered economically effective in the applications described below [5]

	Pumped hydro- electric energy storage, PHES	pumped hydroelectric energy storage (UPHES)	Compressed air energy storage (CAES)	Lead-Acid Batteries	Over batteries	The Flow Battery Energy Storage System (FBESS)	Flywheel energy storage	Supercapacitor energy storage (SCES)	Superconducting magnetic energy storage (SMES)	Hydrogen energy storage	Hydrogen motor
Improving short-circuit pass capability				x		x	x	x	x	x	
Uninterruptible power supply				x	x	x	x			x	x
Emergency power supply			x	x	x	x				x	x
System stabilization and voltage regulation				x		x			x	x	
Load harmonization	x	x	x	x	x	x				x	x
Load following				x	x	x				x	x
Peak shaving	x	x	x	x	x	x	x			x	x
Primary reserve				x	x	x	x			x	x
Secondary and terrain reserve	x	x	x	x	x	x	x			x	x
Renewable penetration	x	x	x	x	x	x	x			x	
Renewable energy reserve	x	x	x	x	x	x				x	

Different storage technologies and their typical power and capacity ranges shown on a Figure 2. Different types of ESS technologies parameters presented in apex 1.

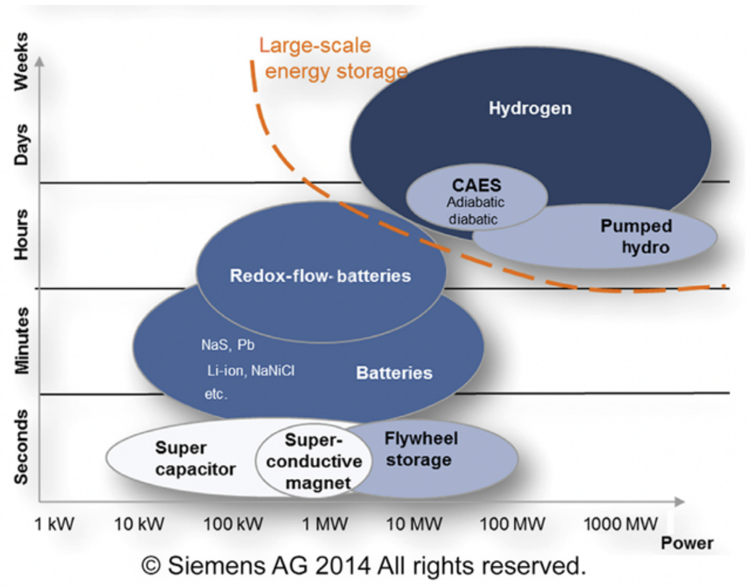

Figure 2. Overview of storage technologies and their typical power and capacity ranges.

1.2.1. Pumped hydro- electric energy storage, PHES

A pumped hydro energy storage system (PHES) (*pumped hydro- electric energy storage, PHES*) consists of two interconnected water reservoirs located at different heights such as a mountain lake and a valley lake. Penstocks connect the upper to the lower reservoir. [11] Its operating principle is based on managing the gravitational potential energy of water, by pumping it from a lower reservoir to an upper reservoir while consuming power from the grid, or by releasing water from the upper reservoir to the lower one when energy needs to be injected into the grid. [13] An electrically powered pump pumps up water from the lower to the upper reservoir during the charging process and a turbine is powered by falling water during the discharging process. The amount of stored energy is proportional to the product of the total mass of water and the altitude difference between the reservoirs. Pumped hydro energy storage is the major storage technology worldwide with more than 183,3 GW installed power and has been used since the early twentieth century [14] Such systems are used as medium-term storage systems, i.e., typically 2 e 8 h energy to power ratio (E2P ratio). [11]

These plants range in size from a few mega- watts to more than 1000 MW, with the largest close to 3000 MW in capacity. Plants can be found in Australia and throughout Asia, across Europe and in Russia, but the largest aggregate capacities are in China, Japan and the United States. Many are used in conjunction with nuclear power plants so that the latter can operate at full power irrespective of demand. Some smaller plants are also used for peak shaving and load management duties independent of the availability of nuclear power. [14]

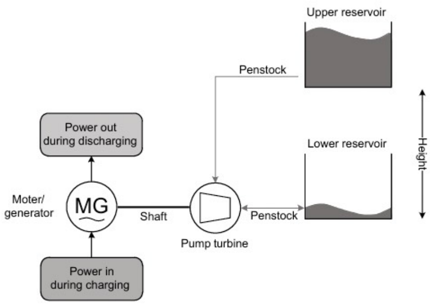

Figure 3. Schematic diagram of pumped hydro storage system

The technology used in pumped hydroelectric installations includes highly developed reliable devices such as electric generators and hydraulic turbines that allow the system to regulate vast power levels with high ramp power rates. The response time of the stations can be up to 10 minutes from complete stoppage to full power in both modes of operation pumping or recording electricity and generating electricity or discharging the recorder. From standby, full power can be reached during 10... 30 seconds. [5] For example, an installation by the First Hydro Company, commissioned in 1984, is capable of moving from 0 to 1320 MW power injection in only 12 s. [13] Technically, these systems are very mature already. Slight improvements in efficiency and costs can be achieved with advanced turbine and generator designs. The most important innovation in the last decades was the implementation of pumps with flexible operation. Older pumps can more or less only work at maximum power or they stop, whereas the newest generation of pumps is able to vary the pumping power over a wide range. This gives more flexibility and more efficiency to the pumped hydro power stations. [11] Due to technology development, PHES can also be used to frequency control in both pump and production mode. PHAJ can be used for capacity firming and to Black restart because it has high unit power and a sufficiently long discharge time. [5]

There is a huge global hydro-storage potential nowadays, estimated at approximately 3000 GW. In the European Union (EU) there is about 7400 MW of new PHES installations projected, which is a 20% increase in the EU's installed capacity. [13] However the deployment potential for new pumped hydro storage systems is limited in central Europe not only by insufficient topographic sites but also by environmental problems. The biggest potential for growth of storage capacity in Europe is the refitting of hydro storage plants with pump sets. The biggest challenge is to find suitable spaces for lower reservoirs. Rivers cannot be used very easily as dams have to be erected and the change in water level has an ecological impact. [11]

Alternative configurations are underground pumped hydroelectric energy storage (UPHES), having the same operating principle as PHES system: two reservoirs with a large head between them. The only major difference is the reservoir locations in UPHES facilities have the upper reservoir at ground level and the lower reservoir deep below the Earth's surface. The depth depends on the amount of hydraulic head required for a specific application. UPHES has the same disadvantages as PHES (large-scale required, high capital costs, etc.), with one major exception. As the lower reservoir is obtained by drilling into the ground and the upper reservoir is at ground level, UPHES doesn't have such stringent geological dependences. The major disadvantage for UPHES is its commercial youth, but all of technology key elements are used already for a long time. To date here are a very few, if any, UPHES facilities in operation. Its relatively large-scale storage capacity combined with location independence can provide storage with unique characteristics. [12] Such kind of zero terrain energy storage project are developing in Estonia in Paldiski with power of 500MW. Water tanks will be built about 575 metres deep. Water is taken from Pakri Bay and diverted to turbines to produce energy. Project approximately cost is 600 million and can be ready in 2029. [15]

A pumped-storage hydropower plant will depend for its revenue on being able to buy power at low cost and then sell it at a higher cost. The income will therefore vary depending on a wide range of conditions. From an economic point of view, the capital cost of building the plant will be the most important factor in determining its viability. This is likely to be relatively high because, like most hydropower plants, pumped storage is a capital-intensive technology. Capital costs are likely to be as high or higher than for a traditional hydropower plant are generally in the range €820/kW to €1650/kW. A 500 MW plant proposed for construction in California has an estimated cost of €0,9 billion and a capacity of 500 MW, or around €1800/kW. In contrast the Tianhuangping pumped-storage plant in Zhejiang province, China, cost €0,91 billion for 1800 MW when it came online in 2001, around $500/kW. Much of the difference can probably be accounted for by the lower labour costs in China. Small pumped-storage plants are likely to be relatively more expensive than larger installations. [14] Estonia 500MW PHES project cost planed at the level 1200€/kW which can be reduce to 300€/kW by the cost of granite which will mined during plant building.

1.2.2. Compressed air energy storage (CAES)

CAES systems are based on conventional gas turbine technology. Energy is stored in the form of compressed air in an underground storage cavern, at pressures between 40–70 bar at near-ambient temperature. Another possibility is to store the air in above-ground tanks. The air is additionally mixed with natural gas and combusted for increased efficiency. When energy needs to be injected into the grid, the compressed air is drawn from the storage cavern, heated, and then expanded in a set of highand low-pressure turbines, which convert most of the energy of the compressed air into rotational kinetic energy. Then, the rotational energy is converted into electrical energy in a generator. While driving the electrical generators, the turbine exhaust is used to heat the air in the cavern. Figure 4 show a descriptive schematic of the system. [13]

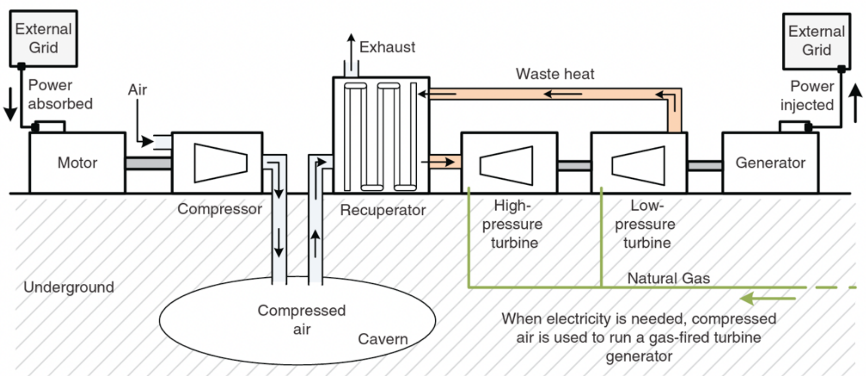

Figure 4. The operating principle of compressed air energy storage (CAES). [13]

The reservoir can be man-made, an expensive choice, or CAES locations are usually decided by identifying suitable natural geological formations. These include salt-caverns, hard-rock caverns, depleted gas fields or an aquifer. Salt-caverns can be designed to suit specific requirements. Fresh water is pumped into the cavern and left until the salt dissolves and saturates the fresh water. The water is then processed at surface to remove salt, and the cycle is repeated until the required volume cavern is created. This process is expensive and can take up to two years. Hard-rock caverns are even more expensive, about 60% higher than salt-caverns. Finally, aquifers cannot store the air at higher pressures therefore have relatively lower energy capacities. CAES efficiency is difficult to estimate, because they use both electrical energy and natural gas. It is estimated that the efficiency based on the compression and expansion cycles is in the range of 68%–75% for adiabatic technology. Typical CAES capacities are between 50 and 300 MW. CAES is used for large- and medium-scale applications. The life of these facilities is far longer than existing gas turbines and the charge/discharge ratio is dependent on the compressor size used and the reservoir size and pressure. [12]

CAES has a fast reaction time with plants usually able to go from 0% to 100% in less than 10 minutes, 10% to 100% in approximately 4 minutes and from 50% to 100% in less than 15 seconds. As a result, it is ideal for acting as a large bulk energy sink or supply, being also able to undertake frequent start-ups and shut-downs. CAES use compressed air so they do not suffer from the excessive heating effect of the conventional gas turbines, when operating on partial load. The CAES flexibilities mean that they can be used for ancillary services such as frequency regulation, load following and voltage control. As a result, CAES is a serious contender in the wind power energy storage market. [12]

There are just two CAES installations in the world so far, one in Germany, with a rated power of 290 MW and the other in Alabama, United States, with a rated power of 110 MW. [13] So CAES cost estimates must be considered tentative. However, it would appear to be an economically attractive. option for energy storage. Proposals within the last 10 years or so for conventional CAES plants in the United States have had installed costs of €329/ kW to €740/kW depending upon size and storage type. An adiabatic plant is likely to be much more expensive, with potential costs as high as €1400/kW. [14]

1.2.3. Flywheel energy storage

Flywheels store kinetic energy in a rotating disk that is mechanically coupled to the shaft of an electrical machine. When the machine accelerates – that is, operates as a motor – energy is transferred to the flywheel and stored in the form of kinetic energy. In opposite terms, the flywheel is discharged when the electrical machine regenerates through the drive; that is, when the speed of the system is reduced. [13]

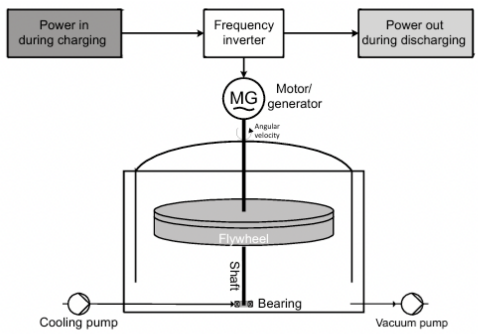

Figure 5. Schematic diagram of flywheel energy storage system

The energy capacity of the system is thus limited by the maximum and minimum operating speeds of the flywheel. The power capacity is limited by the maximum torque produced at the shaft of the electrical machine, which is directly translated into an electric current. Therefore, the ratings of the electrical equipment bound the maximum or peak power of the system. [13] Nowadays, flywheels are high-tech systems. All rotating parts are supported by advanced magnetic bearings in order to reduce friction at high speeds. Also, with the aim of reducing wind shear, the structure is placed in a vacuum. Moreover, advanced lightweight but high-strength composite materials are used in the rotating disk. In addition, an advanced high-speed electrical machine is included in the system. Commercially, axial-flux and radial-flux permanent magnet machines are most often used in flywheels. And, finally, the electric power exchanged with the grid at the connection point of the system is run through controlled electronic power converters. The main technical challenge therefore is to develop cost-effective components with low additional energy demand. Angular velocities vary from about 5000 per min to 100,000 per min. The higher the angular velocity, the smaller the radius of the rotating body. The materials have to withstand the centrifugal forces. [11] All this technology is used to configure two types of flywheels, depending on the rotational speed range. Low-speed flywheels operate in the range of thousands of revolutions per minute (rpm), while high-speed flywheels can reach speeds in the range of tens of thousands. [13] The development of high-speed flywheels is interesting due to lower losses and higher specific energy. There are also initiatives to develop low cost high mass flywheels with a higher energy capacity. [11]

