Otto Pesonen & Tuomas Alakunnas

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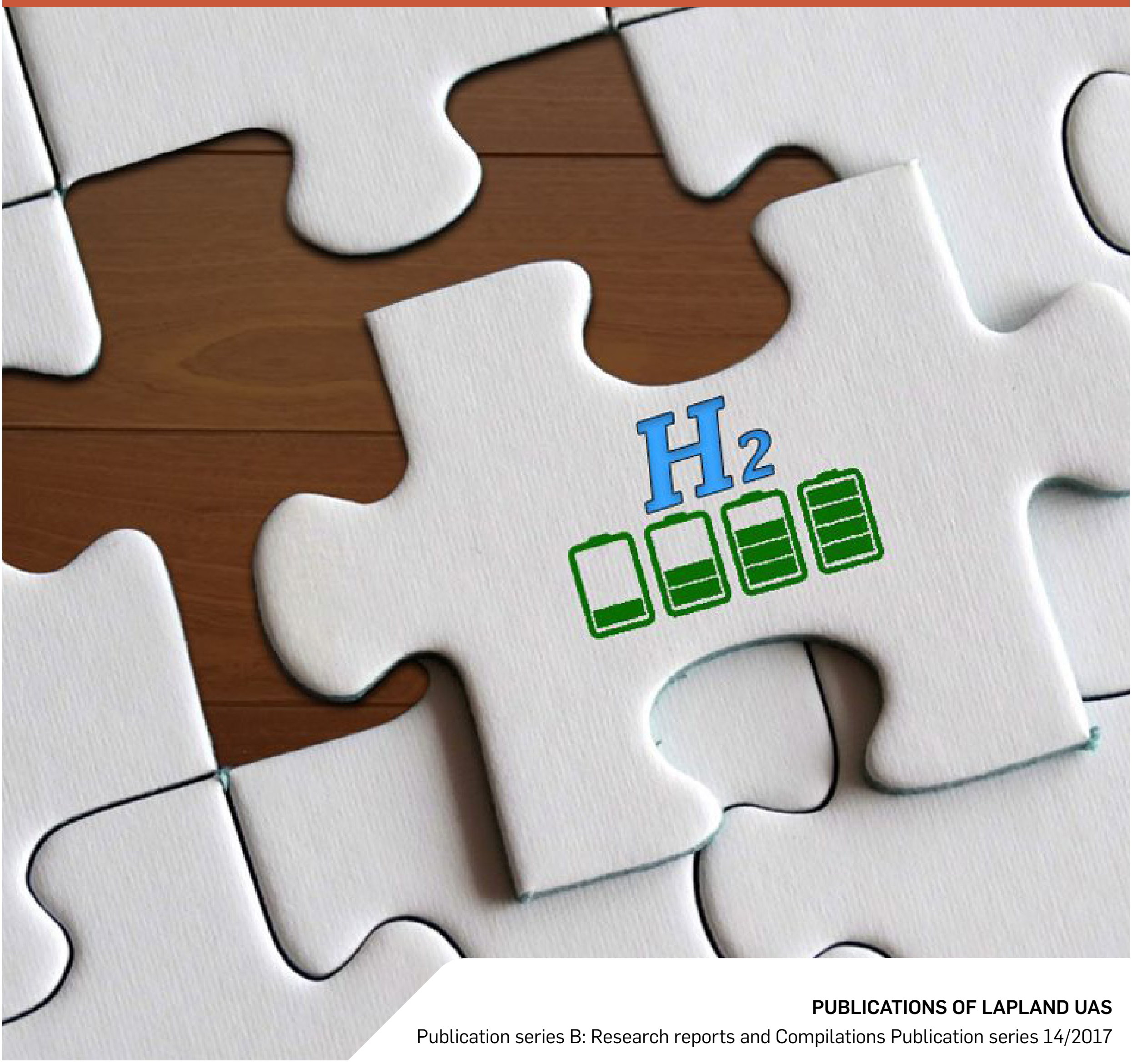
Energy Storage

A Missing Piece of the Puzzle for the Self-Sufficient Living



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1 Introduction

Electrical energy storage in the larger scale has been challenging for the years. Back in the history, when oil and gas prices went high, storing electrical energy came to discussion tables for the first time. The solution back in the time was to build pumped hydro plants to store surplus energy. As nowadays when the demand of renewable energy sources are growing fast, due to the climate policies, it makes the energy storage systems more important than ever. As solar and wind energy are intermitted energy sources, there are need for the grid balancing systems and ways to store surplus energy by efficient methods. Energy storages are the key component for creating sustainable energy system.

