Technologies for storing electricity in medium- and long term – potential in Finland

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1 Abstract

More renewable energy production is being installed worldwide every year. Although the technology of renewable electricity production is constantly developing, various sources, such as wind and solar power, are still prone to intermittent generation. Thus, in order to avoid over- and underproduction via spikes of generation, there needs to be technology implemented to store this excess intermittent energy. As of 2019, the share of renewable electricity generation in Finland was 47 % and the share of wind and solar is further expected to grow in the coming years (Energiateollisuus, 2020). This is mainly because wind is becoming ever more competitive and thermal generation is being reduced in the market due to for example the due coal ban in 2030.

Storage technologies are developing rapidly and the demand for storage solutions continues growing. An analysis of current potential in the Finnish market is thusly needed. Multiple European countries such as Germany, Spain and the Netherlands have announced their hydrogen strategies and for example Germany has earmarked 9 billion euros to support their hydrogen strategy by 2030.

There is a lively discussion upon the perspectives on energy storage in Finland among the experts. On the basis of the polls made during the event organized by Aalto Energy Platform it has been forecasted that:

- The predominant energy storage type in terms of energy capacity will be thermal energy storage in district heating grids. It was followed in the second place by electrical energy storage in grids, integrated with power plants and in electric vehicles. In the third place were Power-to-X technologies.

- The predominant electrical energy storage (in terms of energy capacity) built by 2040 in Finland will be battery installations. In the second place are hydrogen technologies. However, it is worth mentioning that hydrogen technologies got approximately two times less votes than battery technologies. Pumped hydro will have a marginal impact.

- In terms of the application of electrical energy storage, the most economic potential in Finland lies in renewables integration. Right after it are ancillary services and peak shaving. Grid deferral and price arbitrage will have much less impact.

This report provides an initial insight into various energy storage technologies, continuing with an in-depth techno-economic analysis of the most suitable technologies for Finnish conditions, namely solid mass energy storage and power-to-hydrogen, with its derivative technologies. The main goal of the report is to provide a basis for further energy storage research and development in Finland, specifically by presenting initial results of the analysis for the Finnish Energy.

2 Project scope

The project aims to investigate the potential of different energy storage technologies in Finland. These should be able to store electrical energy and use it to produce electricity, heat, or different chemicals. Table 1 represents the general set of technologies that are currently used or researched worldwide. In the Figure 1 a chosen group of them can be compared in terms of discharge time, capital cost and operating cost.

Table 1. Energy storage groups.

Technology group	Type of technology or energy carrier
Electrical	Supercapacitors
Electrochemical	Batteries, Flow Batteries
Chemical (Power-to-X)	Hydrogen, Ammonia, Biogas, Synthetic Natural Gas, Biofuels, Fuel cells
Mechanical	Pumped-Hydro Energy Storage, Compressed Air Energy Storage Liquid Air Energy Storage, Solid Mass Gravitational Storage, Flywheel
Thermal	Sensible and Latent Heat Energy Storage

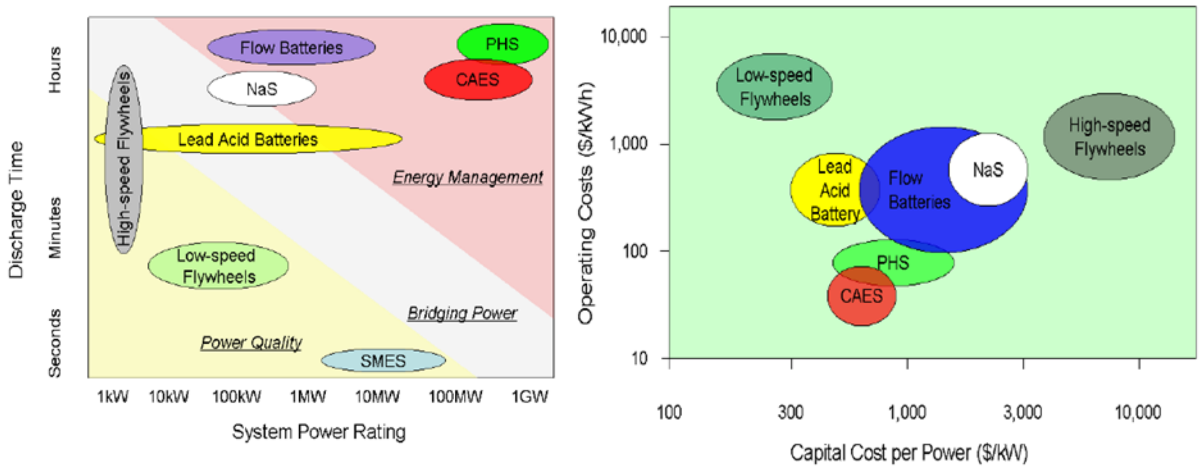


Figure 1: Comparison of CAES with other technologies in terms of discharge time, capital cost and operating cost (Mark Howitt, 2018)

Duration of storage is an important parameter as it dictates if a certain type of storage is well-fitted for the specific application. On one side there are batteries and supercapacitors that are adept at providing operating reserves and balancing power on the short-term while other types of storage, such as hydrogen or other power-to-X technologies often allow storage in the long term in the forms of hydrogen methanol, ammonia, or synthetic gas. This allows proper response towards seasonal variations in the output of renewable electricity and can simultaneously provide substances important for the process industry. Additionally, heat and cold storage technologies allow the usage of cooling or heating storage in seasons when needed, increasing energy efficiency, and reducing the operational cost of installations. For the above-mentioned reasons both long- and short-term energy storage solutions are important. This report focuses mostly on long-term storage solutions and their role in Finnish conditions. The scope will primarily consist of the possibilities in utilizing energy storage technologies for storing excess electricity produced intermittently by various sources. When increased renewable energy capacity is achieved, proper established energy usage strategies need to already be implemented.

There are multiple electrochemical energy conversion technologies available in the market and researched in laboratories. However, these are excluded from the scope of the report. The reason for this is that some of them are not well-fitted for long-term energy storage because of technical and economic issues. Batteries and supercapacitors are used more short-term with the aim to stabilize the local grids and provide backup for shorter time windows. It thus seems more to investigate the potential of other technologies that are less well known to see what their role in the future could be.

After having assessed potential storage technologies, the project goes more in depth into a couple of them, namely Solid Mass Gravitational Energy Storage, and Power-to-Hydrogen with its possible derivatives. The selection was mostly based on maturity or certain lack thereof, feasibility in Finland, cost, and available literature & projects. Many of the other technologies seemed like they had already been thoroughly researched for Finland and mature, or on the other hand too new and underdeveloped for this project. These options may still have their applications and potential, but they are not what we want to focus on for this project.

Solid Mass Gravitational Energy Storage has good potential in old, decommissioned mines in Finland. As other, more conventional potential-based energy storages usually need mountains, fjords or similar, Solid Mass Gravitational Energy Storage provides opportunity for both the utilization of used mines, as well as a new method of storing large amounts of energy.

Power-to-Hydrogen is the basis for countless energy storage solutions. Earlier the problem has been the price of electrolysers, but the current trend is pointing towards a rapid decrease from the current prevailing numbers that are often cited. Hydrogen’s energy density keeps it as one of the most interesting choices for the future. With the current, already planned projects getting realised in the coming years, we wanted to make sure to include Power-to-Hydrogen with all the flexibility it can bring.

The role of thermal energy storage technologies in upcoming years is growing, because in the markets it is seen to be having higher energy density and lower cost than the electrochemical batteries.

The energy sector is in a need to balance the supply and demand with its intermittency problems more efficiently on a large scale. The production surplus caused by for example high winds or industrial waste heat needs to be properly used in the future.

It is very important to find good feasible energy technology solutions because most of the primary energy sources are consumed in the form of thermal energy. Thermal energy storage (TES) has big role in future of energy storages and specially when trying to develop long energy storage systems.

3 Possible long-term energy storage applications

In this chapter we will introduce different long-term energy storage technologies for electrical energy. We have grouped up storage technologies based on their basic operating principles and then further divided them more accurately based on the energy carrier. Then technologies used to produce or store the energy carrier were identified and the most potential ones were researched. The technology classifications can be seen from Figure 2.

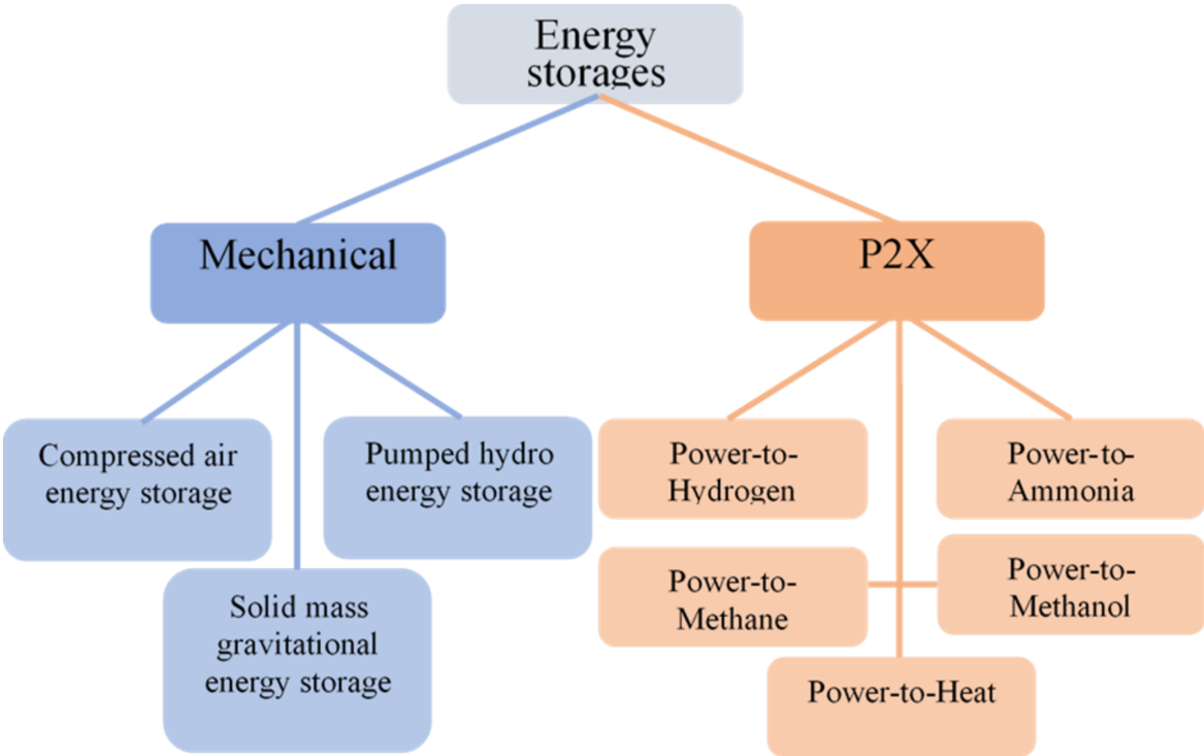


Figure 2: Long-term electrical energy storage classifications that are in scope of this paper

The focus of the research was on energy capacity, lifetime, and economical characteristics of the storage applications. The maturity of the technology was estimated based on characteristics and current ongoing projects and operational units.

3.1 Electrical energy storages

3.1.1 Pumped hydro

Pumped hydroelectricity energy storage (PHES) is one of the most elementary forms of gravitational energy storage, the working principle of which lies within storage of potential energy by pumping water from lower reservoir to a higher one and production of electric energy through release of water through hydro turbines. Currently, PHES is seen as one of the most efficient energy storage forms, with round-trip efficiency of up to 85% and storage duration varying from hours to days. Additionally, advantages of PHES include ability to adapt to drastic load changes, to maintain voltage stability, and possibility of fast response speed (Rehman et al., 2015). However, despite a great potential to provide peak power sufficiency, utilization of PHES in Finland is rather challenging due to geographical restrictions, as pumped hydro plants require sufficiently large water reservoirs and large height difference between lower and higher reservoirs. Specifically, PHES is the most suitable energy storage technology for islands and mountain regions, leaving potential of utilization in Finland relatively low (Gimeno-Gutiérrez et al., 2015).