The major advantages of flywheels are their high efficiency (around 90% at rated power), their very long cycling life (up to 10^7 cycles), their very high ramp power rates, and their high power and energy density. On the other hand, the use of flywheels is limited to short-term storage applications, as the self-discharge rate of the system is around 20% of the stored capacity per hour. Up to 50% of the stored energy can be lost within 5 - 10h. In fact, flywheels are only able to inject or absorb power at full load for a few minutes. [13] They can also be used for stabilization purposes in weak grids. For the integration of renewable energy in Europe flywheels have no major application, but in Canada and the United States projects for supplying power for at least 15 min have been realized for delivering grid services. [11] The adopted example is a flywheel plant for frequency regulation in New York, commissioned by Beacon Power. The system is comprised of 200 flywheel units of 100 kW/0.025 MWh, connected in parallel to increase the ratings of the plant up to 20 MW/5 MWh. All 200 flywheel units are connected in parallel. Accordingly, the power conversion system of the storage plant is comprised of 200 AC–DC–AC bidirectional power converters, one per flywheel unit, all connected on the grid side in a single common coupling with the external network. [13]

The commercial cost of a flywheel system is likely to be around €1650/kW although costs have been put as low as €400/kW. The cost per unit of stored energy is around

€400/kWh€800/kWh for commercial flywheel systems depending on the size. This puts the cost broadly equivalent to that of a battery storage system. However, the application of a flywheel storage system is likely to be different from that of a battery. [14]

1.2.4. Supercapacitor energy storage (SCES)

Historically capacitors have been the first storage technology to store electrical energy. The general principal is very simple: two conducting plates are placed face to face with each other separated by an insulating material. A DC voltage is connected across the capacitor, one plate being positive the other negative. The opposite charges on the plates attract and hence store energy. [12] When a supercapacitor is charged, the positively charged ions of the electrolyte - cations - move to the negatively charged electrode (-), creating a layer of positive charges on the surface, and the anions move to the positively charged electrode (+), creating a layer of negative charges. In the supercapacitor, the charges are collected from the electrode surface through current collectors, and when the + and - together are connected in the external circuit, discharge takes place and the ions move to the depth of the solution. Like its shown on a figure 6. [5]

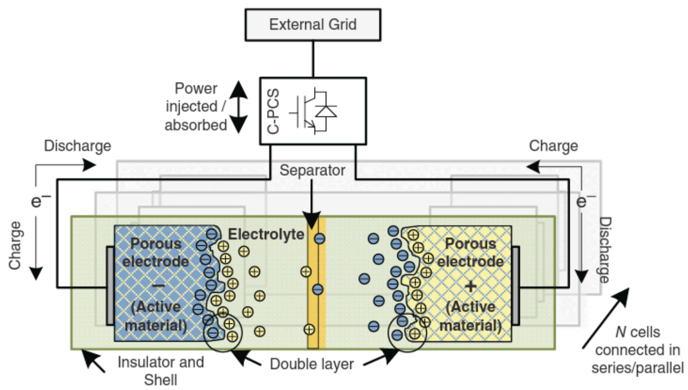

Figure 6. The illustrative topology of a supercapacitor, depicting the electrical double layers at each electrode/electrolyte interface [13]

The amount of stored energy depends on the size of the plates, the distance between the plates, and dielectric properties of the material between the plates. An important parameter for the amount of stored energy is the dielectric constant of the insulating material between the electrodes. Highest dielectric constants can be achieved based on titanates with calcium, strontium, bismuth, or barium. [11] Having huge surface areas, leading the capacitances of tens, hundreds or even thousands of Farads, with the capacitor that can be fitted into a small container of the size of a beer can. However, the problem with this technology is that the voltage across the capacitor can only be very low, usually lower than 3 V. In order to store charge at a reasonable voltage several capacitors are usually connected in series. [12]

The capacitors can provide large energy storage capabilities; they are used in small size configurations as components in electronic circuits and systems. The large energy storing capacitors with very large plate areas are the so-called supercapacitors or ultracapacitors. [12] There are several capacitor technologies available on the market such as ceramic, foil, and electrolyte capacitors and electrochemical double-layer capacitors. These technologies are well suited to applications with very high frequency of charge/discharge cycles (ranging from 1 Hz to megahertz). However, this technology cannot support the integration of renewable energies or serve any other stationary application in the sense of an energy storage system. [11]

Electrochemical capacitors have been used both for energy storage and for braking energy recovery systems in automotive applications. They have relatively high specific power and relatively low specific energy. Supercapacitors are inherently safer than flywheels as they avoid the problems of mechanical breakdown and gyroscopic effects. [12] For grid use, they are best suited to backup or fast reaction grid support, offering a similar performance to flywheels. Although capacitors are not yet widely deployed for grid support, they have been tested in a number of configurations. These include adding rapid response storage to small distributed generation grids or microgrids where they can provide fast reacting grid support when the output from intermittent renewable resources suddenly falls and before a backup engine-based system can take over. Capacitors are also being tested for high voltage grid support services. [14]

The cost of capacitor storage is likely to be similar to that for flywheels at around €1650/kW. Based on the cost per unit of energy storage, the price is again expected to be similar to that of flywheels with costs of around $400-800/kWh. However, some manufacturers have claimed that they can produce devices for as little as $80/kWh. Such a low price is likely to depend on high volumes, perhaps for use in the automotive industry where they might replace batteries. [14]

1.2.5. Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) is a technologically advanced method of storing energy in a magnetic field, which is formed when a current flows around a coil. In order for this to operate efficiently as an energy storage system, the coil must be made of a superconductor that has no electrical resistance so that there are no resistive energy losses as the current circulates. The superconducting materials needed to create the energy storage coil are expensive and the best of them available today must be cooled cryogenically to close to absolute zero temperature before they become superconducting. Higher temperature superconductors are available too but they tend to be less effective. [16]

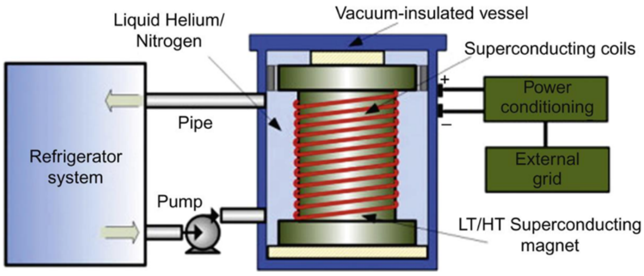

Figure 7. Schematic of distributes SMES system [16]

Storage of energy based on superconducting rings offers perhaps the highest roundtrip efficiency available of all energy storage systems. However, the cost of maintaining the extremely low temperature of the coil increases the operating costs over time and reduces overall efficiency. Even so, SMES has been proposed for load leveling services similar to those offered by pumped storage hydropower plants. SMES is also one of the fastest acting and highest current density storage systems available. [16]

Practical SMES energy storage systems for grid applications were developed at the end of the 1980s. These are relatively small and have been used for grid support and power conditioning. Most can supply 1 MW or less of power. Larger systems have been tested and there have been proposals for massive SMES storage systems, capable of providing an output of 1000 MW or more. No such storage ring has ever been built but smaller SMES devices are being used for grid support roles and this appears to be the main commercial market. However the physical structure needed to contain the enormous magnetic forces generated by such a coil would be massive and such large systems have not so far proved to be economical enough to consider construction. To date, it is the smaller systems that have found commercial success, normally in grid support functions or for power conditioning. [16]

Figure 8 shows a diagram of a typical small commercial SMES system that might be used for grid stability applications. In this type of system the small SMES storage ring is built into a container for ease of transportation and installation. The storage ring is connected to the electricity distribution system at the site where it is needed. Power from the grid is used to drive the cooling system that maintains the actual storage ring below its critical temperature. The SMES ring is then charged from the grid. In this case the ring will be used for grid stability support or power conditioning. Sensors will detect the condition of the grid and if there are frequency, voltage, or phase fluctuations, power can be drawn from the ring to correct the instability. [16]

Due to the limited application areas, SMES systems will hardly become competitive with other technologies for storing renewable energies. They may find their market e.g., for supplying short-circuit currents for power switches in grids. [13] Current technology will allow small commercial SMES storage units with capacities of between 100 kW and 100 MW to be constructed; the largest built unit to date can deliver 10 MW. The storage capacity of these commercial devices is between 10 and 30 kWh, relatively low for utility storage but useful for very fast grid support functions. One of the earliest SMES devices to be used commercially was commissioned by the US Bonneville Power Administration in the 1980s. This unit had a storage capacity of 30 MJ and a power rating of 10 MW. The device could release 10 MJ of energy in one-third of a second to damp power swings on the Pacific Intertie. Today a typical commercial unit has a storage capacity of 3 MJ (0.83 kWh) and can deliver 3 MW of power for 1 second.

Although a few commercial SMES devices are available, costs have been difficult to establish. In general the cost is relatively low per unit size (MW) but high in terms of storage capacity (MWh). For short-term grid stability duty, they appear to be competitive with other types of storage such as batteries, flywheels and capacitors. [14] The price could be in range €165-€400/kWh. [9]

1.2.6. Hydrogen energy storage

Hydrogen offers a potential energy storage medium because of its versatility. The gas can be produced by electrolysis of water, making it easy to integrate with electricity generation. Once made, the hydrogen can be burned in thermal power plants to generate electricity again or it can be used as the energy source for fuel cells. In both cases the only combustion product is water. Potentially it may also be used as an automotive replacement for petroleum or natural gas. Finally, hydrogen has a high-energy density making it an efficient means of storing energy. For all these reasons hydrogen has been seen as a potential fossil fuel replacement in a future energy economy. [14] The most common option for the production of hydrogen is from coal or other fossil fuels. However, it can also be obtained by means of water electrolysis, from various forms of renewable energy, and from gasifying biomass. [13]

The electrochemical decomposition of water to produce hydrogen and oxygen is a quite simple process as depicted in figure 8. Two electrodes in a basic electrolyte are connected to a direct current (DC) supply. Once a sufficient high cell voltage is applied to the cell the redox reaction takes place producing hydrogen at the cathode (negative electrode) and oxygen at the anode (positive electrode).The principle of electrochemical decomposition of water in an EL cell has already been known for more than 200years. Alkaline electrolyzers are well known and available as rugged devices. Large-scale alkaline electrolyzers have been built to supply hydrogen for ammonia plants. Smaller electrolyzers are common and are used to remove oxygen from boiler water. [3]

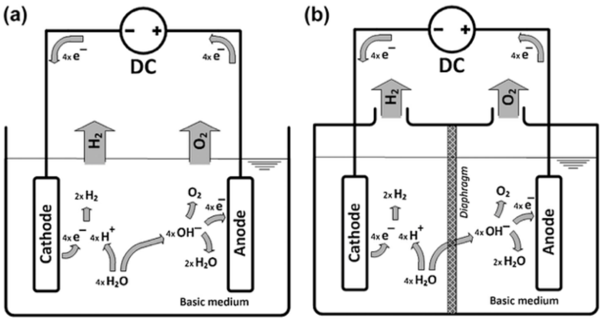

Figure 8. (a) Basic principle of an open EL cell in basic medium. Stoichiometric factors are related to the generation of one molecule of oxygen. As the half-cells are open oxyhydrogen is produced. (b) Deploying a semipermeable diaphragm between the two half-cells allows the separation of the two gases. [11]

The hydrogen can cover energy capacities up to very large capacities and offers a broad power range. That storage type is applicable at the community level, in the distribution grid and also for areas of high population density and at the transmission grid level. Depending on the volume of gas to be stored, and the local conditions, gas storage is either on the surface, such as tube storage, or underground, preferably in salt caverns. Hydrogen-based energy storage systems allows for a wide bandwidth of applications ranging from domestic application till utility scale applications. The power output could start as low as in the kilowatt class like in fuel cell applications; it can also reach several hundreds of megawatt in large-scale combustion turbine-based energy storage systems. [11]

Once the hydrogen has been produced, it can be transported through pipelines to the users to produce electricity, or stored in order to be used later in fuel cells. The so-called regenerative fuel cell (RFC) [7.86] comprises the production process of hydrogen using a water electrolyzer, a hydrogen storage medium, and a fuel cell system, which allows the production of electricity from the stored hydrogen. This is the considered topology in this work for the HESS. In this case, the electric power from wind facilities could be used to feed the electrolyze to produce the hydrogen. Figure 9 depicts the presented concept. [13]

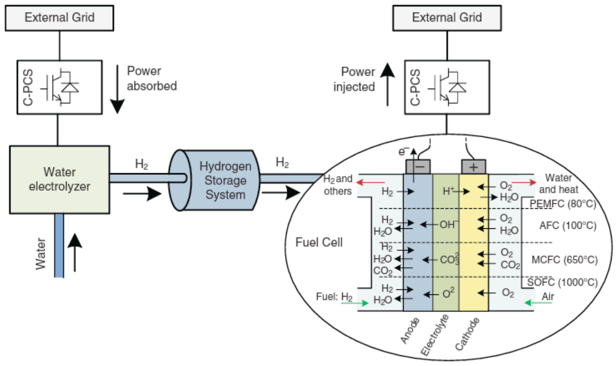

Figure 9. Practical use of HSS [13]

Some of the principal elements of RFCs that are attracting much attention nowadays with regard to R&D are the electrolyzer and the fuel cell, since their performance is critical in order to maximize the overall energy efficiency. As previously noted, the electrolyzer, by using an electricity source, converts water (e.g., 1 mole) into hydrogen (1 mole) and oxygen gas (a half-mole). Then, this hydrogen serves as a "'fuel" in the fuel cell, in conjunction with oxygen gas, to produce electricity, water, and heat, as products of the electrochemical reaction in the cell. Thus, the electrolyze and the fuel cell perform the same reactions but in opposite directions. This is why some fuel cell technologies are also used as electrolyzes by reversing the electric current flowing through them. As electrochemical cells, fuel cells are comprised of two electrodes and an electrolyte, which enables ion exchange between them. The anodic and cathodic regions are separated by a polymeric membrane. The types of electrolyte are diverse and determine the performance of the cell; for example, the pressure of the hydrogen produced and the operating temperature. Electrolytes can be liquid or solid. Conventional electrolyzes use liquid alkaline electrolytes, while modern ones use solid electrolytes. The latter type is known as the proton exchange membrane fuel cell (PEMFC). Depending on the sizing of the system, different types of fuel cells can be used. [13]

For instance, the PEMFC, which is the most used technology (it operates at 80 ◦ C), is preferable for industrial applications, as stacks of 100 kW of rated power can easily be found on the market. For high-power applications (in the range of MW), the so-called solid oxide fuel cell (SOFC) – which operates at 650 ◦ C – is a good option, as 2 MW stacks can be found on the market. [13]