As the pumped hydro storage system is the most popular storage technology we have, it is dependent on geographical location due to need of high falling heights. That reason has brought other storage solutions on the markets. Other solutions for energy storages are supercapacitors, compressed air storages, flywheels, hydrogen and batteries. This report takes a look for hydrogen and battery based energy storage systems.

This publication is part of cross-border project: Artic Energy - Low Carbon Self-Sufficient Community. The goal of the project is to create a model for self-sufficient, low carbon community using local renewable energy sources in the arctic region. The project is funded by EU-program Interreg Nord, Regional Council of Lapland, Länsstyrelsen Norbotten and Interreg-program in Norway.

2 Hydrogen the clean energy of the future?

The Hydrogen economy is a theoretical concept where hydrogen is the main energy carrier along with electricity. It would be the ultimate solution for energy and the environment. Hydrogen and electricity would be produced in large quantities from available energy sources and these would replace all the fossil fuels in applications of today. Even though hydrogen is the most common chemical element on the planet, it does not exist in its pure form. Therefore, it has to be produced from something. Example water, biomass, fossil fuels and hydrocarbons contains hydrogen. Therefore, if the hydrogen economy is going to be reality, the costs of the hydrogen production, storage, transport need to be low as possible and make sense energetically. Otherwise, better solutions will conquer the markets. (Bossel & Eliasson 2003 & Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.)

Producing hydrogen from renewable energy sources such as wind and solar energy or biomass has been under research for years. Using these methods, it would make hydrogen almost perfectly clean and permanent energy carrier for humankind. Unique characteristics that Hydrogen has unlike other fuels makes it an ideal energy carrier. It can be produced from and converted into electricity at relatively high efficiencies. It can be produced by water electrolysis, so it is a completely renewable fuel and it can be stored in multiply ways. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.)

The challenges of today are to scale-up hydrogen generators to meet demands of the growing renewable energy power industry. (Schiller 2014) Lowering the costs of whole hydrogen industry from the production to distribution systems for final users, but step-by-step this all could be a possible solution for our energy system and it would prevent global warming.

3 Hydrogen production methods

The production processes can be grouped into three sections: electrochemical, thermochemical and photochemical. In electrochemical processes, the energy input is given as electricity. In thermochemical processes, the energy input is given as high temperature heat and in photochemical process energy input is direct absorption of photons of light. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.)

As generating sustainable fuel, the carbon footprint is important. Figure 1. lists examples of productions processes along with their raw material. The key attributes for the energy sources are renewable or nonrenewable and for the raw material, the ability of close the material cycle, that is, to regenerate the starting material without emissions discharge to the environment. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014)

	Processes	Raw Materials	Source of Energy
Electrochemical	Electrolysis	Water	Electricity from renewable source
			Wind
			Geothermal
			Solar
			Hydro
			Electricity from nonrenewable source
			Fossil Fuels
			Nuclear
Thermochemical	Reforming	Natural Gas	Combustion of natural gas/ syngas
		Hydrocarbons	Concentrating solar thermal
		+ Water	
	Gasification	Coal	Combustion of coal/biomass/
		Carbonaceous materials	carbonaceous materials/syngas
		Biomass	Concentrating solar thermal
		+ Water	
	Decomposition	Natural gas	Natur gas combustion
		Fossil fuel hydrocarbons	Concentrating solar thermal
		Biomethane	
		Biohydrocarbons	
	Thermolysis	Water	Concentrating solar thermal
	Thermochemical cycles	Water	Concentrating solar thermal
			Nuclear heat
Photochemical	Photosynthesis	Water	Solar radiation, artificial light
	Photobiological	Microbial (algae)	Solar radiation
		+ Water	

Figure 1. Hydrogen production process. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014)