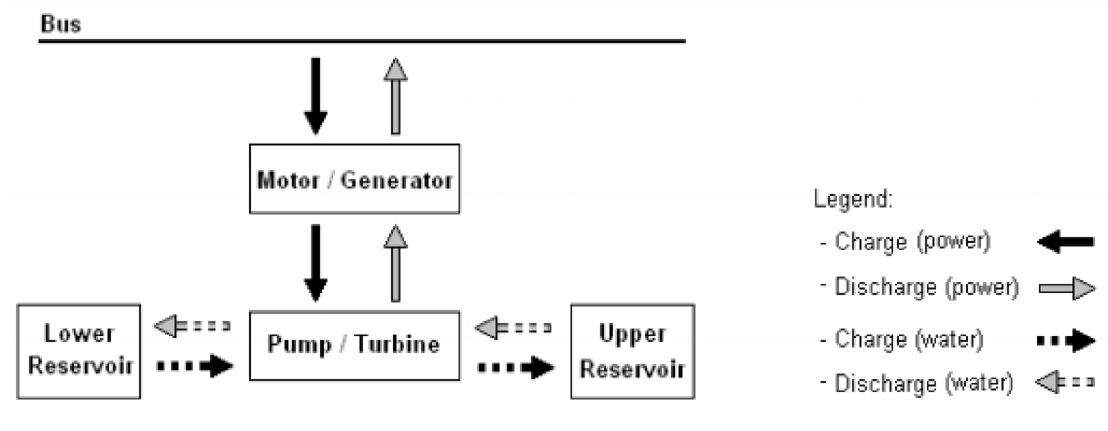


Figure 3: Operation principle of PHS (Faias et al., 2008).

Globally, the largest PHS sites are the Bath County storage plant, the U.S., the Huizhou storage plant, China, and Okutataragi plant, Japan, with installed capacities of 3003 MW, 2448 MW and 1932 MW, respectively. In Europe, the largest storage plant is located in Spain, La Muela, with installed capacity of 1780 MW.

Historically, the largest PHES installation and development was concentrated in countries operating on partially liberalized electricity markets, enabling pumped hydro plants to be operated by state grid distributors. Moreover, researchers debate that the economical feasibility of pumped hydro would be dependent on wholesale electricity market architectures of liberalized markets. Currently, although providing great round-trip efficiency, large-scale pumped hydro plants are among the costliest energy storage systems, with construction costs varying from 1000$/kW to 2500$/kW and with payback period of around 40-80 years (Gimeno-Gutiérrez et al., 2015). Considering geographical and economical complications of the energy storage form, it is important to thoroughly analyze feasibility of implementation of PHES in Finland region.

Although possibilities to build efficient pumped hydro storage plants in Finland are scarce, the usage of decommissioned mines for plant building has potential according to experts of AFRY. Since 2016, a project for pumped hydro plant installation has been ongoing in Pyhäsalmi mine, which is the deepest base metal mine in Europe. The project is operated by engineers of AFRY Pumped Hydro Storage Sweden AB, and Callio Pyhäjärvi. The estimated capacity of the storage plant varies between 200-400 MW (Pumped Hydro Storage SE, 2020).

3.1.2 Solid mass

Unlike PHES, Solid Mass Energy Storage (SMES) is a novel method of utilizing gravitation for energy storage. Although the method is not currently operating as a full-scale technology in the market, researchers claim SMES to be a promising long-term storage technology especially for grids with small demands. Moreover, in comparison with pumped hydro storage, reduction of scale in SMES applications would hypothetically reduce the total cost of plant installation. The method is thoroughly researched in the article by Hunt et al. (2020).

Currently there are various methods of utilizing solid mass and gravitation for energy storage. Some examples include lifting concrete blocks (Energy Vault, 2020), lifting compacted earth materials (Riffat et al., 2019), carrying solid mass with trains (ARES, 2020), and lifting heavy weights in underground shafts (Gravitricity, 2020). Although technological implementations differ in lifting materials and areas of operations – underground or open shaft mines, uneven geographical terrains – the principle is common for every variation.

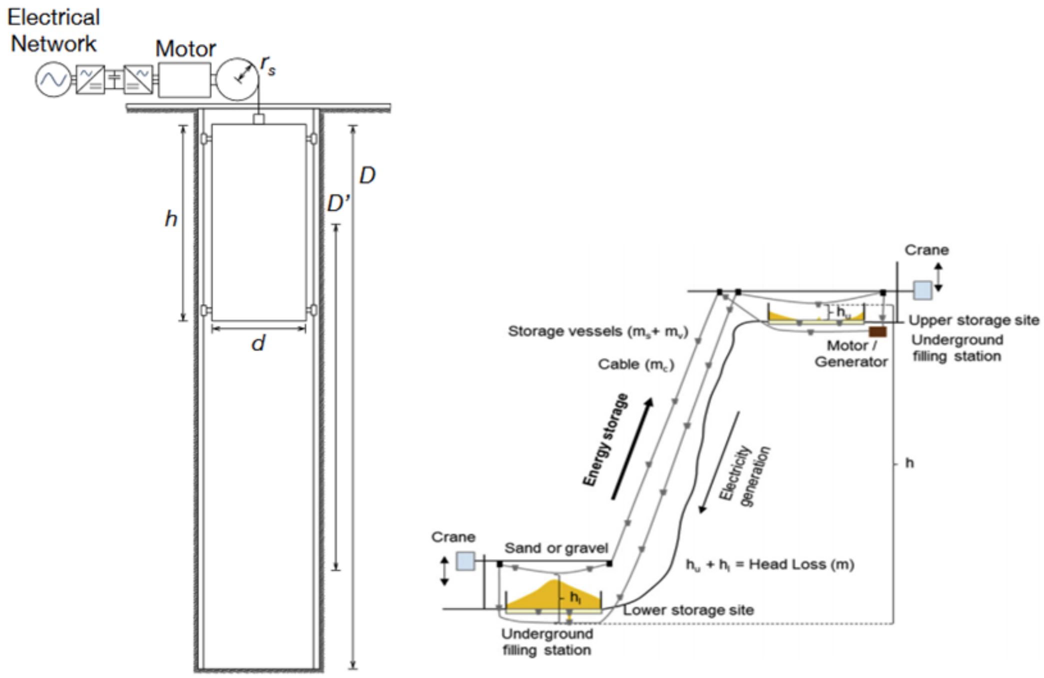


Figure 4: Technological approaches for gravitational energy storage (Riffat et al., 2019; Hunt et al., 2020).

One of the novel applications of SMES is Mountain Gravitational Energy Storage, operating on potential and kinetic energy, similarly to PHES. In MGES, the energy is stored in elevation of gravel or sand from an underground filling station onto upper storage site. The electricity is produced by lowering the mass. The technical efficiency of the method lies within the difference between upper and lower storage sites, as well as storage mass.

As a basis, the storage is done by lifting heavy loads on suitable height, implementing the potential energy:

$$E = m * h * g * e$$

Where E is stored energy, m is load mass, h is the height difference between upper and lower loading sites, g is acceleration of gravity, and e is the efficiency of the system. Additionally, depending on the system functions, other variables can consider, such as head loss (Hunt et al., 2020) or parameters of suspended weight load and characteristics of lifting ropes (Morstyn et al., 2019). The power of the system can be calculated with an equation for power:

$$P = \frac{E}{t},$$

Where P is the generated power, E is the stored energy, and t is the time of load lifting. From the equation it can be seen, the lifting time should be minimized in order to generate more power. However, for Mountain Gravity Energy Storge technology, utilizing natural geographical height differences for load lifting, the comparison of different speed, load mass and height difference arrangements shows that the higher speed of lifting lowers the storage cycle. Simultaneously, larger load masses increase the long-term energy storage potential and storage cycle. Thus, by optimizing system variables and by utilizing existing mines, quarries, and hill terrains, the gravitational storage technology could be suitable in Finnish conditions for long-term energy storage (Hunt et al., 2020).

According to the research, the highest efficiency of the system can be achieved with low speed of mass lifting and by minimizing the mass of storage vessel and cable, as these variables affect the head loss negatively. However, with optimal design and efficiency maintenance, the MGES would achieve yearly storage cost of 40-85 EUR/MWh, whereas yearly storage cost of pumped hydro is approximated to 85-125 EUR/MWh.

One of advantages of MGES includes utilization of decommissioned mine pits, as such location has already a height difference available and could be filled with load mass material. Thus, there is a potential of MGES technology utilization in Finland, especially in decommissioned mines. Additionally, the technology can be combined with hydropower in case the location has river streams, creating a hybrid MGES-hydropower plant and increasing the storage potential of the plant system.

As Finland is one of the most developed country in mining field of Europe, there is a potential to use decommissioned mines for various energy storage methods, among which pumped hydro is one of the piloted projects (Pumped Hydro Storage SE, 2020). Similarly to pumped hydro, other mechanical energy storage forms might be implemented in the mines with sufficient heights. Thus, the potential of implementation of solid mass or gravitational energy storage in Finland has to be investigated.

In order to estimate feasibility of technology in Finland, the case example could be modelled on an existing mine in Finland, which already is under an ongoing energy storage project – the Pyhäsalmi mine. The mine provides a great height difference between the ground surface and shaft bottom of at least 1400 m.

3.1.2.1 Mines in Finland and feasibility for SMES technology

Finland has started mine mapping process, focusing on closed and abandoned ones. According to the Ministry of the Environment of Finland, there are over 1000 mines that have been excavated. However, 428 mines were found to have a high risk for environmental hazards. The rest of the 600 mines consisted of e.g., metal ore or industrial mineral mines. They were not included in mapping if the amount of extracted waste deposit is less than 1000 tones or the total quarrying volume is less than 10 000 tons (Räisänen et al., 2013).

All the mines that are going to be reused again need to go through the risk analysis by the Ministry of the Environment guidelines (Tornivaara, 2020). The risk analysis could include an analysis of the ground content, which helps to assess the heterogeneity of rock/sand content and further investigate the mine in case of collapse or leakage issues.

The risk involved in the reusage of mines for SMES is related to environmental issues and geological characteristics of mines. To evaluate the mines and their feasibility regarding SMES technologies, the following points need to be considered:

- Depth of mine (the maximum possible depth is limited, the wire ropes need to support their own weight, and the overall cross-sectional area of the ropes must fit within the shaft)
- The suspended weight (varying the maximum mass of the suspended weight on the energy storage potential) of the mine shaft will directly affect the energy production (kWh)
- The need to consider the range of power system services when sizing the motor and power electronics.
- The needs of the existing electricity grid system near the mine
- When redeveloping abandoned mines, more information needs to be collected by using surveys and feasibility studies. Also, the cost of the SMES technology needs to be compared to other energy storage options.

With the data of total mines in Finland, their depths and diameters, we could have done the same evaluation as in the article by Morstyn et al. They evaluated gravity energy storage technologies by using suspended weights for existing abandoned deep mine shafts in UK using GIS- program. They were able to determinate the total potential energy storage capacities for all mine shafts.

3.1.3 Compressed air energy storage (CAES)

The implementation of a broad mix of storage technologies will be necessary with increasing amounts of renewable energies. Herein, CAES, as a technology that is able to shift energy in the timeframe of some hours up to several days, fills the gap between short-term battery and long-term conversion storage technologies like Power-to-X. Moreover, CAES installations can operate for a long time (20-40 years).

3.1.3.1 Principle of operation

Compressed air energy storage technology uses 6 major devices, as shown in the Figure 5. The respective devices are indicated with the letters: Compressors (A), Turbines (D), Heat exchangers (B), Heat sources (C), Tanks (E), Motor/Generator (M/G)

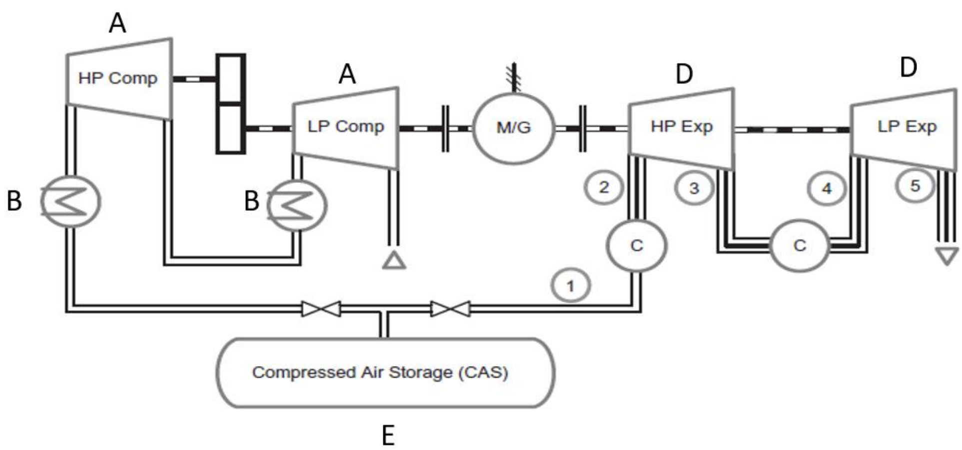


Figure 5: A simplified scheme of a typical CAES installation (Budt et al., 2016)

The excess energy is being transmitted by the motor to the compressors that compress the air. There are several steps in compression because between them the air needs to be cooled down with heat exchangers through which the cooling medium flows. The reason for this is that the air heats up significantly due to compression. After the last stage of compression, the air enters the tanks. Those could be either artificial or natural (underground spaces and caverns). If the energy is needed, the valves to the turbines are opened and the compressed air is released. Before it gets to the turbine it gets preheated to increase the amount of energy that can be harnessed by the turbines. The air is heated up between the stages of the turbine to maximize the energy yield. The turbines are connected to the generator that delivers the electric energy to the grid.