There are several ways to store hydrogen: it can be stored in gaseous or liquid form. The storage of hydrogen gas in metal tanks is currently the most mature, cheapest, and most reliable method. In this way, hydrogen can be stored for several hours (up to 30 h) without noticeable losses. Modular designs of RFC can be built up to 10 MW/100 MWh storage systems. As flow batteries, the energy capacity of the system depends on the stored volume of, in this case, hydrogen. This means that RFCs are able to inject or absorb power continuously for several hours. The remarkable characteristics of this technology are its high ramp power rates, even at partial load, and its great cyclability, which is greater than the cyclability of flow batteries and conventional batteries. On the other hand, the high flammability of hydrogen gas must be properly addressed by adequate safety measures. The major drawback of the technology, however, is its low energy efficiency. Assuming energy efficiencies for the electrolyze and the fuel cell of about 60 and 70%, respectively, the round-trip efficiency of the system falls to 42% [13]

Because hydrogen energy storage as an electrical energy storage medium has yet to be tested, there are no realistic costs available for practical systems. If it is to be of use, it would need to be able to compete with the high-storage capacity technologies such as pumped-storage hydropower, CAES of large battery storage. [14] Cost analysis show that the price for kW power could be around in range €400-€10000/kWh. [9]

1.2.7. Battery energy storage system (BESS)

The batteries are at the present the most practical and widely used electricity storage systems. The terms battery and cell are often interchanged, although strictly a battery consists of a group of cells connected together and built as a single unit. Batteries are classified into primary (non-rechargeable) and secondary (rechargeable).
Chemical energy storage can be further classified into electrochemical and thermochemical energy storage. The electrochemical energy storage refers to conventional batteries, such as lead-acid (LA), nickel–metal hydride, and lithium-ion (Li-ion), and flow batteries, such as zinc/bromine (Zn/Br) and vanadium redox and metal air batteries.
A battery energy storage system (BESS) converts electrical energy into potential chemical energy while charging, and releases electrical energy from chemical energy while discharging. In general terms, it is based on reduction and oxidation reactions (commonly called redox reactions). An electrochemical reduction reaction is one that allows the component involved to gain electrons, while an oxidation reaction allows the component to lose electrons.

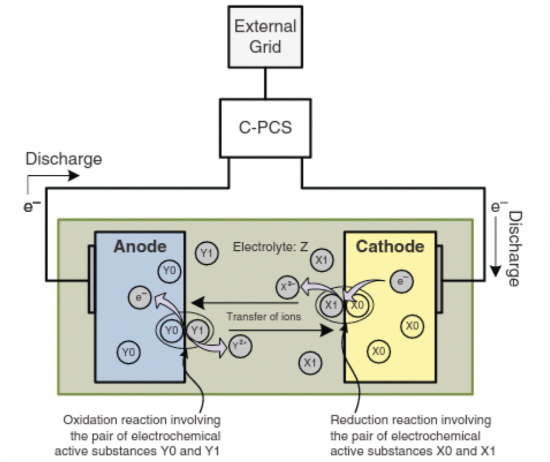

Figure 10. The operating principle of battery

As shown on a figure 10 the battery cell is composed of two electrodes, made up of two materials called Y0 (for the anode) and X0 (for the cathode). They are both surrounded by the electrolyte, Z. Also, the anode (negative electrode) is surrounded by the substance or component Y1. Similarly, the cathode is surrounded by the component X1. Then, the battery is being discharged, and this means that redox reactions start to occur, yielding an electric current through the load. The electrons flow from the negative electrode (the anode, the region with the maximum energy state) to the positive one (the cathode, the region with the minimum energy state). These electrons, and the positive ions Y2+, are the result of the oxidation reaction between substances Y0 and Y1. The electrons are collected by the catholyte electrode, yielding a reduction reaction between substances X0 and X1, which in turn results in the ion X2− . The internal circuit allows the ionic exchange. The ion(s) exchanged depend on the technology used and are usually those presenting the highest mobility. As a result of this process, each of the pairs of electrochemically active substances is weakened, so the electric potential between them is diminished. The electrical potential between the two electrodes can be restored by reversing the flow of the electric current, and hence by applying an external energy source to charge the battery. [13]

Lead-Acid Batteries

Lead-acid batteries were among the first secondary cells to be developed and were used for load levelling in very early power distribution systems. They are the most common electrical energy storage device used at the present, especially in transportation, renewable energy and stand-alone hybrid power systems. Its success is due to its maturity (research has been ongoing for about 150 years), low cost, long lifespan, fast response and low self-discharge rate. They are used for both short-term (seconds) and long-term applications (up to 8 hours). [3] The cell is based on a reaction between lead oxide and Sulphur acid. Efficiencies of lead-acid batteries vary depending on factors such as the temperature and the duty cycle but are typically between 75% and 85% for DCDC cycling. However, cells discharge themselves over time, so they cannot be used for very long-term power storage. If cycled carefully, cells for utility applications can have lifetimes of 15-30 years. [14]

There are two lead-acid battery types: flooded lead-acid (FLA), and valve-regulated lead-acid (VRLA). FLA batteries, described above, are made up of two electrodes (lead plates), immersed in a mixture of water (65%) and sulfuric acid (35%). VRLA batteries have the same operating principle as FLA batteries, with the difference that they are sealed with pressure-regulating valves, to prevent the air entering the cells and hydrogen venting. FLA batteries have two primary applications: starting and ignition, short bursts of strong power, e.g., car engine batteries and deep cycle, low steady power over a long time applications. VRLA batteries are very popular for backup power, standby power supplies in telecommunication centers and for uninterruptible power supply. From application point of view, the lead-acid batteries split into stationary, traction and car batteries. Stationary batteries ensure uninterruptible electric energy supply, in case of the power system failure, undergoing usually only few cycles, so have about 20 years life time. Traction batteries, used for power supply of electric vehicles, electro-mobiles or industrial tracks, etc. are working in deep cycle charging-discharging regime with the lifespan of about 5 years (about 1000 charge-discharge cycles). Automotive (car) batteries, used to crank car engine, being able to supply short and intense discharge current, and also to support car electrical devices, when the engine is not running. [12]

Several very large-energy storage facilities based on lead-acid batteries have been built. These include an 8.5 MW unit constructed in West Berlin in 1986, while the city was still divided into East and West and a 20 MW unit built in Puerto Rico in 1994. Although the former operated successfully for several years, cell degradation led to the latter closing after only 5 years. Lead-acid cells have been very popular for renewable applications such as small wind or solar installations where they are used to store intermittently generated power to make it continuously available. [14]

Lithium Batteries

During the last years, lithium-ion batteries have undergone an increasing deployment in stationary power applications, driven by the significant experience gained from their development in other types of applications, such as electric and hybrid vehicles. [3] Lithium batteries including both lithium-hydride and lithium-ion batteries have become popular for consumer electronic devices because of their low weight, high-energy density and relatively long lifetime. [14]

The typical configuration of lithium-ion batteries consists of a positive and a negative electrode, separated by porous polymeric materials and immersed in an electrolyte. The positive electrode contains a metal ion (such as Co, Ni, Mn) and oxygen, the negative electrode is made of carbon material such as graphite, while the electrolyte consists of lithium salts in organic liquid. Lithium ions are extracted from the cathode and inserted into the anode during the charge process, and the reverse reaction occurs during the discharge process. [17]

Regarding the disadvantages of Li-ion batteries, one of the main issues is the heating of their internal resistance, which can cause battery's failure. Environmental issues can also arise due to the fact that lithium is highly reactive and flammable, while some electrodes and electrolytes are toxic. At last, the cycle DOD can have a negative impact on the battery's lifetime, while they are fragile with their life cycle being temperature-dependent. Beside, Li-ion batteries feature the highest energy density, thus offering a huge potential for deployment in a wide range of energy storage systems. Li-ion technology presents other advantages, including high power density, high efficiency, long cycle numbers, low discharge rate as well as no-memory effect. Additionally, Li-ion batteries are characterized by stable discharge voltage, wide operating temperature, high level of safety and they possess a comprehensive cycle efficiency in the range of 85%. Compared to aqueous battery technologies, they are lightweight and present packaging flexibility. Their cathode material is of low cost and they do not have significant environmental impact since the lithium oxides and salts are recyclable. Other important advantages are their high specific energy, the rapidly lowering costs. [17]

The use of lithium batteries in grid and utility applications is beginning to grow with units being tested in a number of locations. An early large pilot battery storage installation rated at 2 MW was commissioned on the Orkney Islands, which are located off the coast of north-western Scotland, in 2013. This was topped in 2017 when the US utility San Diego Gas and Electric opened a 30 MW battery storage facility based on lithium-ion batteries with 120 MWh of storage capacity. A 20 MW facility is also being planned by the utility Southern California Edison. The future development of lithium batteries may benefit from interest by automotive manufacturers in their use in hybrid and electric vehicles. [14]

Nickel Cadmium Batteries

The nickel cadmium battery is one of the families of nickel batteries that include nickel metal hydride, nickel iron and nickel zinc batteries. There is also a nickel hydrogen battery in which one cell reactant is gaseous hydrogen. All have a nickel electrode coated with a reactive and spongy nickel hydroxide, while the cell electrolyte is almost always potassium hydroxide. Cell reactions vary depending on the second component. [14]

The only nickel-based cell that has been exploited for utility applications is the nickel cadmium cell. Nickel cadmium batteries have higher energy densities and are lighter than lead-acid batteries. They also operate better at low temperatures. However, they tend to be more expensive. This type of battery was used widely in portable computers and phones but has now been superseded by lithium-ion batteries. Efficiencies of nickel cadmium cells are typically around 70% although some have claimed up to 85%. Lifetime of the batteries tends to be rated at around 1015 years although some have lasted longer. These cells discharge themselves more rapidly than lead-acid cells and can lose 5% of their charge in a month. There can also be a problem with disposal because cadmium is highly toxic. The largest nickel cadmium battery ever built is a 40MW unit in Alaska which was completed in 2003. It occupies a building the size of a football field and comprises 13,760 individual cells. [14]

Sodium Sulphur Batteries

The Sodium Sulphur battery is a high-temperature battery. It operates at 300^{0}C and utilizes a solid electrolyte, making it unique among the common secondary cells. One electrode is molten sodium and the other molten Sulphur, and it is the reaction between these two that is the basis for the cell reaction. The cross section of a sodium Sulphur battery is shown in Figure 10.4. Although the reactants, and particularly sodium, can behave explosively, modern cells are generally reliable. However, a fire was reported in 2012 at a sodium Sulphur battery installation in Japan. [14]

Early work on the sodium Sulphur battery took place at the Ford Motor Co in the 1960s, but modern sodium Sulphur technology was developed in Japan by the Tokyo Electric Power Co, in collaboration with NGK insulators, and it is these two companies that have commercialized the technology. Typical units have a rated power output of 50 kW and 400 kWh. Lifetime is claimed to be 15 years or 4500 cycles, and the efficiency is around

85%. Sodium Sulphur batteries have one of the fastest response times, with a claimed start-up speed of 1 ms. [14]

The Flow Battery Energy Storage System (FBESS)

As in the case of conventional batteries, the operating principle of flow batteries (FBESS) is based on the electrochemical reactions that occur in electrochemical cells. However, flow batteries differ from conventional ones in the fact that the electrolyte is not permanently stored in the cells but, instead, two aqueous electrolytic solutions (A and B) are contained in separate tanks. During the charging process, these aqueous solutions are pumped through the electrochemical cells, where the electrochemically active material dissolved in electrolyte A is oxidized at the anode, and the electrochemically active material in electrolyte B is reduced at the cathode. The discharge cycle comprises the reverse process. Figure 11 depicts the operating principle of flow batteries. There are three main types of flow batteries: the vanadium redox battery (VRB), the zinc–bromine battery (ZBB), and the polysulfide bromide battery (PSB). [13]

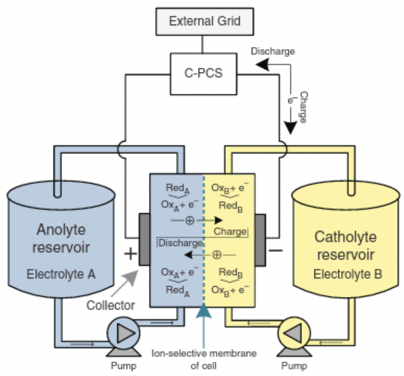

Figure 11. The operating principle of flow batteries. [13]

Vanadium Redox Flow (VRF)

Vanadium redox flow (VRF) batteries are the most widely employed flow batteries. One of the most prominent advantages of VRF batteries is the use of vanadium electrolyte, which eliminates cross-contamination issues. Other advantages are: large number of cycles, flexibility in the design of power and energy capacities, low standby losses and simple cell management. Further advantageous characteristics are the operation at increased current densities and wide range of temperatures, the possibility to provide continuous power with a discharge duration time longer than 24 h, the ability to be brought up to full power promptly and high energy efficiency. Additionally, VRF batteries do not cause significant safety and environmental issues because they do not employ highly reactive or toxic substances, they have low maintenance cost and can be idle for long time periods without losing their storage capacity. Additional advantages include: large storage capacity, high power output, high energy conversion rate and suitability for large-scale energy storage. An important aspect of BESSs based on VRF technology is the possibility to design power and energy ratings independently. Furthermore, an inherent strength of VRF batteries is their very small self-discharge. Since the active materials are separated from the reactive point source, VRF batteries are also safer. [17]

As far as their disadvantages are concerned, VRF batteries are relatively expensive. Due to the complexity of the system structure, VRF batteries are not suited for small-scale storage applications. Rather, they are more suitable for peak-shaving and energy time-shifting applications, due to the relatively low energy density of the vanadium electrolyte. Another drawback is their low performance due to the non-uniform pressure drops and the reactant mass transfer limitation and their high initial self-discharge rat. Finally, an additional disadvantage is the high cost of the vanadium electrolyte. [17] The concept of redox flow Li-ion battery (RFLB) has been addressed in several publications as a solution to low energy density. Combining the safety and flexibility of the redox flow batteries and the high energy density of Li-ion batteries, RFLB can potentially improve the energy density of redox flow batteries by more than 10 times. [17]

The Zinc–Bromine Battery (ZBB)

As in the case of the VRFB, the electrodes of ZBB cells are based on a carbon plastic composite. The separator between the anodic and cathodic regions is made up of polyolefin sheets. The electrolyte is aqueous, containing dissolved zinc bromide salts. Zn is the active chemical species at the anode (the negative electrode), while Br is located at the cathode (the positive electrode. [13]