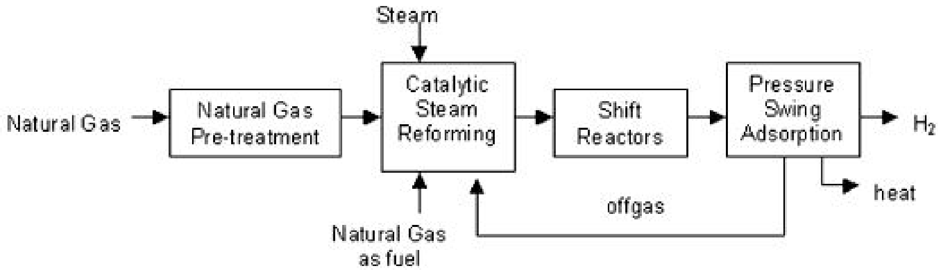


Figure 2. Hydrogen production by steam reformation. (Bargigli, Raugei & Ulgiati 2004)

3.1 STEAM REFORMATION

In the industrial production hydrogen steam, reforming from natural gas or other light refinery hydrocarbons is the most common and lowest cost method. Over 90% of hydrogen what is produced in the USA is produced by this method. In commercial large-scale hydrogen production, steam reformer operates with the catalyst bed temperature typically between 450 - 800 °C at 30 - 45 bar using a Ni-based catalyst held on a ceramic pellet substrate. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.)

For example, in methane (CH_4) steam reformation process, methane reacts with steam (H2O) to yield carbon oxide and hydrogen. The reaction is strongly endothermic:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \; - 206 \text{ kJ/mol}$$

Additional hydrogen can be recovered by lower temperature gas-shift reaction with the carbon monoxide produced. The reaction is mildly exothermic:

$$CO + H_2O \rightarrow CO_2 + H_2 + 41 \text{ kJ/mol}$$

After gas-shift reaction, generated carbon dioxide could be removed by pressure swing adsorption. Therefore, at the end there is only pure hydrogen. Steam reformation is approximately 65 - 75 % efficient.

3.2 ELECTROLYSIS

As the aim is reducing fossil fuels and create more sustainable energy, the answer is produce hydrogen from water and electricity from renewable energy sources. The electrolysis of water is a process in which electricity is used to split water into hydrogen and oxygen. (Raunio 2005)

$$2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$$

At the moment, there are three main methods for the water electrolysis: Alkaline electrolysis (AEL), Polymer electrolyte membrane (PEM) electrolysis and Solid oxide electrolysis (SOEC). Two first mentioned are in commercial use but SOEC is still under laboratory testing. (Götz, et al. 2016)

3.3 ALKALINE ELECTROLYSIS (AEL)

The most mature electrolysis technology there is. In AEL, an aqueous alkaline solution (KOH or NaOH) is used as the electrolyte. Typical efficiency 61 – 71 %. AEL could work either atmospheric or elevated pressure. According to research pressurized AEL have a lower efficiency and produce a lower quality hydrogen, but it produces compressed hydrogen with less additional energy input. (Götz, et al. 2016.)

AEL electrolysers can be operated between 20 and 100 % of design capacity, also overload up to 150 % in possible. AEL is typically used as industrial scale. The biggest disadvantage of AEL is that the used electrolytes are highly corrosive. General overhaul of the system is necessary every 7 - 12 years. Alkaline electrolyser is expected to last in the best case about 30 years, which is high compared to other electrolyser types. (Götz et al. 2016.) Commercial systems range in size and production capacities. Alkaline electrolysers average costs range from 1,000-1,200 €/kW. These costs are expected to reduce to about 600 €/kW by 2020. (E4tech Sàrl with Element Energy Ltd. 2014)

3.4 POLYMER ELECTROLYTE MEMBRANE (PEM) ELECTROLYSIS

The technology is based on a solid polymer membrane. Compared to AEL, PEM has faster cold start, more flexibility (operational window 5 – 100 %) and better coupling with dynamic and intermittent systems and also quality of pure hydrogen is very high. PEM electrolysers are suitable for renewable energy. Efficiency is also higher, 64 – 83 %. Disadvantages are the high price due the costs of membrane and noble metal catalyst and radically shorter lifetime. (Götz, et al 2016 & Gahleitner 2013.)