Although current CAES facilities are equipped with heat recovery systems, they still need to burn fossil fuels to increase both the initial air temperature and the turbine efficiency, thereby causing serious environmental pollution in the form $CO_{2,}$ $NO_{x,}$ and SO_x emissions. Traditional CAES systems generally use (porous, salt, or hard) caves to store high-pressure gas. However, because of its relatively high price and low efficiency, CAES development has remained stagnant.

Additionally, it is worth highlighting that from energy density point of view it is better to store the air in an underground cavern instead of artificial tanks. The former is capable of withstanding higher pressures, which means that from the same volume more energy can be harvested using underground spaces.

The majority of the world's projects on CAES are based on non-independent systems, requiring to be associated with the gas turbine plant. The existing projects tunning on CAES technology can be found in the appendix.

3.1.3.2 Feasibility

CAES systems are designed to cycle on a daily basis and to operate efficiently during partial load conditions. This design approach allows CAES units to swing quickly from generation to compression modes. Installation costs for CAES facilities vary depending on the type of underground storage but are typically in the range from 40 USD/kWh, possibly dropping to 30 USD/kWh if an existing reservoir is available (IRENA, 2017). The location of CAES – based power plants (large scale) relies on the geographical location. It is the most feasible to build such installations near rock mines, salt caverns, aquifers, or depleted gas fields. It is projected that compressed air energy storage, although based on a combination of mature technologies, will see 17% reduction in cost by 2030. It is relatively low if compared with forecasted installed cost reduction of batteries up to 50-60% (IRENA, 2017).

3.1.3.3 CAES in Finnish conditions

CAES may use either natural or artificial gas containers. In terms of the latter, no specific geological characteristics is needed. However, it has to be discussed if there is access to underground natural caverns that would serve well as the storage tanks. It is important because using the natural caverns enables to increase the pressure of stored air and consequently allows to store bigger amounts of energy in the same volume.

Finland has a stable bedrock, resulting in good possibilities for CAES. For instance, it has been described that CAES can be utilized in old mines. Even though there have been studies on the possibilities of building a CAES in Pyhäsalmi, the same mine as discussed in pumped hydro energy storage (PHES), the latter technology has won this competition. It is harder to find good conditions for CAES underground because it requires a closed, tight space in order to build up the required pressure. Rock which is dense and airtight enough is usually found deep in mines, in caverns and smaller spaces. Since Finland has a stable bedrock and abandoned mines, some of them could be a good fit for pilot CAES installation. However, a big number of limitations for it makes it hard for this technology to set off in Finland. The reasons for this and suggestions for improvements are presented in the appendix.

3.2 Power-to-X technologies

Power-to-X technologies are a very versatile option as a storage solution as they offer possibility to utilize electrical energy as different end products through other energy carriers. For example, electrical energy can be stored as heat which can be utilized in the heating sector later. In addition to heat, electricity can be used to produce gases and liquids which have multiple possible end-uses. Some P2X projects have been listed in Appendix 1.

3.2.1 Power-to-Hydrogen

Hydrogen is produced from water with electricity using electrolysers. Electrolysers presented in this paper are of the alkaline and PEM variety. Hydrogen is utilized in the production of methane, methanol, and ammonia so the cost of hydrogen is key for the potential and competitiveness of these other Power-to-X products. Solid oxide electrolysers are not in the scope of the project since they are still in research phase.

3.2.1.1 Alkaline electrolyser

Alkaline electrolysers operation is based on anode and cathode constituted in a potassium hydroxide. Anode and cathode are separated by a diaphragm. Water is split at cathode forming hydrogen and hydroxide. Hydroxide travel through the diaphragm and form oxygen at anode. Alkaline electrolysers are a mature technology (Abbasi et al., 2019; IEA, 2019).

Some key advantages of AELs are brought by their maturity: capital costs are lower than PEMel and they have longer lifetime. The current densities of AELs are lower than with PEM and the response time of AEL is longer which makes them less suitable for operating with variable renewable generation. AELs also operate with lower pressures which requires them to use compressors when hydrogen is stored (Abbasi et al., 2019; IEA, 2019).

3.2.1.2 Proton exchange membrane electrolyser

PEM electrolysers operation is based on splitting water electrochemically into hydrogen and oxygen. Water is pumped to anode where it is split to oxygen, protons, and electrons. Protons move to cathode through membrane. With help of external power circuit, the electrons move to cathode. Then protons and electrons recombine to hydrogen at cathode side (Kumar et al., 2019; Abbasi et al., 2019; IEA, 2019).

Some advantages of PEM electrolysers are high current densities, compact system design and quick response time. Disadvantages of PEM electrolysers are high cost of components due noble metals usage in key components and low durability. PEM electrolysers are in very early commercialising phase and developments are still expected to happen. One advantage of PEM electrolysers over AELs is that they can produce highly compressed hydrogen. This is an advantage if hydrogen needs to be stored since there is no need to invest into a compressor. The features of PEM electrolysers allow them to operate very flexibly which makes them capable to be connected to wind farm or to operate in the balancing market (Kumar et al., 2019; Abbasi et al., 2019; IEA, 2019).

3.2.1.3 Key parameters of electrolysers

National Renewable Energy Laboratory (NREL) did an estimation of the manufacturing costs of PEM electrolysers and extended the analysis to cover CAPEX of PEM electrolysers. In their study they found that the manufacturing costs depend heavily on the power of the stack and on production volumes. At low production volumes 0.2 MW stack cost was estimated to be around 2500 $/kW but for 1 MW system it was estimated to be around 1100 $/kW so roughly 2100 €/kW and 900 €/kW, respectively. In European Green Deal call the CAPEX of electrolysers were estimated to be 600 €/kW for alkaline and 875 €/kW for PEM electrolyser. However, for this data it is not clear what exactly has been included in the costs but at least for PEM electrolyser it seems to be in line with what was estimated by NREL.

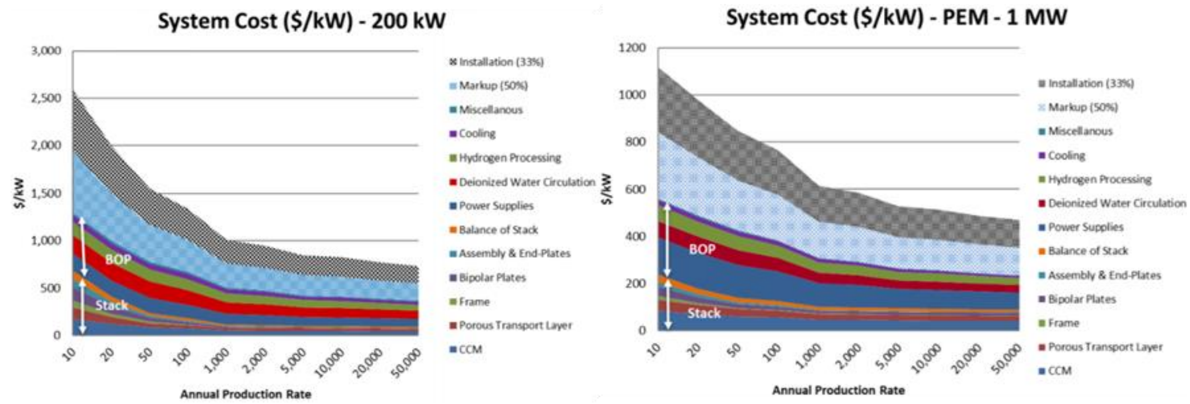


Figure 6: Estimated system costs of PEM electrolyser (NREL, 2019).

Glenk et al. estimated the alkaline costs to be around 1100 €/kW in 2016 and them to drop to 800-900 €/kW in 2020. For PEM they estimated the costs to be around 1800 €/kW in 2016 and 1000-1500 €/kW in 2020. 1000 €/kW is based on estimates from manufactures and scientific journals. 1500 €/kW is an exponential fit of PEM cost estimates.

With different sources of estimates the CAPEX data seems to vary quite a bit and many journals refer to older papers with their CAPEX assumptions. Sources of variation might come from some sources excluding certain components that the plant requires for operation. However, new CAPEX data should become available when all the new electrolyser projects are progressing.

Sources for text and table: (Shiva Kumar, Himabindu, 2019) (Abbasi et al., 2019) (Schmidt et al., 2017) (Selma Brynolf et al. 2017) (NREL, 2019) (European commission, 2020) (Glenk et al, 2019).

Table 2: Parameters of electrolysers.

	Alkaline electrolyser	PEM electrolyser
Investment costs (€/kW)	600-900	900-1500
Efficiency (%) LHV	55-60	60-75
Life span (years)	30-40	5-20
Operating temperature (°C)	30-80	20-80
Fixed OPEX costs	1-3 % of CAPEX	1-3 % of CAPEX

3.2.1.4 Storage and transmission of hydrogen

Hydrogen is in a gaseous form under normal pressure and temperature which opens certain ways of distributing it but can also cause challenges. Naturally, it would be the cheapest option to produce it as close to consumption as possible. The majority of it is therefore produced on-site (around 85%). However, if that is not possible there are multiple different ways to distribute hydrogen and then it depends on local conditions which method is the cheapest. Even though hydrogen has high heating value it has low energy density per volume. This adds a challenge to storing since it requires either very large storage or hydrogen needs to be for example compressed. Different hydrogen transmission methods are:

- Blending to natural gas network
- Pipelines
- Shipping by ground or by sea
    - As compressed gas
    - As liquid
    - As other chemical (for instance ammonia)
      (IEA, 2019)

Table 3: Parameters of different hydrogen distribution methods (IEA, 2019).

Technology	Parameter	Units	Hydrogen
Pipeline (high pressure)	Lifetime	Years	40
	CAPEX	mEUR/km	0.43
	Annual OPEX	% of CAPEX	-
Trucks	Lifetime	Years	12
	CAPEX	tEUR	157
	Annual OPEX	% of CAPEX	12
Trailers	Lifetime	Years	12
	CAPEX	tEUR	Liquid: 850 Gas: 553
	Annual OPEX	% of CAPEX	2
	Net capacity	kgH^2	Liquid: 4300 Gas: 670

The Finnish legislation offers an interesting option to transfer hydrogen on road due to less strict limitations on weight and size of trucks than in Europe in general (Business Finland, 2020). When it comes to utilizing the natural gas grid, the existing infrastructure would have to be modified to include additional monitoring and maintenance measures. In Finland, the pipeline modifications would not be big because Finnish gas network is to a large extent made of polyethylene, which means that it could be converted to hydrogen use at a relatively low cost. However, according to some sources other technical aspects allow only for 1% of hydrogen content in the gas grid (Dolci et al., 2019).

Storage options for hydrogen are presented in Table 6. Based on distribution methods the compressed, liquefied, and geological are the most interesting options.

Table 4: Parameters of different hydrogen storage methods (Korpela, 2020).

Technology	**Geological**	**Compressed gas**	**Liquid hydrogen**	**Pipeline**
CAPEX (€/kg)	0.6-45	460-3300	28-1100	470
OPEX (€/kg)	1.6-6.1	0.9-2.4	1.9-47	0.9-2.4
Capacity (kg)	$1\text{-}20 \cdot 10^6$	0.089-1300	0.089-900 000	-
Operating pressure (bar)	10-150	5-800	1	15-100
Efficiency (%)	97-99.5	99.5	23.2-80.3	-

Geological storage

Large scale and long-term hydrogen storage options are available with the use of salt caverns, depleted natural gas or oil reservoirs and aquifers. They are successfully used in natural gas storage and provide low operational costs, high efficiency, and low land costs. It means that this method can be the most cost-effective to store hydrogen. The geographical distribution, large size and pressure requirements make this method less suitable for short-term storage that can use storage tanks.

Storage tanks

Hydrogen in storage tanks can be kept either in compressed gaseous or liquefied form. The tanks have high discharge rates and efficiencies of around 99% and are well-fitted for smaller scale. Compressed hydrogen has merely 15% of gasoline’s energy density (if compressed to 700 bar). This means that the size of refuelling stations would have to be bigger if they were to be equivalent to the petrol ones existing today. There is an ongoing research into more viable storage solutions using higher pressure (800 bar). There is also a possibility of storing hydrogen in metal and chemical hydrides, but those methods are at their early stage of development.