The Polysulfide–Bromide (PSB)

Flow Battery In PSBs, the electrodes are based on a carbon–plastic composite. The separator between the anodic and cathodic regions is made up of polyolefin sheets. The aqueous electrolytes are based on sodium polysulfide Na2Sy in the anodic region, and sodium bromide NaBr in the cathodic one. [13]

Flow batteries can be fully discharged without any damage, and in terms of cyclability, they present better characteristics than conventional batteries. For instance, the VRF battery can achieve 13 000 charge and discharge cycles at 100% of DoD, with a relatively high energy efficiency of 78%. Turning now to the economics, the cost of these batteries is comparable to that of NaS batteries (around 400€/kWh in the case of the ZBB, for instance). In fact, in general they are cheaper than Li-ion or Ni–Cd batteries. Another common characteristic of these types of batteries is the fact that they require very low maintenance, specially in the case of the VRB, as it uses the same electrolyte in the anode and the cathode, avoiding the risk of cross-contamination of the aqueous solutions. [13]

Finally, we should note that this is not a mature technology yet, especially in the case of the PSB. In fact, amongst the three types of flow batteries reviewed in this chapter, the PSBs are the least developed, with just a couple of pilot plants worldwide. In 2003, Regenesys Technologies built a pilot plant in South Wales, rated at 15 MW/ 120 MWh. However, with a project budget of around €205 million, the system was never fully commissioned. VRB Power Systems, Inc., founded in 2004, was acquired by Prudent Energy in 2009: currently, no specific reference to PSB technology can be found in the company’s product brochure. [13]

The costs of battery systems vary widely depending on type and size. Large batteries are generally cheaper than similar small installations. Battery costs are normally based on the cost per kilowatt-hour rather than the cost per kilowatt and shown in table 2. [14] Battery prices are reducing every year due to technology development. According BloombergNEF’s Battery Price Survey average pack prices in 2020 have sat at around €111/kWh, 89% lower than in 2010. BloombergNEF’s predicts that pack prices for stationary storage will fall to €82/kWh within three and cold fall to €55/kWh by the end of the decade. [18]

Table 2. Prices for different types of batteries [14]

	€kWh min	€kWh max
Sodium Sulphur batteries	200	750
Lead-acid batteries	400	1000
Lithium-ion batteries	330	900
Flow batteries	330	800

1.3. Energy Storage System (ESS) services

The use of energy storage systems in utility networks has become increasingly important and focused on as more storage options become available. Energy storage deployed at any of the five major subsystems in the electric power systems, i.e., generation, transmission, substations, distribution, and final consumers, can help balance customer demand and generation. Intermittent power generation, such as that provided by many renewable energy sources, results in power instability which can damage grid equipment such as generators and motors. By combining renewable energy systems with energy storage technology, renewable energy penetration is increased and overall system performance improves, while flexibility is provided for grid control and maintenance. [9] Some of the applications of energy storage systems present in figure 12.

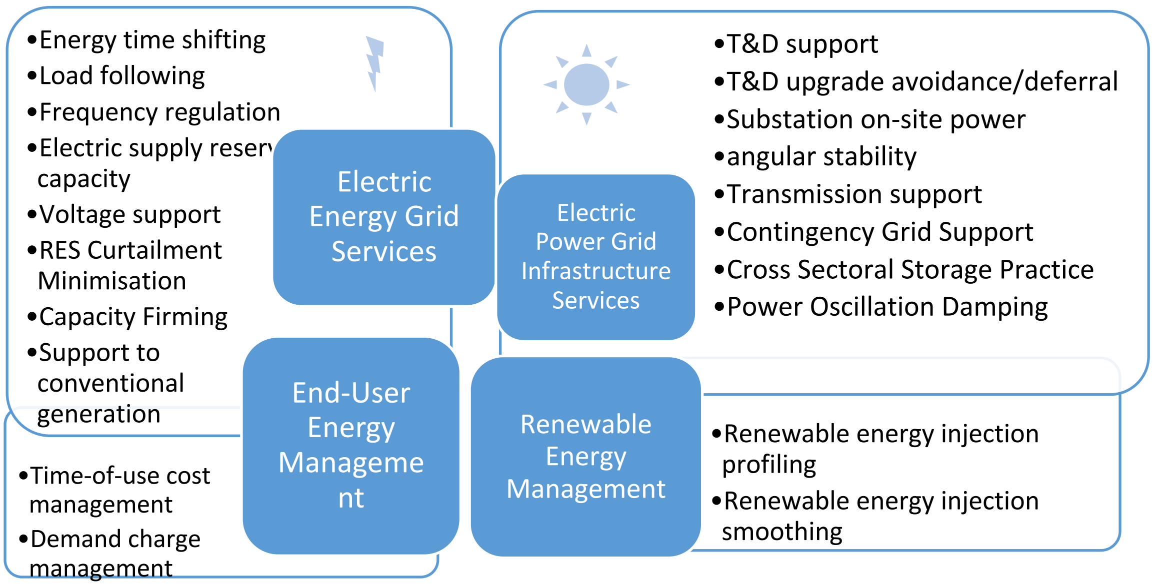

Figure 12. Different type of services by providing ESS

1.3.1. Electric Energy Grid Services

Electric energy grid services are the set of applications of ESS to services that can be provided by electric energy storage to the transmission and distribution grids. Such services can be offered either by utilities or by other potential players, different from traditional grid operators, that can seek revenue generation by operating assets to by and sell electricity in the regulated markets. [7]

Energy time shifting entails the arbitraging of energy by buying electric energy after having changed the ESS at of-peak prices, and selling electric by discharging the ESS

at peak price. Due to the economic nature, high conversion efficiency and low operating cost for ESS are mandatory to avoid the reduction of the revenues coming from differentials between peak and off-peak prices. The use of ESS for energy time-shifting improves the stability of the electric grid by acting as a balancing system. [7]
In future will be Seasonal Arbitrage that is the practice of taking advantage of an electricity price difference in the wholesale electricity market between 2 seasons: Use of storage to charge energy at low price in summer and discharge it at high price in winter.

Load following is the service need to compensate the variations in grid power needs that occur as frequently as every several minutes due to changes in hourly load curves or in power flows from generation between interconnected grids. Load following is up as power output is increased to match an increase in demand, or down if power output must decrease or reduce power supply in case of diminishing load needs. [7]

Frequency regulation is the service provided for the stabilization of the grid frequency that varies as a result of short-term, continuous differences in demand and supply. If power injection and power absorption to and from the grid are not balanced, the energy network becomes unstable and unrealisable. Power units connected to the grid must therefore increase their power output to supply the additional load - up-regulation, when the power units must decrease their power injection due to an increase of power supply – down-regulation. Grid frequency value is constantly monitored by the grid operator to trigger free kinds of response: primary frequency control, secondary frequency, tertiary frequency. [7] The frequency stability of weak grids objective is to maintain the frequency stability by helping to avoid load shedding in islands due to the feasible very prompt response of distributed energy storage systems (DESS). This application is mainly devoted to Small Islands where the FFR service is not always defined or used.

The *electric supply reserve capacity* is the reserve capacity that can be made operational in the short term to compensate when part of normal power supply becomes unavailable. It consist of power generation units that are normally disconnected from the greed but can be connected quickly when there is an unexpected surge in demand or after the inception of technical problems. The service is also known as short-term operating reserve (STOR), and entails three levels of intervention spinning reserve, non-spinning reserve and supplemental reserve is a buck-up capacity that can be made available to the grid in time-frames to 30 min to 1 [7] Typically in electric grids, the reserve capacity is 15-20% of the total capacity normally available. Frequency regulation can be considered within the STOR reserve as regulating reserve.

Load following, frequency regulation and STOR are difficult to be performed by large thermoelectric power units due to operating cost and reduced asset life time. ESS on the contrary, are particularly suited for such application due to their fast response times and quick switching between charging and discharging modes. [7]

Voltage support is the stabilization of the grid voltage level by compensating for the changes in the reactance caused by the different combination of inductive or capacitive loads connected to the grid. ESS can act as devices that absorb or inject reactive power. ESS are indeed capable of operating either in charging or discharging mode while at the same time providing VAR capability. [7]

RES Curtailment Minimisation is use of energy storage to absorb variable RES (wind or solar) that cannot be injected into the electricity grid due to lack of demand, either delivering it to the electricity grid when needed or converting it into another energy vector (gas, fuel or heat) to be delivered to the relevant grid. [10]

Capacity Firming is the use of energy storage to render variable RES output more constant during a given period of time. Energy storage is used to store variable energy production (wind or solar) during hours of peak production regardless of demand. This energy is then discharged to supplement generation when the variable energy unexpectedly reduces its output. [10]

Support to conventional generation is related to optimizing operation of conventional generation assets: Generator bridging: the ability of energy storage systems (ESS) to pick up a generator load while the generator is stopping, until a new generator starts up or the same generator is restarted. ESS can also avoid stopping the unit by charging in moments of low load. Generator ramping: the ability of ESS to pick up strong and fast load variations, giving enough time for a given generator to ramp up or down its production level. [10]

1.3.2. Electric Power Grid Infrastructure Services

Electric Power Grid Infrastructure Services concern the use of electric energy storage by utilities to support and maintain their transmission and distribution (T&D) power line operations.

T&D support is a set of services to maintain optimal functioning of the transmission grid. One typical service is the Black Start of transmission lines or power components that can be provided by ESS to reenergize transmission lines and transformers after grid maintenance stops or crashes. Since power flow in transmission lines is a function of line impedance, certain power systems can experience frequency-deviation effects that can cause instability phenomena. Transmission stability applications usually require power-intensive rather than energy-intensive ESS, while black-start ESS need to have large capacities to recharge the grid and power components. [7]

T&D congestion relief applications aim at avoiding the congestion-related costs when transmission lines are subject to power overdrawn. This service shaves the peak above a pre-determined power threshold by discharging a locally installed ESS that is charged when the transmission line is less congested. [7]

T&D upgrade avoidance/deferral is the possibility, granted by ESS, to delay or avoid the grid system upgrade when the connection of additional loads nears the grid maximum load-carrying capacity as per initial system design. In case peak loads were reached only for a few hours during the week or even months, installing ESS to serve those incremental loads could avoid investments in reinforcement of power lines or new equipment. ESS would add the increased capacity directly close to the loads to be served, creating a more decentralized electric power system with additional benefits on the system reliability and quality of service. [7]

Substation on-site power applications entail the use of ESS for stand-alone, isolated energy supply systems for telecom stations, control sites, power switching components, desalination plants, homes, that would have to be connected to a distribution line but at costs that would make construction unfeasible. As a result, use of ESS makes electrification in rural areas possible. [7]

Participation to *angular stability* is use of energy storage to charge and discharge high levels of energy in short periods when an accident occurs; this may contribute to reduce the load-angle variations, thereby improving angular stability of the system. [10]

Transmission support the objective is to use energy storage to improve the performance of the transmission system by compensating for electrical anomalies and disturbances such as voltage sag, unstable voltage, and sub-synchronous resonance. [10]

Contingency Grid Support the objective is to use energy storage to perform some capacity/voltage support in order to reduce the impacts of the loss of a major grid component. It refers to redundancy provisions to cover the trip of the largest transmission line into an area. [10]

Cross Sectoral Storage Practice of coupling the electricity sector with other energy sectors (gas, fuel, heat) by converting excess supply of electricity to the grid into energy carriers, synthetic fuels, and heat, thus avoiding curtailment of running power generators (RES, thermal power plants, etc.). [10]

POD (*Power Oscillation Damping*) using energy storage to damp electro mechanics oscillations in the system. In large interconnected electric power systems, inter-area electromechanical oscillations may occur due to weak links among power systems. [10]

1.3.3. End-User Energy Management

End-User Energy Management is the set of services that ESS can provide to final users like residential, community or individual customers.

Time-of-use cost management (TOU), also called energy shifting, involves charging of ESS during off or partial peak hours and its discharging during peak hours to save on electricity costs. Knowledge of peak, partial and off-peak prices, and time ranges is straightforward for small customers and ESS programming is easily feasible. [7]

Demand charge management, very often referred to as peak shaving, is the provision of electric power to save on the electricity price apportioned to supplied total power. If the ESS is discharged when power draw overcomes a predetermined threshold, the power is supplied by the ESS rather than the grid therefore reducing the maximum power supplied to the end user by the grid operator. Usually, power draw is checked over a 15-min period and billed monthly. Shaving the 15 min highest monthly power draws above a certain threshold can result in substantial savings. [7]

Power quality and reliability services provide fast response power and energy injection to maintain high standards of the quality of service (QOS) in the customer grid. In case of long outages, ESS can be used to provide uninterrupted service (like emergency back up) for residential customers or maintain stable production output for industrial customers or provide enhanced safety and damage avoidance by safe machine shut downs. [7]

1.3.4. Renewable Energy Management

Renewable energy sources have synergies with ESS that increase their value for the over-all energy system and reduce the need to rely on traditional fossil fuel energy generation.