Average costs of these systems range from 1,860 – 2,320 €/kW and for the future costs reduce at around 1,000 €/kW by 2020. In addition, it is expected that around 2020 PEM electrolysers will be comparable to AEL electrolysers terms of size. (E4tech Sàrl with Element Energy Ltd. 2014.)

3.5 SOLID OXIDE ELECTROLYSIS (SOEC)

SOEC has been recognized as a promising technology for large-scale stationary hydrogen plants. Main advantages to the other is high-energy efficiency, which is reported to be 90 % or more. The difference between SOEC and two other electrolysis technology is that water is steam form. Due high operating temperature, 800 - 1000 °C, there is some pros and cons. High temperature reduces electricity demand, but it causes problems with used materials. It is hard to find durable materials that are also cost effective. This is a challenge to overcome before SOEC will be widely commercialized. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014 & Götz, et al 2016.)

3.6 PHOTOELECTROCHEMICAL SYSTEMS

Photoelectrochemical (PEC) water splitting into hydrogen and oxygen is one the most promising way to generate the sustainable energy system. One way to make hydrogen using sunlight is to use solar panels to produce electricity and use that to power electrolyser. As researchers has founded out, it would be cost effective to combine these two devices together. (Bullis 2013) Visible light has enough energy to split water, but with the current technology, it is still ineffective and the costs of the system are too high. Using sunlight to produce hydrogen like plant leaves does, is under development at the moment. Researchers have converted 10 % of the solar energy that hits the panels into solar fuel, (Lemonick 2014.) however, the solar process should be somewhere between 15 – 25% to make it competitive with natural gas as a way to make hydrogen. (Bullis 2013) Another challenge is the corrosion resistivity of the electrodes used. In the future with evolved nanotechnologies and lower cost materials PEC-cells could be transit to large-scale and commercial solutions. (Nordic Energy Research 2012 & Hypersolar 2017)

3.7 HYDROGEN FROM BIOMASS

There is a large potential to produce clean hydrogen from biomass, which typically contain 6 % hydrogen by weight. Term biomass include resources such as woody energy crops, forest residues, mill wood and logging waste along with animal waste, industrial waste and so on. Hydrogen can be produced by thermal methods (gasification and pyrolysis) or biological methods (fermentation and biophotolysis) from biomass. From all of the mentioned methods, biomass gasification has received considerable attention. Gasification of biomass is generally observed to follow the reaction (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.):

$$\text{Biomass} \ \& \ O_2 \ (\text{or } H_2O) \rightarrow CO, CO_2, H_2O, H_2, CH_4 \ \& \text{ other CHs} \ \& \text{ tar} \ \& \text{ char} \ \& \text{ ash}$$

There are currently no commercial biomass gasification processes for hydrogen production, but demonstration plants of biomass gasifiers for electricity or other chemical production has been made. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014)

For the very large-scale systems, biomass could be the best option because wind and solar systems just does not have the capacity to produce high quantities of hydrogen. Biomass can be collected in quantities ranging in the thousands of tons. A biomass gasifier thermally integrated with a solid oxide fuel cell has been tested in laboratory scale. Conceptually, this distributed energy system could generate between 100 kW and 1000 kW of electrical power. (Zygarlicke 2017.)

3.8 CONCLUSION OF PRODUCTION METHODS

Steam Reformation is the most popular hydrogen production method for industrial scale due to high conversion efficiency and cost-effectiveness in comparison with other production methods. As it uses fossil fuels, it is not the eco-friendliest option for hydrogen production.

Eco-friendliest option is generate hydrogen from renewable sources via water electrolysis. Wind and solar farms could store surplus energy as hydrogen. Disadvantages are low efficiencies and high capital costs of electrolyser systems. Alkaline electrolyser is the most mature technology, it has longer lifetime expectation and lower investment costs than other electrolysers. On the other hand, PEM electrolysers are more suitable for intermittent energy sources due faster cold start and flexibility. What it comes up with SOEC, which is still in development stage, it has greater efficiencies that AEL or PEM but also expected investment costs are higher. As SOEC operates at high temperatures its attractive option if heat sources like nuclear, solar thermal or geothermal sources are available. (Silveira 2017.)