Finnish conditions

In Finland there are no existing hydrogen storage installations using geological formations. This means that the only way to store hydrogen is to apply storage tanks. It generates challenges because of technological barriers that make it hard to store large quantities of hydrogen under specific conditions. The investment and maintenance cost are still too high. This is why only about 15% of world’s hydrogen is stored and the rest is used on-site.

3.2.1.5 Feasibility

Hydrogen as a storage technology is not limited by its storage capacity since the storage is quite cheap and has multiple storing options. However, some complications regarding the storage comes from the lower energy density of hydrogen even though it has a high heating value. Also, the location of the electrolysers can complicate the utilization of the hydrogen. The main limitations for hydrogen are the production costs of green hydrogen versus hydrogen created from fossil fuels.

Hydrogen is very versatile and can be utilized in many different sectors. Hydrogen can be used in CHP production or just to generate electricity. CHP would be preferable in most cases as separate electricity generation has low efficiency. Adding it to the losses in hydrogen generation, very low percentage of original energy amount would be utilized. Hydrogen can also be utilized in transportation sector with fuel cell vehicles and potential can be seen especially in the heavy vehicles of the transportation sector. SSAB in Raahe aims to make their steel production carbon free in 2025. This means that hydrogen has potential also in industry. Chemical industry is also interested in green hydrogen. Hydrogen can be used to make methane, methanol and ammonia which extend the use cases of hydrogen even further.

Based on the versatility, use-cases, attractive investment programs in Europe and scalability, hydrogen can be seen to have significant potential in Finland. The profitability however is unclear and depends on multiple variables. As majority of the lifetime costs of hydrogen come from the electricity costs and smaller part from capital costs (OPEX [excluding electricity] being relatively small) the future electricity prices and their volatility and capital costs define if it economically makes sense to use hydrogen as storage method.

3.2.2 Power-to-Methane

There are 2 alternative ways to produce methane from hydrogen; biological and chemical. Methane is made in an exothermic reaction of hydrogen and carbon dioxide. Current chemical methanation technologies include fixed-bed, fluidised-bed, three-phase and structured reactors. Fixed-bed and fluidised reactors are most mature technologies. As the production of methane requires carbon dioxide a way to capture carbon dioxide from other processes. Potential sectors include for example energy generation and cement industries (Carriveau et al., 2016).

3.2.2.1 Operating parameters

Efficiency does not include efficiency of electrolyser and CAPEX cost does not include electrolyser investment costs either.

Table 5: Parameters of methane plants (Thema et al., 2019).

	Biological methanation	**Chemical methanation**
Investment costs (€/kW)	1200	800
Efficiency (%)	78 %	78 %
Life span (years)	10	10

3.2.3 Power-to-Ammonia

While ammonia traditionally has been produced from mainly gas, hydrogen-based ammonia could prove to be a good solution in terms of versatility and transportability. The chemical industry could see Power-to-Ammonia as a way to go green, either by buying ammonia, or producing it themselves internally. The agricultural sector is the biggest user of ammonia in the world and half of the industrial hydrogen is used in ammonia production.

Because Power-to-Ammonia is based on hydrogen, the same electrolyser costs would generally be used. There are certain production methods that could prove better than those above, but they are either very immature technologies such as Solid Oxide Electrolytic Cell (SOEC) or specific to only ammonia production such as Low Temperature Solid State Ammonia Synthesis (LT SSAS). The exception to this is battolysers, which do not scale linearly but instead to the power of around 0.6 because of the ammonias synthesis loops economies of scale.

3.2.3.1 Feasibility

The feasibility of Power-to-Ammonia is mainly based on the price of gas-produced ammonia. While the electrolyser costs have gone down making green hydrogen-production (and thereby green ammonia) cheaper, it is still not quite at the level of gas-produced ammonia. Higher carbon prices could quickly turn that around however, so green ammonia might be the less risk-filled option to take in not too long. For a few years now the argument has been that the electrolyser cost must be cut from 1000 €/kW to 300 €/kW for Power-to-Ammonia to be feasible. Marginal costs for P-2-A are around 431 – 528 €/t while ammonia from gas is at around 300 – 350 €/t. The competition would equalize if gas rises about 70 €/MWh or the CO2 emission price to over 200 €/tCO2 (Power-to-ammonia in future North European 100 % renewable power and heat system, 2018).

3.2.4 Power-to-Methanol

Methanol, similar to ammonia, has a very broad usage as a product and also share the excellent transportability. The main factor for transportability and storage is the fact that methanol is at normal temperatures in a liquid state and doesn't thus require high pressures. It can be produced at a relatively high efficiency compared to other chemicals and can also be transformed back into electricity. The same electrolyser costs apply as for hydrogen and this is the biggest cost here as well. Methanol is also commonly reused for fuels, which makes the applications worldwide.

The main electrolyser technologies would apply here as well, mainly PEM, alkaline and SOEC. It also uses some form of carbon capture or direct feed to then combine it into methanol.

3.2.4.1 Feasibility

The cost of methanol is around 300 €/t. Because of the better production-efficiency, some estimates show Power-to-Methanol to be about 15% cheaper than P-2-A. These numbers are however based on the pre-2017 P-2-H costs. Most of the world's ethanol usage is in Asia, with China using up 58 % and the rest of Asia-Pacific 16 %. Europe uses only 13% in total and most of that is based around the middle of Europe (Bos et al., 2020).

Without green incentives it is difficult to make Power-to-Methanol profitable. Methane is still relatively cheap which is the main competitor. Methanol production from methane is often a more profitable solution than introducing it as a storage solution

3.2.5 Power to heat- Thermal energy storage

Power-to-heat technologies are technologies that can convert electricity into heat. Electricity can be converted into heat with different technologies by using renewable energy sources or main grid sources via district heating plants, heat pumps and electric boilers.

One of the ways to utilize the heat from different source is using thermal energy storage systems. Thermal energy storage (TES) provides solutions for long term energy storage. Thermal energy storage (TES) uses materials with different thermal properties where wanted products, heat and cool can be achieved.

Thermal energy can be storage through three process stages, which are charging, storing, and discharging.

TES is divided into three categories:

1. Sensible heat storage
2. Latent heat storage
3. Thermochemical heat storage.

Sensible heat is performed by sensible heat of temperature change whereas latent heat is performed by phase change.

Thermochemical heat storage is working on reversible chemical reactions using high reaction enthalpy. The charging and discharging processes can be performed by controlling the reactant concentrations. The advantages of thermochemical heat storage are high energy density and easy adjustments in the system. There are some issues related to technology coupling reaction, heat and mass transfer, that is why thermochemical heat storage is currently only in the lab-scale stage (Celsius, 2020).

Thermal energy storage not only helps with long thermal seasonal storage issues, but it also can reduce peak demand and increase the total efficiency of energy systems.

3.2.5.1 Types of thermal energy storages

Aquifer thermal energy storage (ATES) is based on warm or cold groundwater in an aquifer. The storage media is underground water with sand and gravel layers (Akhmetov et al., 2016).

Tank thermal energy storage (TTES) is used as seasonal tank storage, which is partially buried in the ground. Tank is thermally insulated on the vertical walls and on the top (Akhmetov et al., 2016).

Cavern thermal energy storage (CTES) is using underground reservoir to storage thermal energy in caverns or in pits (Sarbu et al., 2016).

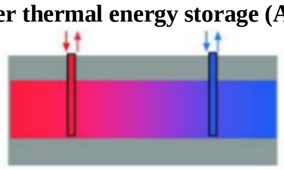
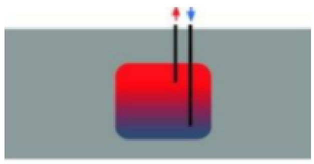
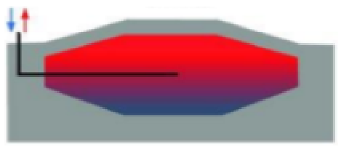
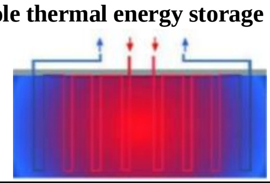
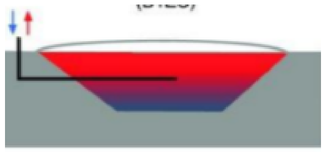
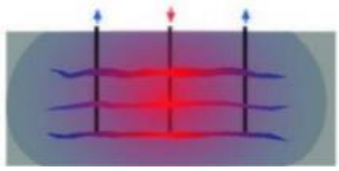
Borehole thermal energy storage (BTES) uses vertical borehole heat exchanger (BHE) where thermal energy is transferring between BHE and subsurface layers. The storage media is underground material, rock, and soil (Akhmetov et al., 2016).

Pit thermal energy storages (PTES) is buried into the ground in the pit, where pit is insulated (Akhmetov et al., 2016).

Fractured thermal energy storage (FTES) is used for seasonal storage of thermal energy, where artificially made fractured hard rock aquifer is filled with fluid and heat transfer takes place between the sub-horizontal fracture planes and the fluid (Janiszewski et al., 2020).

There are different types of thermal energy storages available in the market. The most known ones are listed in Table 6 alongside with their advantages and disadvantages.

Table 6: Types of thermal energy storages, advantages and disadvantages (Source: Hassam, 2020; Janiszewski, 2020; Akhmetov, Bet al, 2016; Janiszewski et al, 2018).

Types of thermal energy storages	Advantages	Disadvantages
Aquifer thermal energy storage (ATES) 	• Efficient for heating and cooling • Green option • Easily applicable	• Geologically dependent • Balance between charging and discharging difficult
Tank thermal energy storage (TTES) 	• Easily scalable • Applicable anywhere	• Space requirement • High capital cost • Heat loss of small systems
Cavern thermal energy storage (CTES) 	• Large storage capacity • High power in charging and discharging	• Geological specification (needs hard rock) • High capital cost
Borehole thermal energy storage (BTES) 	• Good for seasonal storage • Practical and modular	• Low storage efficiency • Limitation in power when charging and discharging
Pit thermal energy storage (PTES) 	• Good for seasonal storage • Large storage capacity • Can be installed anywhere	• Low energy density • Gravel costs high
Fractured thermal energy storage (FTES) 	• Investment cost lower than in BTES • Good for seasonal energy storage	• Homogenous rocks • Successful operation depends on aperture in the fracture planes

3.2.5.2 Feasibility

The feasibility of TES is based on a specific design and technology. The boundary conditions are related to operation cost, storage material and requirements for charging and discharging the storage device.

The cost of sensible heat storage (SHS) decreases as the size of the storage material increases, but overall sensible storage is inexpensive technology. The SHS costs depend on application, size and the insulation technology that are used.

The cost of latent heat storage (LHS) system is based on phase change material. Thermochemical storage system costs are higher than in SHS and LHS (Sarbu, 2018).

Better comparison with selected thermal energy storage systems is shown in chapter 5.

There are numerous projects under the thermal energy storage. Some existing project related to thermal energy storage are listed and can be found in the Appendix 1.

Table 7: Parameters of thermal energy storage (Source: Sarbu, 2016).

TES system	Capacity (kWh/t)	Power (MW)	Cost (€/kWh)	Efficiency (%)	Storage period
Sensible (hot water)	10-50	0.001-10	0.1-10	50-90	d/m
PCM	50-150	0.001-1	10-50	75-90	h/m
Chemical reactions	120-250	0.01-1	8-100	75-100	h/d

*h=hours, **d=days, ***m=months

4 Techno-economic analysis of the chosen technologies

In this chapter we will analyse the potential of solid mass gravitational storage and hydrogen in Finland. We have used AFRYs BID3 electricity market modelling tool to identify the short-term need of large-scale electrical energy storages in 2025. The model showed very modest need for large-scale electrical energy storages from the viewpoint of electricity system. However, the need for storages is obvious in longer term as variable renewable generation capacity and demand is expected to grow significantly more.

Potential of hydrogen usage in Finland is large and demand for hydrogen is most likely going to grow due carbon neutrality target for 2035 set by the government (Ympäristöministeriö, 2019). Hydrogen showed potential especially in steel, cement, and chemical industry but despite recent rapid development in electrolyser manufacturing sector the cost of green hydrogen has to reduce more for it to be economically feasible in comparison with the fossil fuels.