Renewable energy injection profiling, also called time-shifting, makes it possible to choose when energy from renewable sources can be injected in the grid. This can be useful to improve renewable energy asset profitability as well as controlling the energy flow to the grid to avoid injection when demand is lower than supply. [7]

Renewable energy injection smoothing consists in filtering the uneven energy injection pro-files typical of wind or solar PV conversion. ESS can be charged when RES energy is above a certain threshold and discharged to smooth peaks and troughs to avoid grid instability. ESS are one of the most interesting solution to this issue and can foster larger quotas of RES penetration in the electric power system. [7]

1.4. Cost Models and Economic Analyses of ESS

The techno-economic feasibility assessment of energy storage technologies, as for any other type of technology, is subjected not only to aspects inherent to the technology itself (e.g., capital costs, energy efficiency, maturity, and so on), but also to exogenous factors related to final application (e.g., electricity price, regulations and limitations for usage, etc.). Therefore, one should take all these factors into account so as to come up with the right decision on whether or not the inclusion of an storage system is beneficial for the provision of particular services in specific environments. [13]

Ultimately, the total expenditure of the project should take into account aspects such as the capital costs of the technology, the operating and maintenance costs, and the possible replacement costs of components during the lifetime of the system, as well as those costs derived from the disposal and recycling processes. The sum of all these factors yields the so-called "total life-cycle cost" of the system. Such a total cost is preferably expressed in annualized form, to give yearly figures over the entire life span of the system. In this way, these annualized costs can be intended as the expenditure that the system operator is supposed to pay yearly, considering all of the operations around the technology (e.g., purchase, installation, operation, repayment of loans, and interest). Since the value of money will vary throughout the life span of the project, the annualized costs are levelized, and hence adjusted by taking into account future costs at a predicted discount rate. [13]

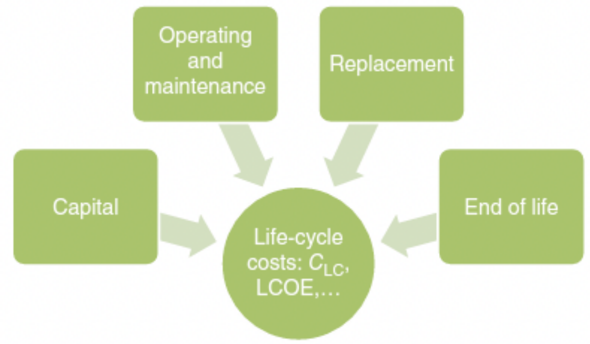

Figure 13. The concept of life-cycle costs. [13]

Taken together, all this makes up the "annualized life-cycle cost" C_{LC} (in €/kW-yr). Note that this magnitude is expressed per unit of power delivered by the storage system. Figure 13 graphically depicts the concepts presented above. For decision-makers, the annualized life-cycle cost thus becomes an useful metric with which to address the economic feasibility of the project. Moreover, dividing C_{LC} by the number of yearly operating hours of the system, one can determine a second metric, which is the widely utilized Levelized Cost of Energy (LCOE), expressed in c€/kWh. The LCOE gives the economic resources that the storage operator (e.g., a utility), needs to charge the storage system per energy unit that it delivers, hence covering all costs around the technology. The LCOE is thus calculated as follows:

$$\mathrm{LCOE} = 100\frac{C_{\mathrm{LC}}}{n \times h}, \quad (1)$$

where n is the number of discharge cycles per year and h is the discharge time, in hours. First, tackling the model description, the "annualized life-cycle costs" C_{LC} (in €/kW-yr) are formulated as

$$C_{\mathrm{LC}} = C_{\mathrm{I}} + C_{\mathrm{O\&M}} + C_{\mathrm{R}} + C_{\mathrm{EoL}}, \quad (2)$$

where C_I weights the capital costs, which are associated with the acquisition and installation of the system, $C_{O\&M}$ are the operating and maintenance costs during the system's lifetime, the term C_R represents the expected replacement costs due to wear, and C_{EoL} computes the disposal and recycling costs at the end of the lifetime of the system. All these terms are expressed in annualized form, and hence in €/kW-yr. [13]

Considering the principal characteristics of each of the storage technologies presented (e.g., batteries, flow batteries, PHES, CAES, flywheels, and so on), there is no doubt that each one is best suited for a different purpose. The ESSs can be classified into three main categories, addressing their suitability for providing one type of service or another. This facilitates the evaluation of results and supports their credibility. In particular, the three categories are defined below in terms of the required energy and power capacity for ESSs while providing particular services investigate in current model:

Long-term, high-power storage. In this category, ESSs are rated at 100 MW/ 600 MWh, so they are able to provide huge amounts of power continuously, for up to 6 h. Such a high capacity defines ESSs as suitable, for instance, to time-shift the output of renewables when convenient, and even to store energy seasonally. The storage technologies included in this category are PHES and CAES. [13]

Figure 14 compares the life-cycle cost breakdowns for PHES and CAES systems. As can be noted, the annualized cost per installed power capacity is presumably lower for PHES than for CAES systems. Despite the fact that the capital costs are higher for PHES, the electricity and fuel costs incurred for CAES systems boost the annualized costs for this technology considerably. [13]

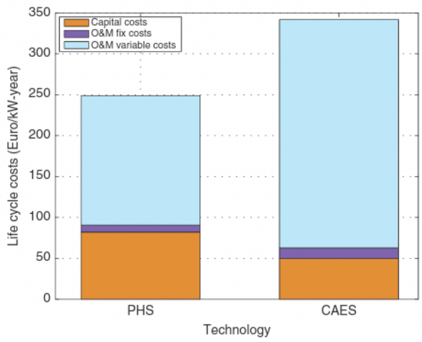

Figure 14. The annualized life-cycle costs for long-term ESSs. The systems are rated at 100 MW/600 MWh, and are deeply discharged once per day throughout the project horizon. [13]

Translating these results into an equivalent LCOE (Table 3), it can be derived that the cost of both technologies, under the assumptions of the present study and while performing the previously indicated service, turn out to be quite similar to the cost of conventional fossil-fuel power plants (around 12 c€/kWh). The low LCOE of PHES explains its extensive deployment in the power system. [13]

Table 3. Data for long-term Energy Storage Systems.

	Pumped Hydro Energy Storage	Compressed-Air Energy Storage
LCOE (c€/kWh)	11,4	15,6

Mid-term, mid-power storage. In this category, ESSs are rated at 10 MW/10 MWh. The capability to inject or absorb multi-megawatt power for up to 1 h defines the ESSs included in this category as suitable for helping renewables to meet their output targets, and to help the network operator to continuously ensure the required balance between generation and demand, among other applications. The storage technologies included in this second category are batteries, flow batteries, and hydrogen-based technologies. [13]

Figure 15 compares the life-cycle cost breakdowns for conventional batteries, flow batteries, and hydrogen-based systems. As can be observed, the capital costs of secondary and flow batteries greatly impact the system's life-cycle costs. Furthermore, and because of the limited cyclability of storage containers, they are to be periodically replaced, thus adding important expenditure. [13]

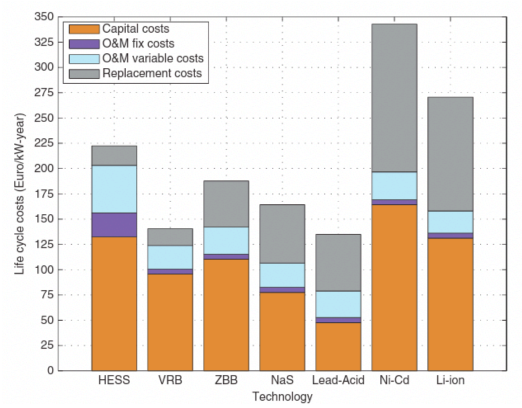

Figure 15. The annualized life-cycle costs for long-term storage systems. The systems are rated at 10 MW/10 MWh, and are deeply discharged once per day throughout the project horizon. [13]

The presented costs breakdown also indicates that economic resources for purchasing electricity (affecting the O&M variable costs) are less important than for the case of bulk storage systems. This is because of the specificities of the final application that the storage systems are providing here. However, it is worth noting that the expenditure for purchasing electricity for hydrogen-based systems is comparatively higher than for batteries and flow batteries. This is because of the relatively low round-trip efficiency (around 42%) of regenerative fuel cells, in comparison with the other technologies. [13]

Evaluating the global picture, we can conclude that the low capital costs of lead–acid batteries define this technology as the one with the lowest life-cycle costs. However, the high cyclability, life span, and low replacement costs of flow batteries (especially for VRBs), configure them as promising alternatives for mid-term, multi-megawatt systems. The still high capital costs of Li-ion batteries greatly constrains their applicability, especially when configuring multi-megawatt systems. Currently, there are other options that seem economically preferable. However, with regard to the high performance and intensive research and development activities for lithium batteries, the costs indicated here will presumably begin to diminish in the near future. [13]

Table 4. Data for mid-term Energy Storage Systems. [13]

	Hydrogen	VRB	ZBB	NaS	Lead-acid	Ni-Cd	Li-ion
LCOE (c€/kWh)	60,9	38,5	51,4	44,9	36,9	93,9	74,1

If we now evaluate the LCOE indices (see table 4), it is clear that lead–acid batteries are viewed as the most economical alternative, but if flow batteries technology will develop they can offer a good alternative to lea-acid batteries, and its necessity of reducing the costs for Li-ion (and also Ni–Cd) batteries. [13]

Short-term, low-power storage. Third category concerns those ESSs rated around 1 MW/3 kWh. The key characteristics of the ESSs included here are their high cyclability, their short time response, and their limited energy capacity. Accordingly, the technologies included here are principally flywheels, supercapacitors, and superconducting magnetic energy storage (SMES). [13]

Figure 16 compares the life-cycle cost breakdowns for these technologies. As can be noted, the predominant cost concept contribution for all three technologies is the capital cost. Furthermore, it can be derived that SMES life-cycle costs are [13]

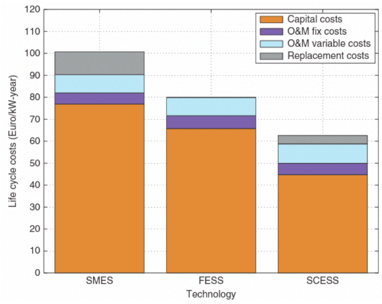

Figure 16. The annualized life-cycle costs for short-term storage systems. The systems are rated at 1 MW/0.003 MWh, taking 50 000 equivalent discharge cycles per year into consideration. [13]

Table 5. Data for short-term Energy Storage Systems

	Superconducting magnetic energy storage	flywheels Energy Storage	Supercapacitor energy storage
LCOE (c€/kWh)	72,5	57,5	41,1

2. CHALANGES OF BALTIC ENERGY SYSTEM

2.1. Baltic States energy policy

Though the Baltic States politically and economically are the members of the EU, however, electricity system are still connected with the systems of the former Soviet Union. This situation was determined both by historical and political circumstances and by limited internal energy resources. From the point of view of European integration, the Baltic States in some extent still remain an isolated "energy island" since electricity systems were developed as an integral part of the Interconnected Power System/Unified Power System (IPS/UPS) and work synchronously with power systems of Belarus, Russia and other Eastern countries. In order to be integrated with the European electricity system, the project of synchronization of the Baltic States' electricity grid with the European Continental Network (ECN) is foreseen to be implemented by 2025. [19] Formerly an "energy island", the Baltic States is now connected with the EU through recently constructed electricity lines with Poland, Sweden and Finland, it contributes to the establishing a unified European energy market. Apart from being in BRELL (Belarus, Russia, Estonia, Latvia and Lithuania) ring and operating in parallel with the IPS/UPS, energy systems of the Baltic States. [19]

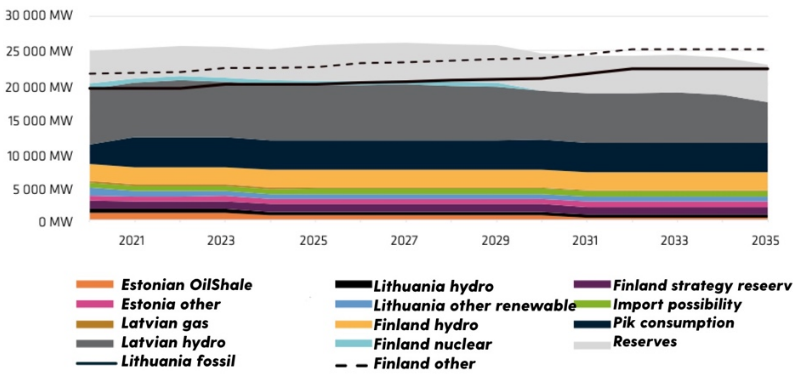

Figure 17. Available production and transmission capacities in the Baltics and Finland in the period 2020-2035 [1]

Figure 17 depicts the production and transmission capacities used I n the Baltics and Finland in the period 2020-2035 in Estonia, Latvia, Lithuania and Finland. In Estonia and Latvia, the production capacity of wind or solar energy used during peak hours has not been taken into account, as today there are still hours in the winter period when the total production of the Baltics from these sources is zero. The same figure also shows the forecasts of peak consumption and reserve requirements for the period, taking into account the synchronization with the Central European electricity system at the end of 2025. The analysis shows that the countries concerned are dependent on foreign imports to cover the peak load. Today, there are a total of 4,800 MW of import capacity per country, and in 2026, according to forecasts, already 5,500 MW. [1] The same forecast shows that by 2027 where without energy imports in the region may occur energy shortages.

In Elering's opinion, the Baltic States must be ready for the Baltic synchronous area scenario at any time, and if this scenario will realized energy system should be steal able supply energy. By the end of 2025, the synchronous work of the Baltic States with the IPS/UPS energy system will be finished. The Baltic States have remained part of island operation and form a separate Baltic synchronous area. Fast resynchronization with the IPS/UPS system is not possible, the ability to work independently for up to 12 months is required until an emergency synchronization with the mainland Europe. After 2025 - the Lithuanian-Polish AC connection has been interrupted and the Baltic States will have to cope independently until the AC connection is restored. DC connections with the Nordic countries and Poland are usable, but on a reduced scale, given the maximum element limit of 400 MW. The largest generation capacities are also limited to 400 MW. In this situation, the Baltic States depend on direct current connections with neighboring systems for fast frequency reserves. There must be sufficient production capacity in the Baltic States. [1] Although as you can see in the Figure By 2023, the Baltic states may become dependent on imported energy and their production capacity may be insufficient. From 2031, a situation may arise where production and import capacities do not cover the region's energy demand.

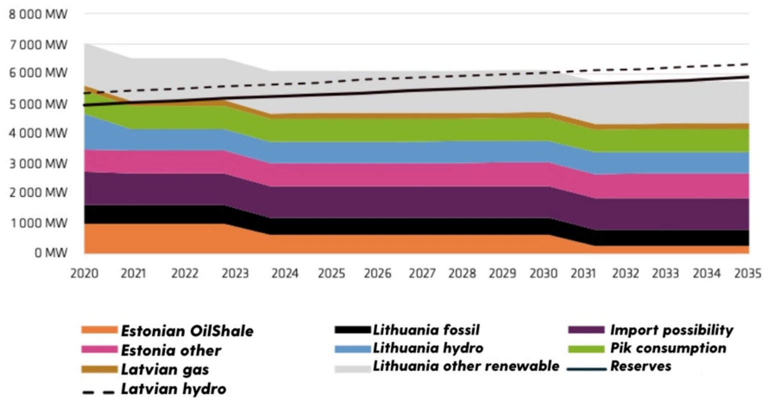

Figure 18. Baseline scenario for the Baltic synchronous area [1]

In 2020, the total energy production of the three Baltic States amounted to 15,240 TWh, while 28.4 TWh of energy was consumed. As a result, the negative balance imported from other countries amounted to 13.1 TWh of energy. In Finland, 63.77 TWh of energy were produced and 78.353 TWh were consumed, resulting in a negative balance of 14.6 TWh of energy. A total of 27.7 TWh of energy was imported into the area. This clearly speaks of the region's energy shortage and does not allow us to talk about high energy independence.

In 2020, the busiest connection was Kaliningrad-Lithuania; the connection worked 73% of the time with 100% load for one month, reaching 90%. 100% load of the NordBaltic cable from Sweden to Lithuania accounted for 59% of working time. The higher monthly load of the Estlink cable from Finland to Estonia reached 75%; 100% of the cables were loaded 34% of their working time. On the Estonian-Finnish cross section in 2019, there were a total of 1272 bottleneck hours in the Finnish-Estonian connection, or about 14.52% of the hours per year, of which: All installed transmission capacity was used (i.e. EstLink was used at full capacity without restrictions): 875 hours or 9.99% of the year; Transmission capacity was limited to 179 hours or approximately 2.04% per year due to Elering's or Fingrid's network. [1] The restrictions on the speed of power change in the Nordic countries were 39 hours or 0.45% per year. The least busy was LitPol Link from Lithuania to Poland, and in 2020 the team's 100% workload accounted for 31% of the working time. [20]

2.2. Estonian energy system

Estonia is the only country in the world that has oil shale as the primary energy source in the country and as a dominating fuel in the energy mix. On the one hand, such high consumption of oil shale as a local fuel ensures high level of energy security. On the other hand, it is highly carbon-intensive fuel, thus oil shale based energy production processes emit a large amount of greenhouse gas (GHG), which has negative impact to the environment. /10,5/During last decade oil shale part in energy production reduce. In 2020, total production of electricity in Estonia amounted to 4.803 TWh. Share of energy was produced from renewable recourses 46,3% which shown in table 6. Where as total demand for electricity was 8.434 TWh. Second year Estonia has negative energy balance 3,360 TWh of electricity was imported from Finland and Latvia. [21]

Estonia has two power connection lines with Finland, which allowed for total of 1000 MW transmission capacity between tow countries. first high-voltage direct current interconnection "EstLink 1" with nominal transmission power of 350 MW was already commissioned in 2006. In 2014, new power connection line "EstLink 2" has added 650 MW. One of Fingrid possible future scenario is "EstLink 3" by the year 2035. Estonia is connected with Latvian energy system by tow 330 kV electric power transmission lines and Russia three 330 kV electric power transmission lines. Elering announce that there are no energy trade between Estonia and Russia. Estonia is actively promoting the development of RES and has already in 2011 reached the national RES target of 25% for 2020. [19]

Table 6. Baltic countries power production and consumption in 2020

	Estonia GWh	%	Latvia GWh	%	Lithuania GWh	%
Energy production	4803		5509		5124	
Renewable power sources	2224	46,30	3084	55,98	2968	57,92
incl. wind energy	824	17,15	175	3,18	1544	30,13
incl. hydro energy	27	0,57	2520	45,74	1065	20,78
incl. biomass	1254	26,11	391	7,10	251	4,90
Fossil fuels	2579	53,70	1739	44,02	1914	42,08
Import	7160		1620		11261	
Consumption	8434		7059		11937	
Export	3530		0		3352	
Balance	*-3630*		*-1620*		*-7509*	

Estonia's overall electricity consumption is still showing a growth trend, but the peak loads of the electricity system have remained essentially unchanged over the last ten years, remaining between 1423 and 1587 MW. The peak load of 1587 MW was registered 10 years ago in 2010, which coincided with an exceptionally cold winter period. However, it should be borne in mind that due to the increase in consumption, some increase in peak load is also expected over the next 10 years and a subsequent decrease in the annual growth rate of consumption. According to the Elering forecast, according to all assumptions, the peak load will remain within the limits of 1600 MW in 2021, but in 2032 it has already increased to the level of 1700 MW. [1]

As of 1 January 2020, the total installed net generation capacity is 3041 MW, of which the peak generation capacity is 1779 MW. [1]. To date, the following capacity closures, capacity reductions and temporary shutdown of production facilities have been announced: 2021 Closure of Estonian power plant units, 815 MW; 2021 Closure of the Baltic power plant unit, 130 MW; 2024 Closure of additional units at Estonian power plant, 346 MW; 2031 Closure of units in Estonian and Baltic power plants total 386 MW [1] Total production capacity to be closed during 2019-2024: 1291 MW. According to Eesti Energia's assessment, three units of Estonian power plant will be closed at the end of 2020 and Unit 12 of Baltic power plant will also be closed by the end of 2020. As the actual utilization of the working hours provided for in the limited working life derogation depends on the price levels developing in the wholesale electricity market, the exact planned closure time of these power units is not known. [1] This situation is also reflected in the Figure below. This means that as of 2021 Estonia will not have enough production capacity to cover the energy peak loads, and at some points energy consumption will depend to a large extent on imports.

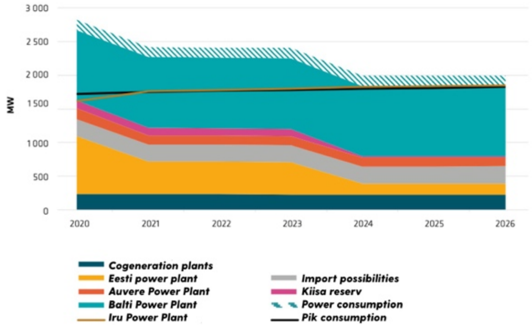

Figure 19. Comparison of the forecast of the total demand for distribution networks and Elering's system load with a 10% margin and its coverage through domestic production capacities and external connections. [1]

Figure 19 depicts an assessment of the developments of currently known and used generation capacities in Estonia until 2035 in terms of the adequacy of the electricity system. From the point of view of conservatism, the closures of power plants are expected to be partially accelerated in comparison to the data provided by producers when assessing the production margin necessary to meet the consumption demand of the Estonian electricity system. As of 2020, according to current plans, Estonia will normally have more than 2,000 MW. [1] From the point of view of the adequacy of the electrical system, it is also important to look at the emergency situations of the system. Figure 20 illustrates the state of adequacy of the electrical system in a N-1-1 situation where the two largest elements of the electrical system are out of order. [1] In 2019, 2.45% of working time or 218 hours one of the two largest elements of the electricity system were out of order.

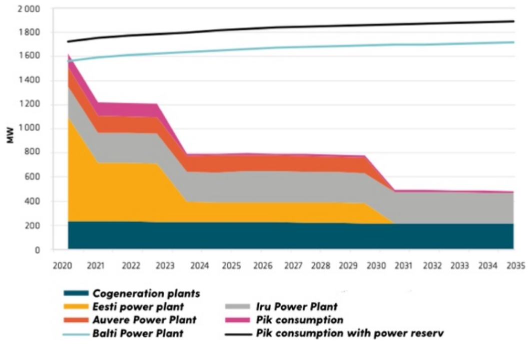

Figure 20. Estimate of the composition of available production capacities until 2035 [1]

2.3. Latvian energy system

RES have a dominant share in total production of electricity in Latvia (68,3% in 2020) shown in table 6, mainly being generated by hydro 2,514 TWh (45,6) [18]. As total demand for electricity in 2016 was 7.059 TWh, the rest of the demanded electricity 1,62 TWh (23%) was imported, mostly from Estonia (61.8%) and Russia (22.9%). Heat production also mostly relies on natural gas. Since Latvia does not have its own resources, all natural gas consumed is imported from a single source Russia. Unlike the other Baltic States, Latvia operates the Incukalns Underground Gas Storage Facility, which ensures the stability of regional natural gas supply. Natural gas is injected into the storage during the summer, when consumption is low, and supplies gas during the heating season. [19]

Due to strong hydropower production, Latvia is one of the leading countries according to the share of energy from RES in the EU and achieves its 2020 RES target. Latvia's RES target for 2020 is 40%, which is also twice as high as the EU average of 20% . [19] Hi level of RES is barrier for developing of new RES facilities. Only 0,152 TWh of energy produced from wind power (compere to Estonia 2,24 TWh). Latvia developing a new wind power facilities onshore and offshore, but they are far to go.

2.4. Lithuanian energy system

The considerable change in the Lithuanian energy system occurred at the end of 2009 after closing the Ignalina Nuclear Power Plant (NPP). It radically changed the energy resource structure and suddenly country from exporting electricity overnight became country importing electricity. [19] In 2020, total production of electricity in Lithuania amounted to 5.124 TWh. In table 6 shown, that the big share of energy production was from wind 1,544 TWh (30,1%), and hydro 1,065 (20,9%) including 0,768 Twh Krunio PHES. However, total demand for electricity in Lithuania in 2020 was 13,051 TWh, Lithuania consumed 11,973 TWh, including 1,077 TWh Krunio PHES load. 3,352 TWh was exported, manly in Poland 2,33 TWh and Latvia 0,466TWh. [22]

At the end of 2015, two new power connection lines, accordingly "LitPol Link" with Poland of 500 MW and "NordBalt" with Sweden of 700 MW were commissioned, thus, their real benefit in terms of decreased electricity price and diversification of electricity supply is felt from 2016. It was major step in terms of strengthening the country's energy independence and security. [19]

The main strategic directions of energy policy development pointed out in new National Energy Independence Strategy (NEIS) of Lithuania are energy security, competitiveness, green energy development and innovations. According to the NEIS, the main vision of the Lithuanian energy sector is complete independence from fossil fuels by 2050. The country in 2014 has already reached the national RES target of 23% for 2020 defined by the renewable energy directive. [19]

In conclusion, it is clear that without the creation of additional capacities and connections of other countries, the region will can have an energy production deficit in the Baltic and Finnish regions by 2035, in the Baltic region in 2031 and in Estonia by 2024. Wind and solar energy can be solution but without energy storage penetration of green energy wouldn’t be totally effective.

2.5. Energy price overview

Baltic countries belong to Nord Pool energy trading system. The price analysis of the three Baltic countries shows that the prices per electricity unit are relatively equal, and if there is a price change, then the dynamics of the price change is equal. The price clearly reflects the energy market situation. If the capacity is many times more than the consumption then the price is low, if all the capacities are in use then the price becomes high, if there is not enough capacity then the price increases even more.

Table 7. Description of the price of Estonian electricity in the period 2016-2020 [23]

Aasta	**Average price (Eur MWh)**	**Price > 90euro MWh (h)**	**Price < 5 euro MWh (h)**
2016	33,28	50	8
2017	33,2	16	17
2018	47,06	78	66
2019	44,85	65	109
2020	33,64	88	489

The price becomes especially high in the event of a system failure. Whether during the high consumption some units go out of the latch or if there are failures in the transmission lines then it immediately finds a reflection in the price. Last year, consumers saw two extreme situations. First, the price of electricity was negative for four hours. The consumer was paid for consumption. This is possible thanks to the subsidy of green energy. And another extreme case when the price of electricity rose above 250 euros per MWh. Such a high price was caused by an accident in the Latvian transmission network on June 6, where more than 160 thousand households were left without electricity for several hours.

The table 7 shows the numbers that describe the price change. The number of hours per year is shown as the price was over 90 and less than 5 euros per MWh. The limits of €90 and €5 have been taken subjectively to describe the situation. There are clear dynamics in the direction of stable price growth, there are worse situations where the price is several times higher than the average and situations where the price is several times lower than the average. The high price indicates a situation of energy deficit in the system, and in the case of lower prices it is difficult to rely on a private investor for projects, and too low a price makes it impossible to build new volumes without subsidies. Using energy storage is the only way to balance the system, their use helps to harmonize the price schedule and ensures the stability of the system in the event of a failure in the energy transmission system. 2020 was clearly an exceptional year, in terms of price policy, clear consumption and the subsequent fall in prices was justified by the pandemic situation.

2.6. Desynchronization of the Baltic States from IPS/UPS system and frequency stability

The Estonian electricity system is part of the large synchronously operating interconnected system IPS/UPS. The Estonian electricity system is connected to the interconnected system via cross-border 330 kV alternating current lines. Two 330 kV electricity transmission lines connect the Estonian electricity system with Latvia and three 330 kV electricity transmission lines with Russia. Automatic frequency control is provided by the Russian system operator and have been done on a Volga-Volga hydro plant cascade. The role of the Estonian electricity system in regulating the frequency of the synchronous area is to keep the AC balance of the system within the necessary limits. In accordance with the agreement between the system operators of the Baltic States, which entered into force in 2019, we are moving step by step in the direction of achieving unified coordinated balance sheet management in the Baltics in real time. [1] The Baltics must start to support the frequency band and the regional frequency with two types of reserves – the Frequency Containment Reserves (FCR) and the Frequency Restoration Reserves (FRR). [1]

In addition, the penetration of renewable energy in the network increases significantly the number of frequency events. This statement can be considered on the example of the Great Britain (GB). In GB, has been a transition away from large fossil-fuel thermal plant to renewable and decentralized generation. Currently, just short of a third of electricity generated in GB is now renewable, which is mostly due to increases in wind and solar generation over the last few years. It is predicted that 25% of generation will be decentralized by 2022 and renewable generation output will hit 60% by 2025. Wind and solar hinder the balancing of generation and demand for three reasons: their inherent intermittency and unpredictability, their lack of inertia, and their lack of frequency response capability. Decentralisation is also adding to this stability problem because embedded generation is largely invisible to the system operator, so generation forecasts are harder. [33]

Measure of system stability is the volatility of the grid frequency. The system operator of the grid has a responsibility to keep the frequency very near the nominal frequency, which is 50 Hz in Great Britain. The operational limits are ±0.2 Hz: during normal grid operation, the system operator should aim to keep the frequency within these limits. The statutory limits are ±0.5 Hz. A frequency event is defined as: *High frequency event* - when the frequency goes above 50.2 Hz for any length of time and *Low frequency event* - when the frequency goes below 49.8 Hz. [33]

Figure 20 shows the number of frequency events that occurred during each year from 2014 to 2018. This rough doubling of total number of frequency events from 2017 onwards is due to an increase in both high and low events and then in 2018 it increases again to 1990. A likely reason for the rapid increase in frequency events since 2017 is the rise in renewable penetration on the GB grid because this has been facilitated by a rise in wind and solar, which are intermittent and offer no inertia. Overall, there were 4949 frequency events in the 5 year period. [33]

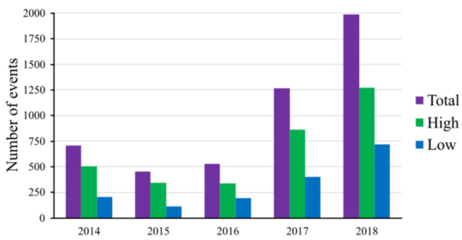

Fig. 21. Number of frequency events each year in GB. [33]

Notably, as can be seen in figure 21, in every year there are more high events than low events. The number of high events is between 63% and 76% of the total number of events for each year. This suggests that it is more common to have periods when generation has unexpectedly risen higher than demand than the other way around. There are more individual demand units than generating units on the grid at any one time. [33]

If the Estonian electricity system operates in isolation, it is necessary to regulate the frequency with the power plants of the Estonian electricity system. A major challenge in frequency management is the growing share of renewable energy in the electricity system. The dependence of the output capacity of wind and solar power plants on weather parameters can cause differences in the capacity balance in the system, which must be compensated by the use of capacity reserves. [1] Their share in energy production in 2020 was almost one-fifth, or 17.8%. Another major challenge is the closure of energy units. By closing these, the ability to generate active energy as well as reactive energy is reduced. According Baltic reserve capacity study Estonia need after desynchronization Frequency Containment Reserve (FCR) +/-8 MW, automatically activated Frequency Restoration Reserve (aFRR) up 40 MW and manually activated Frequency Restoration Reserve (mFRR) up 209 and down 257 MW. [32] According to this document Estonia currently does not have sufficient reserve capacity to implement frequency control independently. In desynchronization moment in Estonia it will be aFRR upward reserve only 13MW and downward 29MW, mFRR upward reserve is 260MW and downward 126MW which is 131MW less what it needs to be. [32]

Tabel 8. Baltic States following reserve needs for frequency control. [32]

	FCR	aFRR		mFRR	
	+/-, MW	UP, MW	DOWN, MW	UP, MW	DOWN, MW
Estonia	8	40	40	209	257
Latvia	8	30	30	145	37
Lithuania	9	60	60	226	276
Total	25	130	130	580	570

With increasing penetration of wind and solar generation on electricity grids around the world, concerns are being raised about the effect this has on system stability. One measure of system stability is the volatility of the grid frequency. Additional reserve capacity needs must be taken into account. The energy storage can be good alternative to introduce solve system stability problems.