4.1 Electricity market analysis

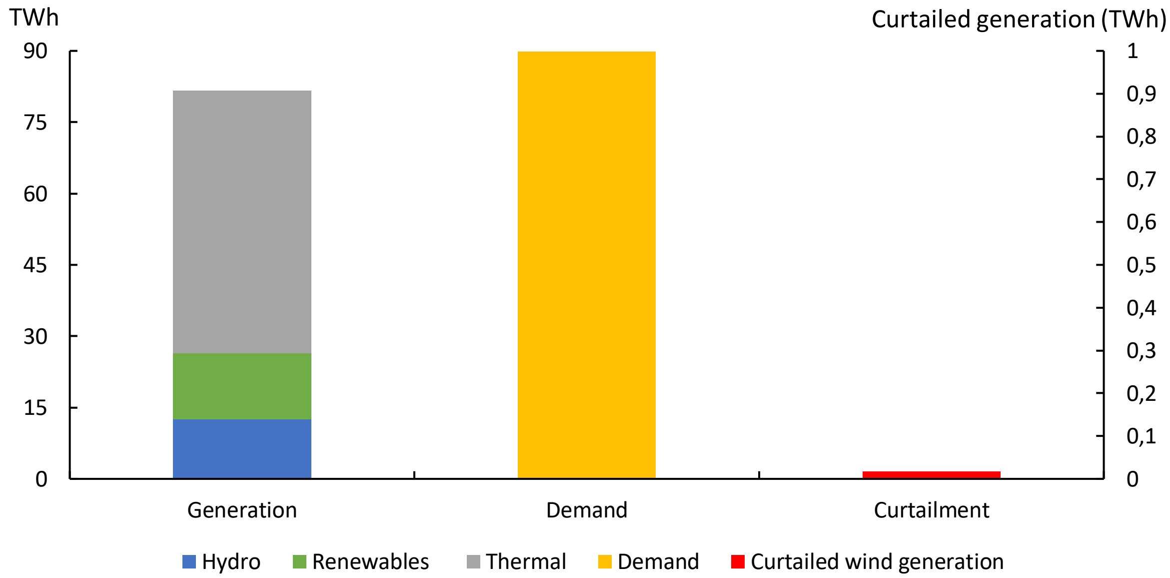
To estimate the amount of excess generation and the need for storage capacity we performed an analysis using AFRYs electricity market modelling tool BID3. The excess generation was estimated for year 2025. The following assumptions were used in the analysis:

- Demand
    - The demand estimate is based on base scenario of low carbon roadmap -report that was made by AFRY Management Consulting and published by Energiateollisuus in 2020. The demand was assumed to grow linearly and to be 90 TWh in 2025 (AFRY Management Consulting, 2020).
- CHP production capacity
    - Existing plants that are closed before 2025 have been removed from production capacity and new plants added
- Nuclear powerplants
    - Olkiluoto 3 was assumed to be operational alongside the current operational nuclear powerplants
- Wind capacity
    - Based on low carbon roadmap, Tuulivoimayhdistys and TEM (sähköntuotannon skenaariolaskelmat 2050) The wind production capacity was assumed to be between 4500-5000 MW so 4750 MW capacity was used. This means an annual increase of 400-450 MW of new wind power capacity from 2019 level (Tuulivoimayhdistys 2020; Työ- ja Elinkeinoministeriö 2019; AFRY Management Consulting, 2020).
- Crossborder transmission capacity
    - New transmission line between Finland and Sweden was assumed to be operational adding additional 800 MW transmission capacity from SE1 to FI zone (TEM, 2019)
    - Interconnectors are modelled but not shown in the results as focus is on curtailed generation
- Solar capacity

- Solar capacity was doubled from current levels but the produced amount of electricity was nearly insignificant (TEM, 2019).
- Weather
    - Years used were 2009-2018. An average result was formed based on these years. With utilization of BID3 the analysis was able to capture the effects of weather more accurately.

As can be seen from Figure 7, the amount of curtailed generation on average between years 2010-2019 was only 0.017 TWh. Depending on the weather year the amount of curtailed generation varied between 0.02-57 GWh being quite insignificant in relation to total generation amount. The average generation amount was around 82 TWh where 14 TWh was generated with solar and wind.

Figure 7. Generation and demand based on average weather year (2010-2019) and BID3 modelling. Curtailed generation has been plotted on the secondary axis.



Based on the results the demand for large-scale storages to capture excess generation is not yet on a high level in 2025. However, a separate analysis was performed using the hourly production data which was scaled to correspond to the production numbers of the average weather year with the following assumptions:

- Scaling the hourly production amounts and demands of 2018 per technology to the 2025 numbers
- Calculated the hours where renewables + nuclear were over 80-90 % of the hourly demand

The estimated number of hours where the price was assumed to be low was in the range of 50-450. As BID3 was **not** used for the price analysis (because of lack of own fuel scenario and hence not being allowed to report prices), the analysis could not capture the effects of water levels of Norwegian hydro plants or cross-border transmission capacities. It is very rough and simplified but works as a ballpark estimation. (Energiateollisuus, Sähkön tuntidata, 2019) The lower prices are interesting for storage capacity providers.

As described later the demand of electricity will likely rise a lot due to electrification of different industries. In response from the market side, it is very likely that in addition to the already planned nuclear capacity additions (Hanhikivi), the share of wind will rise significantly. Strictly viewing this from a market perspective, it will most likely have a few interesting implications:

1. Price volatility will increase, which is optimal for storages
2. As the majority of new industrial loads are caused by production of hydrogen or synthetic fuels, the demand is quite flexible

Combining flexible demand with overproduction of electricity is ideal for P2X. However, the remaining problem is the optimization of costs from an individual actor's point of view. The three main factors are:

1. Electrolyser CAPEX
2. Electricity cost
3. Storage cost

On one hand, if the cost of hydrogen or synthetic fuel storage is high, it might economically make sense to produce hydrogen even outside lower priced hours to keep the industrial processes running. On the other hand, the CAPEX cost of electrolysers also affects the price of hydrogen especially if full load hours are low (IEA, 2019). The future flexibility of the power system might strongly depend on the storage cost of hydrogen.

4.2 SMES technology analysis

In this chapter, the investigation is done by analyzing economic feasibility of theoretical storage plant installation, resulting in cost and risk estimation, as well as recommendations on technological implementation.

4.2.1 Economic feasibility

The economic feasibility of implementation is set with three variables: initial CAPEX, round-trip efficiency, and OPEX costs (Fyke, 2019). For estimation of economic feasibility of gravitational storage implementation in Finland, different variables of storage system and their costs have to be taken into account. For rough approximation of costs, we make assumptions for the system.

In order to estimate the initial CAPEX, the following variables of the system are to be considered: the type of mass load, the type of elevation gain, and the mechanism of mass movement as it is transitioning through the elevation. Thus, the most cost-efficient approach is to exploit the cheapest material as possible since the metric of greatest importance is the cost of load material.

As per article of Fyke A., the marginal cost of energy storage can be calculated as following (Fyke, 2019):

$$E\left(\frac{€}{kWh}\right) = \frac{load\ material\ cost\ per\ ton\ \times\ energy\ per\ kWh}{acceleration\ of\ gravity\ \times\ lifting\ height}$$

Let us assume a system with energy per kWh being 3600 J/kWh and lifting height being 100 meters, as in example of Fyke's calculation. In case of load material being building concrete, the cheapest cost of which would be 94,86 € /m^3 (Rudus Oy, 2020), the marginal cost of energy storage would be:

Material cost per ton:

$$V_{concrete} = \frac{m_{concrete}}{\rho} = \frac{1000\ kg}{2400\,\frac{kg}{m^3}} \approx 0{,}4167\ m^3$$

$$cost = 94{,}86\,\frac{€}{\mathrm{m}^3} * 0{,}4167\ m^3 \approx 39{,}525\ €$$

Storage cost:

$$E\left(\frac{€}{kWh}\right) = \frac{39{,}525\ € \times 3600\,J/kWh}{9{,}81\,\frac{m}{s^2} \times 100m} \approx 145\ €/kWh$$

The equation leads to a conclusion that the most efficient way of reducing the marginal cost of the system would be decreasing the material cost and maximizing the lifting height – already at lifting height of 500 meters the marginal costs would drop to 29 €/kWh. Although the material cost can be optimized, one of the possible solutions for minimizing the marginal cost would be usage of excess solid mass of decommissioned or operating mines, where the storage system could be installed.

Along with material costs, the round-trip efficiency is another factor impacting the economic and technical feasibility of the technology. Thus, it is recommended to design the storage system in a way, where the friction of the load lifting or moving mechanism would be minimized. Such a mechanism would provide the system with increased efficiency and consequently decrease initial CAPEX. For instance, the system designed by Energy Vault increased the round-trip efficiency close to 90% by implementing vertical wire ropes for lifting the load.

Finally, the final costs are dependent on Operation and Maintenance costs, which constitute of moving parts of the system. As per Fyke, the O&M costs can be minimized by designing the moving parts of the system to be as simple as possible (Fyke, 2019). According to Berrada et al. (2017), the Operation and Maintenance cost can be estimated as 4€/kWh.

4.3 Hydrogen market analysis

The classification of hydrogen type is based mainly on its origin. There are three main origins referring to three different colours, described below:

a) **Blue hydrogen** is generated from fossil fuels, but it is CO_2-neutral. This is possible through CO_2 separation, storage and/or reuse.
b) **Grey hydrogen** is also generated from fossil fuels, but here CO_2 is not captured or stored. An example here could be using natural gas that is converted under heat into hydrogen and CO_2. This process is called steam reforming. It is estimated that to produce one ton of hydrogen, nine tons of CO_2 needs to be emitted.
c) **Green hydrogen** production uses water electrolysis. On this process water is split into hydrogen and oxygen under the influence of electric current and with the help of

electrolyte. This process is CO_2-free if the electricity used for electrolysis comes from emission-free sources like renewables.

To define the potential in hydrogen in Finland, we researched potential end-use sectors for hydrogen use. The most potential industries were defined to be cement, chemical, steel, energy, and transportation industries. For each of these industries we investigated the following questions:

- How much energy those industries use
- What is replaced by hydrogen
- Demand for hydrogen in those branches
- Electricity needed for hydrogen

4.3.1 Fuel consumption and emissions from the industry in Finland

Large-scale production is now the only way to produce enough goods for fast-developing branches of technology and business. Industrial scale of production needs large quantities of energy to run successfully. Figure 8 shows the industries that are the most energy – consuming. The main representatives are here chemical, metal and cement industry and heavy transport, including maritime. The majority of fuels consumed by these are fossil type, consisting of oil, and coal and natural gas. A part of electricity production also comes from non-renewable sources.

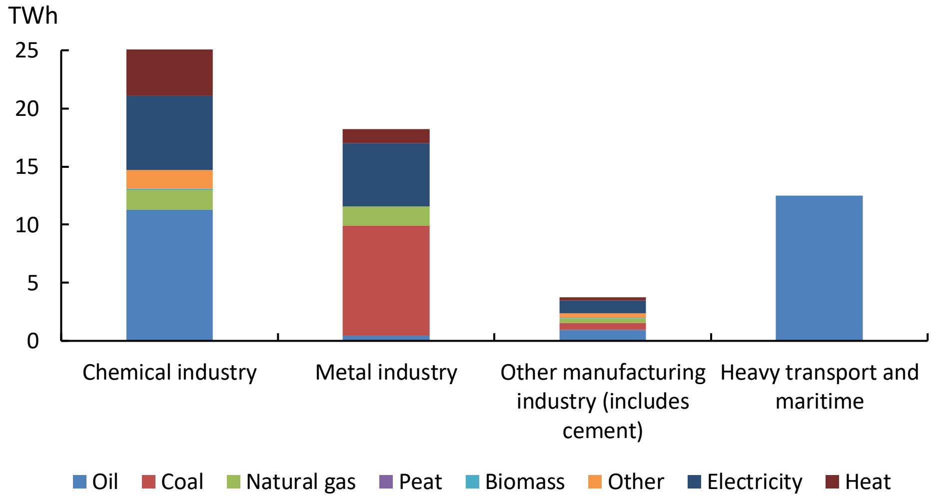


Figure 8: Consumption of fuels by different industrial sectors (Statistics of Finland, 2019).

The use of certain fuels reflects their impact on environment in the form of CO_2 emissions, as shown in the Figure 9. Decarbonizing the biggest emitters in Finnish industry is a big challenge, but the reward for it would be big as well. This ambitious goal can be accomplished partly by introducing hydrogen energy into their mix. The industries have been introduced and analysed in more detail in Appendix 2.