3. ENERGY STORAGE APPLICATION IN THE ENERGY SYSTEM

The first chapter presents a number of functions for which ESS can be used and suitable technology for them. Different types of ESS technologies parameters presented in apex 1. The number of applications is wide and will probably expand in the future. Based on the previous chapter, the challenges of the current system in the Baltics are related to the integration of renewable energy into the energy system, energy price volatility, frequency regulation, reactive energy compensation and network reliability. The following chapter addresses these issues separately.

3.1. Frequency control

Frequency control may be one of the first markets in which battery storage system can compete with conventional power generators. Frequency control is a service to the power system that is necessary to keep demand and supply in balance. Frequency control is an existing worldwide market and parts of it, especially the quickly responding segments, can be provided well by battery storage system. [13] The system frequency – 50 Hz, e.g., in the European electricity grid, 60 HZ, e.g., in the USA – is measure of the balance between supply and demand of electricity. The frequency rises if generation is higher than demand and the frequency drops if demand is higher than generation. [13] The use of ESS for grid frequency regulation can be dated back to the 1980s, e.g. the Beacon Power Corporation has already implemented flywheels to provide fast frequency regulation services. However, ESS remains to be an expensive technology although there are declinations in the cost in recent years. [25]

Today, frequency regulation typically uses plants that burn fossil fuels. Fast-response natural gas power plants are a common method of fossil fuel frequency regulation. In addition to natural gas, oil-shall and coal is also used for frequency regulation. Pumped hydro storage and demand response can also be used for frequency regulation. There are issues with many of these frequency regulation methods which make them less ideal for regulation. Coal and oil-shale plants may not always accurately follow the control signal and can have difficulties providing precise frequency regulation services. Natural gas and other combustion turbines must run continuously while providing frequency regulation. Pumped hydro storage requires a location for water storage with higher and lower elevations to work and cannot be easily installed in many areas. Demand response requires significant coordination with the grid and consumers which makes demand response frequency regulation more complex than other profitable uses for demand response. [27]

Today, frequency regulation in Estonia is possible with the help of existing energy blocks, with the help of reserve stations, but also with the help of external connections. Narva blocks take a long time to start up, and over time they will be shut down, external connections may be out of order or neighboring countries will not be able to transmit enough energy. [1] Currently, the emergency reserve is based on a gas boiler plant, which is ultimately not carbon neutral. In the future, Estonia must offer part of its capacity for the frequency maintenance system of the Baltic countries. For this, it is possible to effectively use an energy storage system.

Frequency regulation principles

Generally, ancillary services are classified into three different categories depending on its response characteristics. The first category is primary frequency control, also known as frequency regulation or response, which manages minor frequency fluctuations within seconds. Primary frequency control is divided into two different categories, governor free response and automatic generation control. The governor free response is a mechanism that senses speed of the generator, and adjusts the input value to change the mechanical power output to restore frequency to nominal value within few seconds. Due to the stringent requirement on the response time, primary frequency regulation is the most expensive regulation reserve. This is because traditionally the primary frequency regulation is performed by thermal generators, which are designed to commit bulk load, but not as quick response reserves. [29] Primary reserves are delivered until replaced by other power reserves in the network, typically named secondary and tertiary reserves. The activation of these reserves brings the electrical frequency back to its initial setpoint. The deployment of power reserves in the event of a power imbalance in the network is graphically depicted in figure 22. [28]

The frequency regulation is a hard task in conventional power grids as load demand is not impeccably predictable and power generation plants have limited ramp up/down capabilities. In modern power grid paradigm, the frequency regulation task has become even more challenging due to the integration of RE sources which adds unpredictability to the generation, like it shown in previous section. Moreover, RE share in the power system is expected to increase, and this leads to an increase in required capacity for frequency regulation. Novel techniques for procuring and settling frequency regulation are necessary. The current mechanisms are unreasonable and inordinately discriminatory against faster ramping resources that are clearly required to meet future frequency regulation needs, especially at the higher penetration levels of RE sources. Furthermore, the use of faster ramping resources for frequency regulation has the potential to enhance technoeconomic efficiency of the electric power grid. [29]

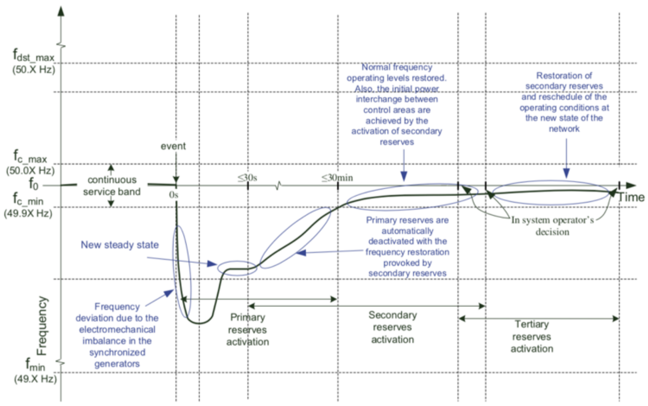

Figure 22. Deployment of power reserves in the event of a network frequency disturbance [28]

Possible technologies

Some ESSs, such as batteries and flywheels, are already in use for frequency regulation (FR) services and avoid the issues associated with other frequency regulation technologies. [27] In literature different strategies have been presented for FR. These studies have been carried out either considering a generic battery energy storage system (BESS), or focusing on a specific energy storage technology like lead acid batteries, Li-ion batteries, vanadium redox flow batteries, flywheels, or super conducting magnetic energy storage. [29] The fast response and relatively high energy and power capacity of pumped hydro storage and compressed-air based systems, were identified as suitable technologies for the provision of power reserves for frequency regulation in. [28]

Evaluated vanadium redox flow batteries for frequency regulation and concluded that this technology was economically feasible, though it could still be more expensive than traditional frequency regulation methods and will need policy intervention to be implemented across the grid. [27] Was found that lead acid batteries could have positive life cycle benefits. However, in both cases, other battery energy storage system (BESS) and flywheel energy storage system (FESS) technologies were superior. Was determined that FESS is cheaper and more effective than both lead acid and lithium ion BESSs. Compared lithium-ion batteries and lead acid batteries to FESS technologies and was found that flywheels performed significantly better in terms of economic viability.

However, despite their high efficiency and effectiveness, the startup cost of these systems is higher, which discourages investors. This high initial capital investment is another area where government intervention through policy is needed. [27]

In literatures there are a lot discussion that have evaluated the economic benefit of utilizing ESS for frequency regulation. The best type of ESS for frequency regulation was lithium-ion ESS, which has a relatively long lifecycle even when it is charged and discharged frequently, has high energy density, and has a high charge or discharge efficiency characteristics compared to other types of battery ESSs. [26] Other possible technologies is hybrid energy storage system (HESS), system with tow types of energy storages with different characteristic. For example, BESS and ultracapacitor/supercapacitor (UC) technology can be coupled to build HESS, in the same way flywheel energy storage can be couples with BESS to create HESS.

ESS have significant operational differences – primarily due to their limited energy capacity – when compared with conventional providers of FR services, such as open cycle gas turbines and pumped hydro storage; it is therefore necessary to design new services to realize the benefits of ESS in maintaining the system frequency. [29]

Frequency regulation free market principle

Independent system operators (ISOs) that manage and operate electric power grids are liable for FR. Multiple ISOs, e.g., Cal-ISO in California, ERCOT in Texas, NYISO in New York, PJM across multiple states in the eastern U.S., MSA in Alberta, IESO in Ontario, AEMO in Australia, and New England ISO in England, Germany provide market-based FR. In a regulation service (RS) market operated by an Independent system operator, RS resources counter the detrimental effects caused by change in generation/demand for stable and reliable operation of electric power grid. RS providers are paid for dynamically supplying/consuming electric power to/from the electric power grid, in response to the regulation signals provided by the ISOs. It is predicted that the total revenue from the RS market would be between €20 – €50 billion by 2022. [29]

Korea is one of the largest power systems that is managed by single Transmission System Operator. The installed generation capacity is 97,649 MW (2015), but even a not market-based system is meant to use ESS frequency regulation. In 2014, 52MW of ESS for frequency regulation was built in Korea costing €49 million of investment. The Korea Electric Power Company (KEPCO) is currently building a 500 MW ESS for frequency regulation (planned to invest €500 million). [26]

In recent years, a substantial contribution has been made to research on provision of FR via ESS. Knap et al. explore the sizing of ESS for both inertial response and primary frequency response. The presented method employs simulations of the power network and the storage system; a set of droop controllers is used to provide inertia as a function of the ROCOF and primary response as a function of the frequency deviation. The results indicate that, in a system with 50% renewable generation, the required storage capacity is around 5% of the total generation capacity, and the power to energy ratio is approximately 2–1. [29]

Today, it is not clear which path Baltic will take when on a way to desynchronizing, FR by regulator or market-based FR. Rather, the documents set out the plan for each country to allocate a certain amount of capacity, which allows it to keep the frequency under control. However, another way could be chosen and the free-market trading path taken, where different energy producers could compete with each other. Then ESS technology would certainly have a better chance of entering the electricity market. There are several various options for frequency control systems considered in current work, in my opinion the most effective of them is PHES. This kind of installation could be built in Estonia. Based on the analysis, for frequency regulation, 40 MW of energy is needed in automatic mode and 209 MW up and 257 MW down in manual mode, representing approximately 300 MW of energy reserve capacity. Assuming that the investment in such a plant might be 1000 € kW, then the creation of such a plant could cost approximately 300 million euros. Based on the needs of all three Baltic countries, the need for reserve capacities will increase. That means 130 MW of power in automatic mode and 580 MW in manual mode shall be required. In this case, the capacity of the installation could be 720 MW and cost of such a project would be about 720 million euros.

3.2. Reactive Power Compensation

The over problem, is the lack of inertia issue has already challenged the frequency stability. This is because renewable energy sources (RESs) are often connected to the grid through fast-response power electronics converters, which do not naturally provide any inertia, as conventional synchronous generators do. [31]

To address the lack of inertia issue due to the large penetration levels of RESs, several methods have been proposed. In conventional power systems, it is known that active and reactive powers are mainly regulated by synchronous generators. Specifically, the kinetic energy stored in the rotors of synchronous generators will autonomously be released under low frequency events for active power and frequency support, and such an effect is caused by the synchronous inertia. In this sense, the most straight-forward way to increase the inertia is to employ more back-up synchronous generating units. Although being an effective and simple method of increasing the inertia, the employment of stand-by synchronous generators will lead to high cost and reduction of efficiency. Along with the integration of RESs, power electronic converters and energy storage devices are increasingly developed and employed in modern power systems. [31]

Instead of being used in VSGs, independent energy storage systems (ESSs) are also very helpful and effective in terms of frequency regulation. For selection of energy storage units, batteries, supercapacitors, and flywheels are common choices. In, the battery being applied to electric vehicles can establish the grid frequency. In and, supercapacitors are used to emulate inertia and improve frequency regulation. In addition, flywheels are also potential candidates for frequency regulation. When compared with batteries, flywheels have a much longer lifecycle and higher power density. To be specific, flywheels can provide several hundreds and thousands charge-discharge cycles, which are several times better than those of batteries. Compared with supercapacitors, flywheels have a higher energy density. In general, the energy density of flywheels is dozens of times higher than that of supercapacitors. [31] For instance, the cost of installing a 20 MW/10 MW h Flywheel Energy Storage Systems (FESS) is approx. €27 m–€30 m. The large-scale deployment of ESS is still not feasible in a short term. [25]

Today, three synchronous compensators planned to be built in Estonia and a total of nine in the Baltic countries to remove inertia. [1] However, based on the practice and theoretical literature, it is understood that the ESS could be successfully used to compensate for inertia.

3.3. Transmission and Distribution infrastructure support

UK widely use ESS for T&D infrastructure support. At least twenty-four BESS projects have been used in power system, for a total installed power equal to approximately 25.5 MW in 2020. The largest battery energy storage facility in the UK and Ireland is lithium ion storage with rated power 10 MW, installed within Kilroot coal-fired generation plant, with the aim of providing frequency regulation for the Irish electricity system which is characterized by high penetration of onshore wind energy. The majority of the projects is installed at the distribution system. This is mostly due to the cost of BESSs with increasing voltage levels. [17]

Table 9. Total capacity of the most widely deployed ancillary services in the UK.

Service Name	***Total Capacity (kW)***
Electric energy time shift	9105
TS/DS upgrade deferral	9100
Voltage support	3110
Renewable capacity firming	2285
On- site renewables generation shifting	1031
Renewable energy time shift	496

The total installed capacity for the most widely deployed services is provided in table 6. Based on this data, there has been a trend towards utilizing the BESSs for time-shifting applications, including those in which the battery units work in conjunction with RESs. The second most popular application consists in using BESSs for deferring investments for the upgrade of the transmission system (TS) and distribution system (DS). [17] This service refers to delaying or avoiding the replacement or retrofitting of existing transmission and distribution equipment. This can be achieved by means of small amounts of energy storage, able to provide adequate incremental capacity in order to defer the investments in new infrastructure. Among the benefits arising from this application are: decreased costs for the ratepayers, improved utilization of the utility assets, allocation of the capital for other projects and decreased financial risk related to the investment. Concurrently, the equipment's life can be extended, which may be of critical importance for equipment such as ageing transformers or underground circuits whose replacement or upgrade is costly. [17]

Elering does not consider using ESS to support its grid, at least the author did not find any mention of such a plan. The energy supply report describes grid development, construction of new lines and development of substations. The report talks about new EES technologies, but rather in the general educational context, unfortunately not for the purpose of stable operation of the grid, or for some other purpose. On the one hand, due to its compactness, Estonia is able to efficiently transmit energy everywhere. On the other hand, it is constantly the case that some areas are left without electricity, due to weather conditions. And these regions are usually the same, especially southeastern Estonia and the Islands. EES could be one effective solution to keep the grid stable even if an area loses connection to the transmission grid.

3.4. ESS in EU Renewable Energy Directive

Directive 2018/2001 sets specific targets for EU countries to achieve renewable energy sources goals by 2030. The directive defines the rules by which the results can be achieved. On the basis of the directive, the member-countries of the European Union have created mechanisms for subsidizing new capacities of renewable energy sources. Subsidies, which at one point seemed absolutely necessary to launch renewable energy projects, have now become a source that prevents the creation of new capacities and the development of new projects. Today, investment in new capacities has been slowed down, everyone is waiting for new subsidies. Technologies continue to develop and today the creation of new capacities of renewable energy sources is possible without subsidies. The directive hardly mentions energy conservation devices. It is necessary to include them in the directive. But again, the question arises whether to subsidize them or not. The launch and creation of such projects with the help of subsidies will definitely speed up the process of creating new capacities of energy storage facilities. At the same time, a similar system of subsidies at a certain stage can become an obstacle to the development of the system. An important element in any case is the definition of equal rules for all market participants. and even if it is decided that such systems will not be subsidized, this will be a decision for the participants of the European energy market. The definitions and procedure for the creation of energy storage systems should be described in the EU directive.

The main questing is who will build storage facilities, whether public- or private sector. It is constantly declared that the energy sector must move to the principle of a market economy. Although currently, the entire energy system is built completely on state subsidies. The state has allocated funds for the construction of energy units, emergency units, and the entire green energy sector has been built up with the help of a grant. It is not so easy to get out of this circle, as the situation is complicated by the fact that the internal decisions of one country mean nothing, because the energy market is global and the decisions of other countries clearly affect the whole market. There is a risk that a storage technology owner investing in an installation in one country will find itself in an unequal competitive position if, for example, a similar project in a neighboring country that belongs to the same trading space receives state grant of another country. Building a large-scale energy storage project with a state grant, it will be a step away from the plan to bring the energy sector closer to the market economy principles.

Energy storage is a key enabler of a RES-dominated system. The transition to a renewable-based energy system needs to be supported by energy storage in order to ensure security of supply, efficient energy system operation, and the competitiveness of EU industries. Energy storage can increase the share of renewable electricity used in the energy mix by reducing or avoiding curtailment of renewable electricity generation. By shifting the use of excess renewable electricity forward in time to periods of deficit, RES essentially become dispatchable, which greatly facilitates their integration into the energy system, and ensures optimal use of installed RES capacities. Some of these technologies, for example Power-to-Gas and Power-to-Liquid, can be used to produce renewable and/or low-carbon fuels. Add a renewable and low-carbon ehydrogen definition encompassing all of its potential. When optimally located, energy storage solutions can optimise the use of the transmission and distribution grid, avoiding congestions. Define a comprehensive methodology to assess flexibility needs, which could be used to define an energy storage target to support the cost-effective integration of RES. The methodology and target should be technology and location neutral and reflect the need for flexibility at different timescales serving the electricity, heating and cooling, gas, mobility, and industry sectors.

If desigion will be suport ESS construction support schemes should explicitly be open to RES plus storage projects to encourage more hybrid projects. This will become increasingly important at higher shares of RES when new capacity is built to replace conventional dispatchable generation that is going offline. Furthermore, it could be assessed whether coupling RES with storage should be made obligatory to access support schemes once a Member State reaches a very high share of RES deployment (e.g. more than 80%) and/or in areas with congestion or other grid constraints. For islands and outermost regions in particular, there should be more focus on support schemes considering energy storage, since there are fewer alternative flexibility options available.

Directive should reduce barriers to deployment of hybrid RES plus storage projects. Ensure that RES electricity fed into storage and subsequently discharged is still considered renewable under renewable energy certification schemes. This requires a comprehensive methodology to avoid double counting and to differentiate clearly between energy storage charging from the grid versus charging directly from RES.

Directive should simplify and accelerate administrative procedures and permitting for energy storage facilities. Proportional national rules concerning the authorisation, certification, and licensing procedures for RES and associated transmission and distribution networks also apply to energy storage projects. Simplified permitting and authorisation procedures should in particular be promoted for hybrid RES+storage project

CONCLUSION

The global energy system is facing major challenges. Europe and other countries have posed a rather difficult but very important challenge, to make energy production carbon-neutral, and many countries want to abandon nuclear energy. These changes are difficult to implement, but in case they succeed, we will have a completely new energy supply system, which consists entirely or largely of renewable energy sources and which is no longer centralized, involving a large number of energy suppliers. When creating a new system, both production sources and ways of energy transmission are developed, but certainly the new system has an important place for Energy Storage Systems.

Estonia is actively participating in achieving the new energy goals, while in the coming years, together with other Baltic countries, it plans to separate itself from the IPS/UPS frequency regulation system. If we analyze the energy capacity of the Baltic States, despite the fact that at present the production capacity in the region is sufficient, part of the production capacity will not compete with cheaper Scandinavian energy. In order to compensate for the shortage, it is planned to increase the volume of renewable energy production and this will create an even greater need for ESS. Today, new energy storage projects are emerging around the world, technology is constantly evolving and new ways of energy storage are being tried out. Examples are hydrogen and flowing batteries. Existing technologies are also actively used and developed. Reservoirs for pumping water used to be built next to nuclear power plants, so this technology is now the most widespread in the world for energy storage. Now such stations are used purposefully to implement green energy into the grid, as Spain and other states do.

Lithuania reached the farthest of the Baltic countries in developing ESS technology at the present moment. Firstly, for many years Lithuania operates PHES, which was once built next to the Ignalina nuclear power plant, which provide 768 GW of energy in 2020 year to the grid, secondly, Lithuania plans to build a 100 MW Battery Energy Store System. Some energy storage projects are also planned in Estonia, the largest of which is PHES in Paldiski with a capacity of 500 MW.

Electricity can be stored in electric fields (capacitors) and magnetic fields (SMES), and via chemical reactions (batteries) and electric energy transfer to mechanical (flywheel) or potential (pumped energy storage) energy or pressure (compressed air energy storage) energy forms. Different technologies are suitable for solving different problems and achieving different goals. ESS technology can be divided by the duration and response speed. There are long, medium and short run systems and fast or fast response speed storage technologies. Pumped energy storage has been the main storage technique for largescale electrical energy storage (EES). Battery and electrochemical energy storage types are the more recently developed methods of storing electricity at times of low demand. Battery energy storage developments have mostly focused on transportation systems and smaller systems for portable power or intermittent backup power. Different technologies also have different costs. A more favorable price is achieved with a scale effect, ie the higher the capacity of the EES to be built, the cheaper the MW hour construction. However, it is not always possible to achieve the required result by a large scale to solve local problems. Although measuring ESS only by construction price does not fully reflect the picture. As a more specific parameter, LCOE is used, which includes not only construction costs but also operating and disposal costs. The long-acting lowest cost level is PHES, the medium-acting Lead-acid and the short-acting lowest cost level is Super Conductor Energy System storage.

The ESS can be implemented in the energy system in several ways. There are lots of ways to use energy storage in power systems, which include increasing renewable energy penetration, load leveling, frequency regulation, providing operating reserve, improving micro intelligent power grids and s.o. And different technologies are suitable for different purposes. The same technology can be used for many different purposes, so PHES is suitable for peak shaving, load leveling and frequency control. However, there is no universal technology, it is not possible to choose one specific technology, there is its own suitable technology for every situation. It is much more important to find the answer to how the technology is chosen. Many countries have gone the path of a free market economy, for example by purchasing a frequency regulation service. With that said, there is hope that the market for energy storage technology will be based on the principle of a market economy and that state subsidies will not be tied to the free market. Then market participants will certainly be able to choose the most appropriate technology according to the principles of a market economy and the objectives set for the specific situation.

I am sure that sooner or later the first storage devices will be built in Estonia, it is clearly which technology will be used though. And it's hard to say whether this will be done on an experimental basis or at the point where energy storage is being built all around. It would certainly be very good if Estonia were a pioneer of new technologies. For example, despite the fact that PHES technology is the most widespread, the planned PHTES system in Paldiski has not yet been implemented anywhere in the world. All Estonian energy producers trade in a large energy market, where energy projects compete with each other and the most important task for the state is to ensure that the creation of new storage projects takes place in all countries of the trading area on the basis of the same principles. If we succeed in achieving a situation where the energy storage market operates as a free market, it is then up to investors to decide which technologies are best suited to solve the task of one grid or another, and to choose the most efficient ways to store energy.

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Annexes

Annex 1. Technical and economical specifications of various ESS technologies, part 1

ESS technology	Power range (MW)	Energy rating (kWh)	Energy density (Wh/kg)	Power density (W/kg)	Discharge time (ms-h)	Response time (ms-h)	Round trip efficiency (%)
Mechanical Energy Storage Systems							
Pumped hydro-energy storage	10-5000	$2x10^5$ - $5x10^5$	0.5-1.5	—	1 - 24+ hrs	min	70-85
Flywheel Energy storage	0.01-0.25	25-5k	29342	700- 12000	sec - 15 min	sec	90-95
Compressed air storage (underground)	5-300	$2x10^5$ – 10^6	30-60	—	1 - 24+ hrs	min	41-75
Compressed air storage (overground)	3-15	2 - 8.3	140-300 bar	—	2 – 4 hrs	sec - min	70-90
Electrical Energy Storage Systems							
Supercapacitor energy storage	0.01-0.3	0.001-5	0.05 - 15	10 – 10^6	ms – min	ms	85 - 95
Superconducting magnetic energy storage	0.01-10	15-100, 5x106	0.5 – 5	500 - 2k	ms – sec	ms	90 - 97
Chemical Energy Storage Systems							
Hydrogen (FC)	0.3-50	< 200k	600-1.2k	5 – 800	sec –24 hrs	Sec	30 – 50
Electrochemical Energy Storage Systems							
Conventional							
Pb-A	< 20	18k-100k	30-50	200-400	sec – 5 hrs	ms	70-90
Ni-Cd	< 40	6.75k	15-55	150-350	1 – 8 hrs	ms	75
Ni-MH	< 0.03	0.01-500	60-80	150-460	hrs	ms	70-80
Li-ion	0.05-100	250-25k	120-230	150-2k	min - 1 hr	ms	85-95
Na-S	10-34	245k	150-240	150-230	6 - 7.2 hrs	ms	75-90
Na-MeCl2	0.005-1	120-5k	86-140	180-245	sec-hr	ms	90
Zn-air	0.01-1	60-150	1k – 1.3k	90-105	10 – 15 hrs	ms	50 - 65
Flow Battery							
VRFB	0.01-10	4k-40k	25 - 35	—	5 – 10 hrs	ms	60-75
HFB (ZBB)	2-10	50-500	65 – 75	—	8- 10hrs	ms	60-80

Annex 1. Technical and economical specifications of various ESS technologies, part 2 []

ESS technology	Lifetime (yr)	Lifecycle (cycles)	Instalation cost €/kW	Energy cost €/kWh	Daily self-discharge (%)	Operating temperature (oC)	Nominal V oltage (V)	Technical maturity
Mechanical Energy Storage Systems								
Pumped hydro-energy storage	30-60	—	500- 1.8k	5-100	Null	Ambient	—	Mature
Flywheel Energy storage	15-20	20k- 100k	400- 1650	1000- 5000	1.3-100	20 to 50+	—	Commercial
Compressed air storage (underground)	20-40	8k-13k	500- 1.4k	50-400	~0	Ambient	—	Developed
Compressed air storage (over ground)	~ 20	0.5k- 1.8k	1k- 1.55k	200- 250	~0	Ambient	—	Developed
Electrical Energy Storage Systems								
Supercapacitor energy storage	25-30	100k- 500k	80- 800	300-2k	10-40	-40 to 85	2.3-400	Developing
Superconducting magnetic energy storage	20-30	20k – 100k	165- 400	1k – 10k	10-15	-162 to - 253	—	Demo/early
Chemical Energy Storage Systems								
Hydrogen (FC)	5-15	1k – 10k	400-10k	1 – 15	~0	50-100, 600-1k	0.2 - 1.1	Demo
Electrochemical Energy Storage Systems								
Conventional								
Pb-A	5-15	500-2k	150-500	150- 400	0.1 – 0.4	-30 to 50	2.0-2.35	Mature
Ni-Cd	10-20	800-2.5k	500-1.5k	600- 2.4k	0.2-0.3	-45 to 60	1.2	Mature
Ni-MH	5-10	800-3k	120% of Ni- Cd	120% of Ni-Cd	0.4-1.2	-20 to 45	1.2	Mature
Li-ion	20-25	1k – 10k	1.2k- 4k	400- 2.5k	0.15-0.3	10 to 60, -20 to 60	3.6-4.2	commercial
Na-S	10-15	2.5k-4k	3.2k- 4k	300- 500	0.05-20	300-350	2.1	commercial
Na-MeCl2	5-15	1k-1.2k	150- 300	230- 345	15	270-350	2.58	commercial
Zn-air	>1	1k - 2k	100- 250	60-160	very small	0-50	1.0 – 1.3	Demo
Flow Battery								
VRFB	10-20	>12k	1.4k – 3.7k	500- 800	small	10-40	1.4 – 1.5	Developing
HFB (ZBB)	5-10	>2k	1.8k – 2k	100- 700	small	20 - 30	1.82	Developing