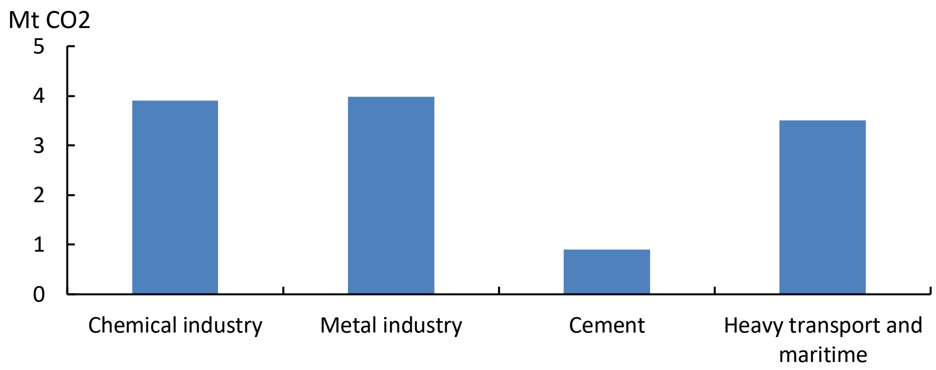


Figure 9: CO_2 emissions of biggest emitters from industrial sectors (Energiavirasto, 2019).

4.3.2 Hydrogen storage – A key to carbon neutrality?

Electrification of steel, cement and the chemical industry would increase the demand of electricity for hydrogen production by at least 19 TWh. This is roughly 2.2 GWh an hour. In Figure 10, the scaled-up wind production of 2018 (Energiateollisuus, 2019) is presented alongside the electricity demand for hydrogen by industry. The demand was expected to be flat. Due to high variety in supply to capture the excess energy and survive the times of low supply, storage of hydrogen is needed. The yearly amount of wind production is equal to demand.

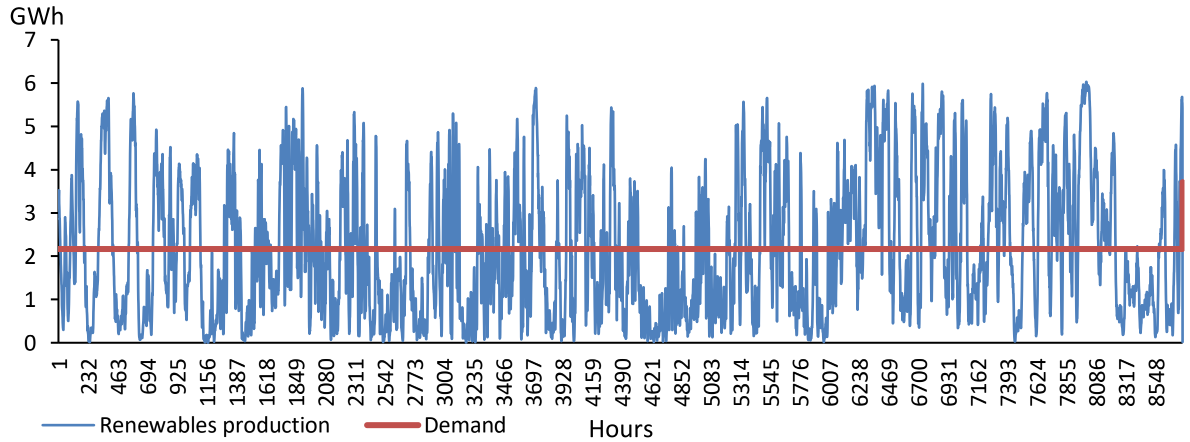


Figure 10: Hourly wind production and demand

In Figure 11 a very rough estimate of the needed hydrogen storage is presented in case hydrogen would be produced only with wind power. Amount of hydrogen is calculated based on hourly production levels with 65 % efficiency assumed for electrolyser and then turned the energy of hydrogen to kilograms. It is important to note that it may not be economically the best option to produce hydrogen with wind only as the required storage capacity is quite large. Especially during longer lower production times other sources of electricity could be utilized to significantly lower the needed storage capacity.

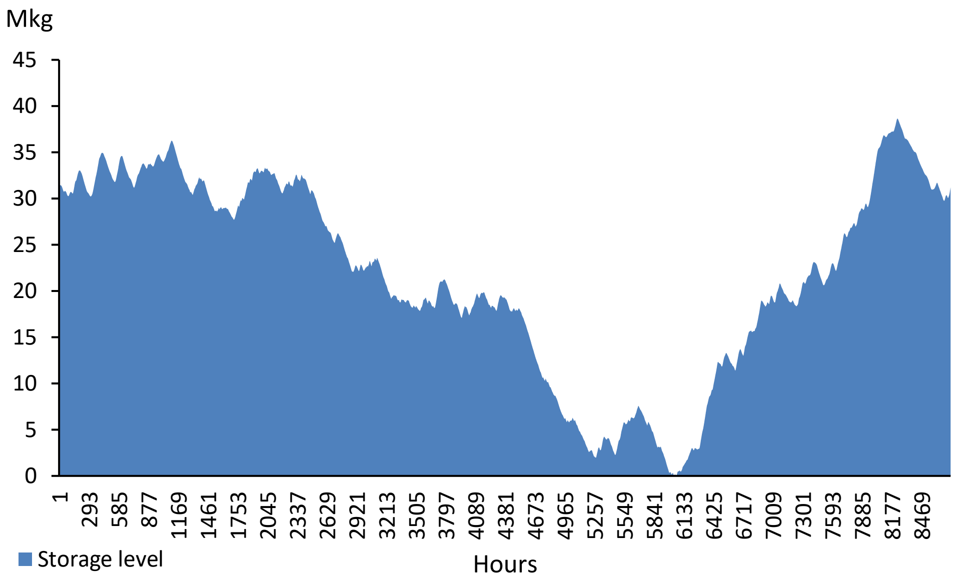


Figure 11: Very rough estimate of storage level of hydrogen

Since the increase of demand is large and wind power is currently one of the most potential technologies to be used to fulfil the demand of P2X technologies, storages are needed to balance the consumption and demand.

5 Energy storage capacities and comparison

The research done on different mechanical energy storage technologies provided characteristics for comparative analysis of technologies. The information on characteristics can be used to estimate the feasibility of technologies in Finnish conditions and to facilitate the decision-making in technology implementation. As shown in Table 9, solid mass energy storage has greater potential for successful implementation in comparison with PHS and CAES, as it has better overall efficiency, while the cost can remain relatively small. Although the range of the storage cost is wide for SMES, it can be reduced, as estimated in chapter 4.2.1 , and even the higher end of the range remains smaller in comparison with battery storage technologies.

Table 8: Comparison of characteristics of P-2-X storage technologies. (Source: The Engineering ToolBox; James, 2017; Karlsruhe IoT, 2018; Bos, 2020)

	Hydrogen	**Ammonia**	**Methanol**	**Methane**
Storage form	Gas / Liquid	Liquid*	Liquid	Gas
Mass Capacity (%)	100	17.5	5.3	25.1
Efficiency (%)	55-75	60-80	50	75
Storage capacity price €/kWh	13.8-99 / 0.84-33	2.9	0.44-0.58	-

*Applications for solid storage of ammonia exist, ** Stationary- and fuel cell vehicle applications

Moreover, the fixed O&M cost is the smallest in SMES among other mechanical storage technologies. As a result, SMES shows the highest potential for implementation among the mechanical storage technologies, especially since the technology is designed for long-term storage. In the scope of this report, battery storage technologies were not researched thoroughly, as the technology is designed mainly for short-term storage.

Table 9: Comparison of characteristics of mechanical and battery storage technologies.(Zakeri and Syri, 2014), (Cole *et al.*, 2020), (Flett, 2020)

Storage technology	**Overall efficiency**	Lifetime	Number of cycles	Storage cost (EUR/kWh)	Fixed O&M cost (EUR/kWh)
PHS	**0.8**	50	-	64	6.7
CAES	***0.55***	40	-	68	19.1
SMES	***0.85***	40+	-	29-145	4
Lead-acid	***0.85***	15	4500	416	3.4
Vanadium Redox Flow	***0.72***	15	10000	496	4.3
Li-ion	**0.95**	15	8000	320	3.4

The most commonly used seasonal or large- scale thermal energy storages are aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), pit thermal energy storage (PTES) and tank thermal energy storage (TTES).

Former stated thermal storage applications with large scale systems, can provide thermal storage capacity at moderately low cost. With the larger store, heat is lost less over time and cost benefits are much better than using many small stores with same capacity range.
The thermal losses are minimized during storage with insulation and the heat transfer medium is kept in the underground storage. The storage efficiency and capacity are varying depending on again on thermal insulation and storage medium. The most commonly used large- scale thermal energy storage systems are compared in Table 10. (Gustavsson, 2016; Celsius, 2020)

Table 10: Comparison of thermal energy storage systems (Source: Akhmetov, 2016; Janiszewski, 2020; Hassam, 2020).

Technology	**Storage medium**	**Heat capacity (kWh/m^3)**	**Storage efficiency %**	**Cost (€/kWh)**	**Storage volume for 1 m^3 water equivalent**
ATES	Sand-Water	30-40	70-90 %	2-8.55	2-3 m^3
BTES	Soil/Rock	15-30	30-60 %	2-3	3-5 m^3
PTES	Water	60-80	Up to 80 %	-	1 m^3
	Geavel-water	30-50		96.2	1.3-20 m^3
TTES	Water	60-80	50-90 %	167	1 m^3

6 Conclusions

While a lot of the technologies reviewed seemed interesting and showed future potential, only solid mass energy storage and power-to-hydrogen were fit for further investigation based on the scope. These technologies are currently being investigated worldwide, and especially power-to-hydrogen has several reviews scheduled to be released in the near future.

Compressed air energy storage is able to storage electricity long periods of time; however, Finland lacks natural reservoirs for air, and the plausible mines would benefit more from the use of hydro power or solid mass energy storage. Power-to-heat in large scale thermal energy storages such as aquifers, boreholes and caverns seem promising for the future. The currently limiting factors are material properties, geological conditions, market entry requirements and cost. The potential is significant and will need more investigating in the future as the technology has not yet reached maturity. The techno-economic analysis was further made based on the technologies that best fit our scope and seemed to have the most potential in the relative short-term, namely solid mass energy storage and power-to-x technologies excluding power-to-heat.

While other mechanical energy storage technologies have long been used, solid mass has several advantages that increases the potential for the future. As old mines are lying without use, solid mass could potentially find relatively easy applications there. Environmental problems and other hazards along with the limited amount of invested time and research projects makes the future still a bit uncertain. Because of the scalability, relative technological novelty, and potential storage cost reductions, it is one of the best bets for future gravitational energy storages.

Power-to-hydrogen currently seems like an excellent way of decarbonizing Finnish industry. While the storage technologies for pure hydrogen are currently underdeveloped, the need for it might not be too big, at least in the short-term. A lot of applications for hydrogen in for example the steel industry would be done on site and would thus not require huge amounts of storage. The derivatives of power-to-hydrogen, namely ammonia, methane and methanol all have varied uses. For example, the fertilizer industry relies completely on the availability of ammonia while the heavy transport and maritime industry need mainly liquid fuels, which can be filled by methanol. The strength of hydrogen lies in its varied use. As demand for hydrogen increases, so does also the storage need. The three big parameters are the costs of electrolysers, storage, and electricity. These three determine whether hydrogen production is feasible and economical and will probably be even more linked in the future.

Further investigation into all the technologies will be fruitful as the possibilities still have not been properly researched. While some technologies still have a long time until feasible, other storages such as hydrogen are already expanding.

Appendix 1

SMES Projects

Currently, there are various pilot projects either testing or aiming to utilize SMES, summarized in the table below. The information of existing pilot projects can be helpful to estimate the storage capacity or investment costs for implementation in Finland.

Table 11: Solid mass gravitational energy storage projects and companies (Energy Vault, 2020; Riffat S., 2019; ARES, 2020; Gravitricity, 2020).

	Energy Vault	**EarthPumpStore**	**Rail-based Gravity Storage**	**Gravitricity**
Storage capacity	20-35-80 MWh	-	Small installations 100-200 MWh Large installations 16-24 GWh	10 MWh
Country	Switzerland	-	USA	Scotland
Project Phase	Final testing of commercial demonstration		Construction	Construction
Timetable	2020 – final testing	2019 – filing a patent	2019 – expected construction finish	2021 - testing
Investment costs	~92 M€	~42 €/kWh		~1.2 M€
Working method	Concrete blocks	Compacted earth in open-cast mines	Carrying solid mass with trains	Heavy weight in abandoned mine shaft

CAES

There are several large scale projects that are being run using CAES technology. The two biggest facilities are placed in Huntorf (Germany) and McIntosh (United States). Their specifications are shown in Table 12 (Olabi et al., 2020)

Table 12: Chosen parameters for two most common CAES plants (Menéndez and Loredo, 2019)

	Huntorf	**McIntosh**
Investment costs (€/kW)	410	410
Efficiency (%)	42	54
Plant capacity (MW)	290	110
Number of salt caverns	2	1
Discharge time (hours)	2	26
Charge time (hours)	8	40
Max energy (MWh)	480	2000

In 2012, the world's third CAES project was completed - a 2MW wind generation project located in Texas, USA. Unlike the two other CAES projects, the Texas project, which involves near-isothermal CAES, uses no fuel. Since then, a few other CAES projects have been presented. Storelectric Ltd. plans to build a completely renewable energy plant in Cheshire, UK, which will store an energy of 800 MWh. Apex plans to construct a CAES plant in northern

Anderson, USA, and research is growing into no-fuel CAES technologies. Haddington Ventures Inc. plans to construct a 2700 MW plant in the United States at Norton, Ohio. Iowa Association of Municipal Utilities is planning to start a project with 200 MW of CAES generating capacity, with 100 MW of wind energy the compressed air will be stored in an underground aquifer, and wind energy will be used to compress air, in addition to available off-peak power. Additionally, Chubu Electric (Japan's third largest electric utility) was surveying its service territory for appropriate CAES sites (Chen et al., 2013).

Table 12 presents the key parameters of two already existing large scale CAES installations, including the efficiencies. The typical current value of storage efficiency of CAES is in the range of 60-80%, depending on the type of technology used and level of innovation of the solutions (Chen et al., 2013).

Similarly, to other energy storage technologies, CAES would be most economically feasible if it were used not only for one, but for combined purposes like peak shaving, load leveling, renewables support and emergency power supply.

Limitations and suggestions for improvement of CAES

There is a number of reasons why CAES has not become popular. Below are listed the most important ones:

- With combined cycle gas turbines (CCGT) and fast starting hard coal plants more economical flexibility options in comparison the D-CAES have arisen over the decades.
- CAES show lower cycle efficiencies than PHES (pumped hydro ES) or batteries.
- There is still no off-the-shelf machinery available that is suitable for highly efficient CAES plants, especially not for high temperature adiabatic ones.
- Geological restrictions and uncertainties arose in exploring suitable sites for underground CAES
- There is yet no specialized compressor and expansion equipment for high-efficiency CAES plants.

CAES, compared to other technologies, could become relatively cheap storage technology for a typical discharge period of several hours to days. Such discharge periods today are not viable economically in the majority of countries. Nevertheless, CAES might become successful if there is a business need for longer discharge periods. Additionally, this technology will be more attractive if the following issues are addressed:

- Increasing the start-up time to participate in the ancillary services market
- Decreasing the cost of the air reservoirs
- Enabling turbomachinery to be capable of being used as compressor and turbine (comparable to pump-turbines of PHES plants) which would lead to reduction of CAPEX
- Designing tools for detailed simulations of the performance of heat storage devices, operation of machinery and economic performance for charge/discharge profiles to enable fast decisions when a storage technology has to be chosen for a certain application in a certain market scenario.

Additionally, there some new ideas how to store the air. For this purpose, deep ocean bags can be used to fulfil the role of the natural cavities that are used at the moment. The deep-water acts as the pressure vessel. Scientist from Nottingham University claim that with this proposed technology the cost per unit of energy stored is in the order of 1-11 EUR / kWh, where pumped storage come in at 56 EUR / kWh and electrochemical stores are about 560 EUR / kWh. This comparison makes the technology based on ocean bags particularly attractive.

Power-to-Hydrogen projects

Multiple power-to-Hydrogen projects are ongoing in Europe now. However, these projects are pilot projects and not yet commercial projects. We have gathered basic information of some of these projects in Table 13.

Table 13: Selected hydrogen projects. Sources: (Orsted, 2020; Bioenergy International, H2Energy, 2019, Refhyne, 2020)

	GIGASTACK	EVERFUEL	H2ENERGY	REFHYNE
STARTING TIME	2019	2022	2017, 2019	2018 (planning, operational in 2021)
COUNTRY	United Kingdom	Denmark	Switzerland	Germany
PROJECT PHASE	Design study and stack development	Planning (20 MW electrolyser)	0.2 and 2 MW PEM electrolysers	Currently under construction (10 MW PEM electrolyser)
TIMETABLE	Mid-2021 and forward for deployment of the electrolyser	2023 for the first electrolyser	Both are operational	2021 forward
PROJECT TYPE	Pilot	Pilot	Pilot	Pilot

In addition to these there are multiple additional projects announced that have a target of large-scale electrolyser plants. Electrolyser projects in are running currently in North America, Europe, Australia, China and India. In Europe especially Germany has most electrolyser projects ongoing (62) according to IEA (IEA Data and assumptions).

From the start of 2000s to 2020 the average size of electrolysers power has been rising as well as the number of projects (Figure 12). From the start of 2020, which is not visible in the figure due missing data points, it is notable that the average power of electrolyser projects has started to rise significantly. The average project size in the database jumps to 113 MWe after 2020.

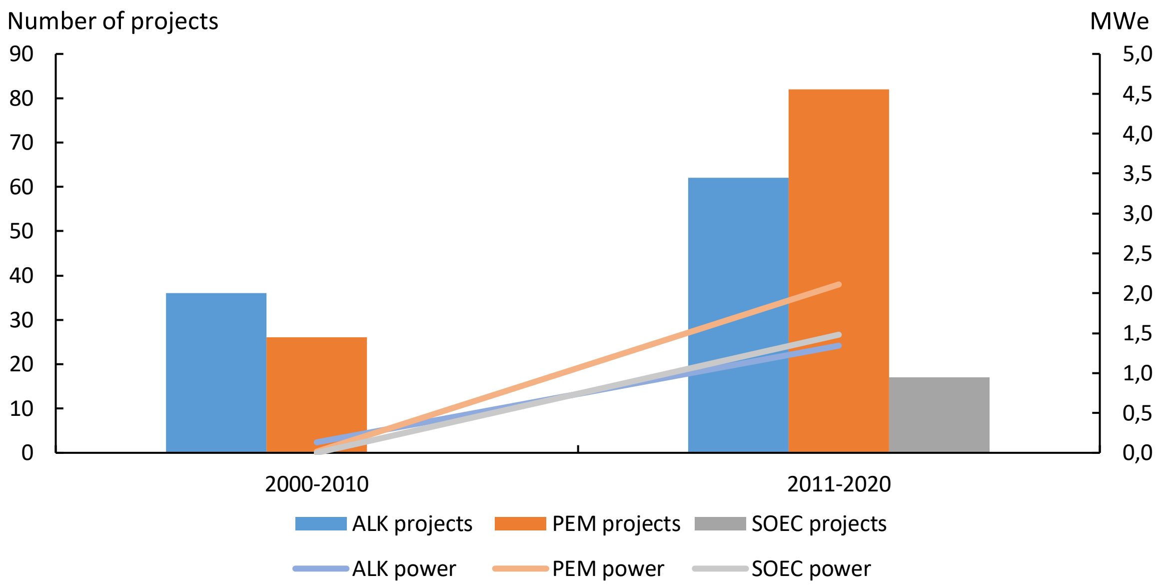


Figure 12: Number of electrolyser projects and their average size between years 2000-2020 (IEA project database, 2019)

Power-to-Methane projects

Some functional projects of Power-to-Methane are mainly located in Germany. Audi has 6.3 MW plant in Germany which utilizes CO2 from nearby biogas plant. In Finland Vantaan Energia and Wärtsilä are researching a possibility to build a 10 MW production plant producing biogas in Vantaan Energia's municipal waste CHP-plant. Produced gas could be utilized in replacing natural gas in their natural gas HOBs or alternatively as a fuel in transportation sector (Carriveau et al. 2016, Vantaan Energia, 2020).

Power-to-Methanol projects

Recent projects such as the industrial-scale demonstration plant built by the INOVYN consortium in Antwerp, Belgium, aim to reduce CO2 through carbon capture and combine it with hydrogen from renewable energy. The minimum emission reduction here would be 1t of CO2 per 1 ton of methanol produced (O'Reilly et al., 2020).

Tests in Germany by BSE Engineering have also proven conversion of wind power to renewable methanol with alkaline electrolysis.

Power-to-Ammonia projects

The ISPT has studies three potential projects as P2A business cases in the Netherlands. The NUON Eemshaven Case where ammonia would be used to store and/or import CO2, the Stedin Goeree-Overflakkee case where and islands power storage could be handled by ammonia and thus reduce grid investments, and the OCI case where renewable energy would be used for ammonia production to reduce gas usage. These projects were deemed to not be profitable but were based on the old 1000 €/kW estimations.

The thermal energy storage projects

There are numerous projects under the thermal energy storage. In this chapter we have chosen some existing project in Finland and other projects/ ideas that might be suitable for Finnish scale. Following projects could be suited in Finnish scale:

1. **Vojens** pit thermal energy storage in Denmark 210,000 m^3 of water and price is 24 EUR/m^3, the cost of building was 5.01 millions of EUR. Th idea of pit is to use solar energy to heat the water in the pit, which can be utilize as districting heating and cooling (Baerbel Epp, 2019).

2. **Helen Oy** has a project in Vuosaari, where heat pumps are used to utilize the heat from seawater. This project is supposed to finish by 2022, where district heating capacity of the heat pump is going to be 13 MW and the district cooling capacity is going to be 9.5 MW (Uusitalo, 2019).

3. Cavern Thermal Energy Storage : **Helen Oy** is building Finland's largest heat storage facility in the old oil caves in Mustikkamaa, where district heat can be stored. The cave is filled with water, which have the storage capacity of 260,000 m3. The amount of energy stored per year is approximately 140,000 MWh (Galkin-Aalto, 2018).

4. **Electric thermal storage** system by Siemens Gamesa Renewable Energy in Hamburg-Altenwerder, Germany. A custom built of 1000 tons of volcanic rock as a storage medium has been custom-built. The rock can be heated up to 750 °C by converting electricity into hot air with resistance heater and blower. During the peak periods, ETS releases the stored heat to regenerate electricity via a steam turbine. The thermal capacity of pilot ETS system can reach 130 MWh (around a week) (Gamesa Renewable Energy, 2019).

5. **SUNSTORE 4**: Provide power and heat production in periods with low production from solar and wind. A solar thermal system + A thermal storage + An electrical driven heat pump + A CHP-plant connected to district heating = produce heat to a price around 55 €/MWh (under Danish conditions) (Kjaergaard et al., 2014).

6. The aquifer thermal energy storage: **The city of Pukkila in Finland.** Project cost 1,06 million euro and overall energy production cost is to be 41.5 €/MWh (Todorov et al., 2020).

7. **Helen Oy's geothermal heating plant in Helsinki.** The production volume of a deep geothermal heat plant is estimated at 7GWh of heat per year. The project received a finance support of approximately EUR 5,892,000 (Työ -ja elinkeinoministeriö, 2020).

Appendix 2

Steel manufacturing industry

Production of metals is one big source of emission in Finland. One of the main sources is SSABs factory in Raahe. In 2019 the factory emitted 3.3 million tons of CO_2. The process can be electrified utilizing hydrogen and electricity. This would make it possible to produce so called "green steel" and lower the emissions of Finland significantly. As can be seen from Figure 13, the current process consisting of coking plant, blast furnace and basic oxygen furnace relies heavily on the use of fossil fuels. The lower option which utilizes hydrogen and in direct reduction shaft and electricity in electric arc furnace are more environmentally friendly options if electricity is produced with CO_2 free production methods. Bhaskar et al. estimated that from global emissions 61 % in steel making come from blast furnace and 21 % from coke production. Most of the emissions come from the utilization of coal (Bhaskar et al., 2020).

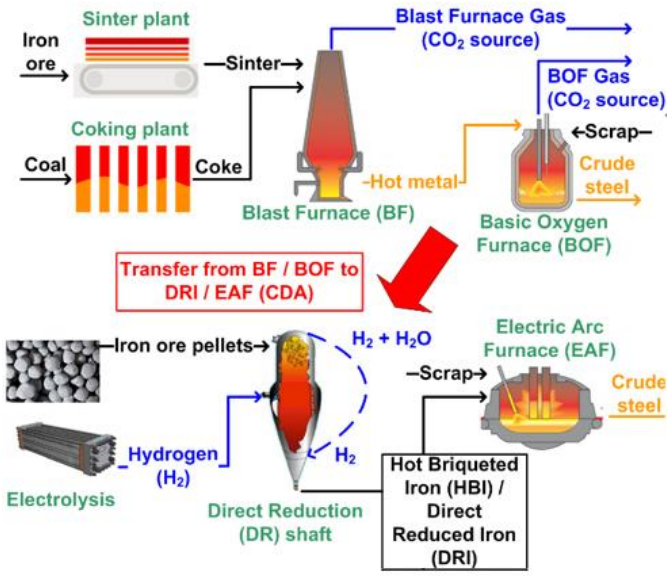


Figure 13: Old production method and new electrified method. (Source: LowCarbonFuture)

AFRY presented an estimation that electrification of steel industry would increase the electricity demand by 9 TWh where 7 TWh of electricity would go into electrolysis of hydrogen and other 2 TWh for other process electrification (AFRY Management Consulting, 2020).

Cement industry

Cement industry is a big global CO_2 emitter, contributing to around 8% of emissions worldwide (Lehne and Preston, 2018). This is due to the fact that cement production consumes substantial amounts of heat for preheating and the heating, calcining and sintering. It has been estimated that cement kiln heat demand is 870 kWh and electricity demand is 114 kWh per ton of cement. In 2017 Finnish cement industry produced 1 534 000 tons of cement and 1 181 000 tons of clinker (Finnsementti 2018). This leads to vast consumption of fossil fuels. However, it is possible to use renewables as fuels here, but currently the majority of companies use fossil fuels for those purposes. In Finland, the fossil fuel use in cement industry is around 50%, which is already a good achievement. The typical current composition of the fuels for cement production in Finland is as follows (Kuparinen, 2016):

- Coal – 9%
- Petcoke – 43%
- Crushed car tyres – 5%
- Recovered fuels (different plastics (not PVC), timber, non-returnable paper and cardboard, Styrofoam, and plastic foams) – 43%

Operation of thousands of kilns in the world could be improved by introducing new fuels based on renewables. In Finland only cement and lime factories were responsible for around 2.2% of CO_2 emissions in 2014.

Hydrogen combustion in cement kilns as a replacement for fossil fuels

One of the ways to reduce the negative impact on the environment is to use hydrogen in the cement kilns. It has been modelled that for the case of 85 MW cement kiln, if no solid fuels are used but only hydrogen, the plant would need 2 552 kg of hydrogen per hour. In this case there would be no need for hydrogen storage – an electrolyser would operate as an online equipment. In that case the electrolyser would have to have power of 126 MW (Kuparinen, 2016). It can reflect the cost of electricity for hydrogen production given the information that the facility operates 340 days per year. Investment profitability for electrolyser depends highly on electricity price and investment cost. Additionally, oxygen as a by-product would be sold or used as an enrichment in combustion. This would lead to savings in terms of fuel cost and emission allowance fee. It is estimated that if all of the Finnish cement were produced using hydrogen, the electrolysers would need approximately 2 GWh of energy. If the share of the hydrogen in the fuels would be 2.5%, the energy needed by the electrolysers would be approximately 0.18 GWh.

Energy industry

Hydrogen use in power generation and buildings

According to the projection of hydrogen demand for Finland by 2030 depicted in Figure 14, it can be concluded that power generation facilities and buildings will need substantially smaller amount of hydrogen for their operation. Therefore, it is suggested that more focus should be put on other parts of industry. However, it is worth introducing several options of use of hydrogen in above-mentioned fields.

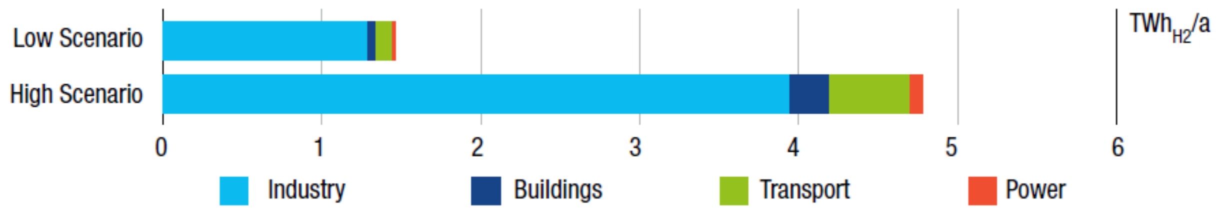


Figure 14: Scenarios for introducing Hydrogen Energy Technologies Considering the National Energy & Climate Plans (Fuel Cells and Hydrogen Joint Undertaking (FCH))

Hydrogen injection to the gas grid

Finland has consumed approximately 20.21 TWh of energy from natural gas in 2019. In total, over 90% of the natural gas is sold to large installations rather than by retail (Energiamarkkinavirasto, 2013). However, in Helsinki there are about 30 000 network-connected gas domestic users and around 300 restaurants. Both large and small installations can use the hydrogen-enriched blend to decrease their carbon footprint and increase the quality of air due to less NOx and SOx emissions, but its impact on the Finnish energy mix would be marginal, as it is estimated that in Finland hydrogen's share can be only 1% of the composition in the gas grid.

Use of ammonia in exhaust fume purification

Using ammonia to reduce emissions in coal-fired power plants is another way of utilization of this substance. Selective catalytic reduction (SCR) is a method of converting nitrogen oxides with the aid of catalyst into nitrogen and water. A reductant is typically ammonia or urea. The latter is easier to store because it is solid in room temperature. Ammonia on the other hand is either anhydrous or aqueous, which makes transport and storage much more problematic. If ammonia is produced locally from green hydrogen, it will create good symbiosis with selective catalytic reduction installations in power plants using fossil fuels and biomass.

Hydrogen use in power plants

It is not advisable to use hydrogen directly as a fuel because in this case the overall efficiency of the process will be low – combining efficiency of electrolyser (65%) and combustion (30-40%). However, in the case of combined heat and power the second efficiency will be higher, which makes this solution more economically feasible. It has been experimentally established that the CHP installation performs the best in terms of electrical efficiency when it operates with 10% of hydrogen in the fuel mix. Additionally, the enrichment of the mixture with oxygen can influence positively the efficiency. The best result in this case was obtained for 21.5% volumetric share (Basso and Paiolo, 2016). Nonetheless, it might be difficult to make modifications of safety and control parameters in commercial turbines to adapt them to hydrogen combustion. There are already hydrogen-fuelled gas turbines available in the market. General Electric alone has over 70 gas turbines supporting power generation with hydrogen and associated fuels around the world.

Recently a new fuel cell powered plant was built in Seosan, South Korea. It is an innovative project that has a power of 50MW and is claimed to generate 400 000 MWh of electricity annually. It uses recycled hydrogen from petrochemical manufacturing. Direct on-site hydrogen production skips the problem of storage in this case.

Finally, the service of demand response is another option for hydrogen use because of the flexibility and amount of base generation capacity of Nordic electricity market.

Transport industry

The transport industry is not only one of the biggest energy users, also one of the bigger polluters. Transport uses about 15% of the total energy in Finland at about 190,000 TJ and accounts for 21 % of greenhouse gases. By electrifying the transport industry, the use of petroleum products can be reduced significantly. The full reduction potential for road & sea freight in Finland is about 3.5 Mt carbon dioxide, which would be replaced by having 45,000 TJ of hydrogen-based fuels in heavy trucks and ships (Liikennefakta, 2020).

Road industry

Hydrogen can in various forms be used in road transport. Currently the price is still high for fuel cell vehicles as seen in Figure 15, but it is expected to fall drastically as the price of fuel cell systems drop in the future (Ajanovic & Haas, 2018). The biggest advantages here are that you can use pure hydrogen and thus keep the production chain as short as possible, reducing complexity

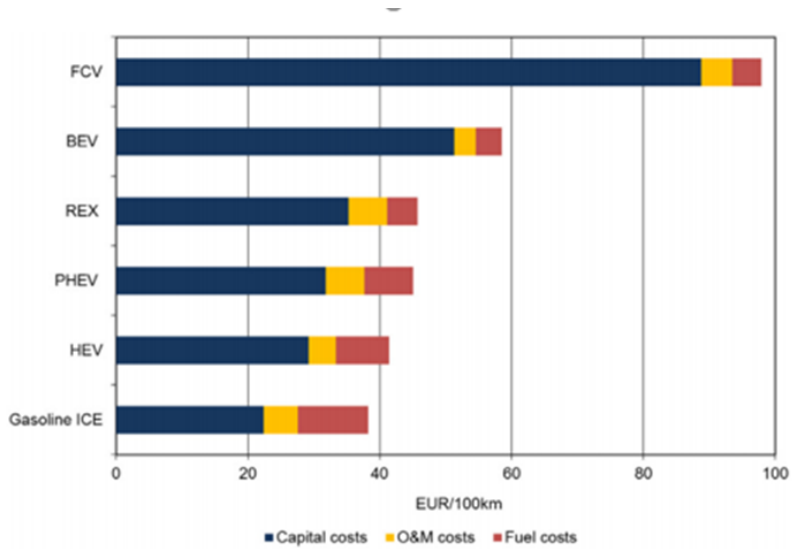


Figure 15: Costs for fuel cell vehicles (Ajanovic & Haas, 2018).

Maritime transport

The potential for different hydrogen-based fuels in the maritime industry is significant. While it in Finland only accounts for less than 10,000 TJ, the global numbers are high. The applications look promising, especially in terms of hydrogen and ammonia. Hydrogens advantages lie mainly in the low fuel weight and required volumes seem to be not as high as earlier studies have shown (Thaker et al., 2015). It would however require a lot of new infrastructure to allow refuelling, and as the storage tanks are cylindrical, it might not be as optimal for heavy industry logistics as it reduces the available storage area.

Ammonia has great potential when it comes to the hydrogen's problems. It could either be used as ammonia fuel cells or cracked back to hydrogen for usage. The efficiencies for this process are relatively high but would be quite difficult on-board ships, even if the costs are roughly the same as when keeping hydrogen chilled for transport. Ammonia fuelling at ports would be easier and an existing global supply chain exists, even though it is not optimized for maritime use. Currently the costs are still relatively high according to Table 14, but that it is still in no way a mature market technologically (Thaker et al., 2015).

Table 14: Required energy, additional weight and cost to provide 9270 MWh & 6350 MWh respectively (Mckinlay et al., 2020).

Fuel type	*LNG*	*Diesel (HFO)*	*Hydrogen (gas at 700bar)*	*Hydrogen (liquid)*	*Ammonia*	*Methanol*	*Batteries (Li-ion)*
Efficiency	58%	20-40%	40-60%	40-60%	30-60%	55-60%	70-95%
Energy density	*5.83*	*9.7*	*1.4*	*2.36*	*4.82*	*4.99*	*0.30*
Required input energy (MWh)	*15983*	*23175*	*15450*	*15450*	*15450*	*15450*	*9758*
% of total storage mass	*1.68%*	*2.99%*	*0.69%*	*0.69%*	*4.42%*	*4.17%*	*66.3%*
Fuel per voyage (€ Millions)	*0.39*	*1.51*	*9.56*	*9.56*	*2.18*	*1.24*	*7.64*
Required input energy (MWh)	*10948*	*15875*	*10583*	*10583*	*10583*	*10583*	*6684*
% of total storage mass	*1.15%*	*2.05%*	*0.47%*	*0.47%*	*3.03%*	*2.86%*	*45.40%*
Fuel per voyage (€ Millions)	*0.26*	*1.03*	*6.55*	*6.55*	*1.5*	*0.85*	*5.23*

Chemical industry

Ammonia production

Ammonia production uses 2% of the global energy and account for 1% of carbon dioxide emissions. In Finland, the chemical industry's fuel usage is the fourth largest, with approximately 18,000 TJ per year. Ammonia is mainly used for the production of fertilizers. Currently ammonia is produced by extracting hydrogen from natural gas or naphtha, so the process would not need any changing. The Haber-Bosch process could be used, only the hydrogen source changes. The energy need for ammonia-production lies at about 10-12MWh per tonne ammonia if achieved through electrolysis and about (3/17) tonnes of hydrogen are needed per ton ammonia (Green hydrogen opportunities in selected industrial processes). In Finland, the biggest fertilizer-producer uses about 150 000 t ammonia per year just from one plant. That would in and of itself give a demand of 26 000 t hydrogen that could be filled through renewable needs. It is used to produce 0.5 Mt nitric acid, 0.2 Mt nitrates and 1.2 Mt NPK fertilizer in Uusikaupunki per month (Yara reports, 2020).

Oil refining

Energy usage in the production of refined oil-products in Finland is mainly fuel usage. It stands at about 34,000 TJ annually as the third largest fuel-user. By using hydrogen and carbon capture in order to produce methanol, the need for refining goes down a lot. Hydrogen is used to remove sulphates when refining oil, and has so far mainly been done through fossil means. As with Ammonia, it doesn't change the process itself much, instead the materials for production get sourced differently. This would also reduce carbon dioxide emissions significantly. The need for hydrogen in oil refining has been estimated at about 1 t hydrogen per 1 kt of crude oil. This gives a significant market for hydrogen (Green hydrogen opportunities in selected industrial processes).

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