4 Hydrogen storage systems

Hydrogen could be stored in multiple ways. Figure 3. shows storage options and used materials, along with some of their identified strengths and weaknesses. Depth discussion about the most common options will be in the following chapters.

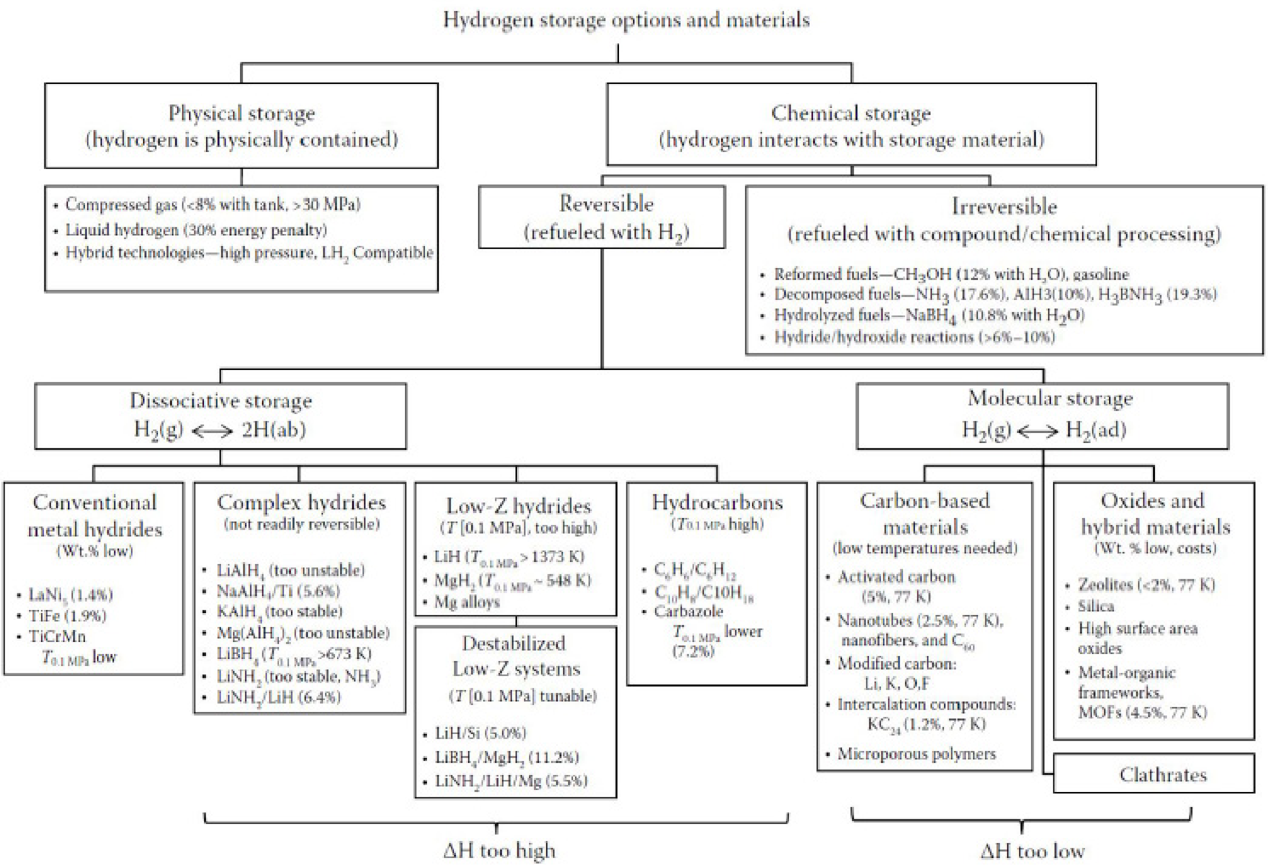


Figure 3. Hydrogen storage technologies (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014)

Hydrogen gas has the largest energy content of all fuels, with the ability to hold 120 MJ/kg, so relatively small amount of hydrogen could store a significant amount of energy. Hydrogens stable chemistry also gives a chance to store energy for long periods (Figure 4). (Schiller 2014) Due to hydrogens low density, storage methods meets some challenges. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014)

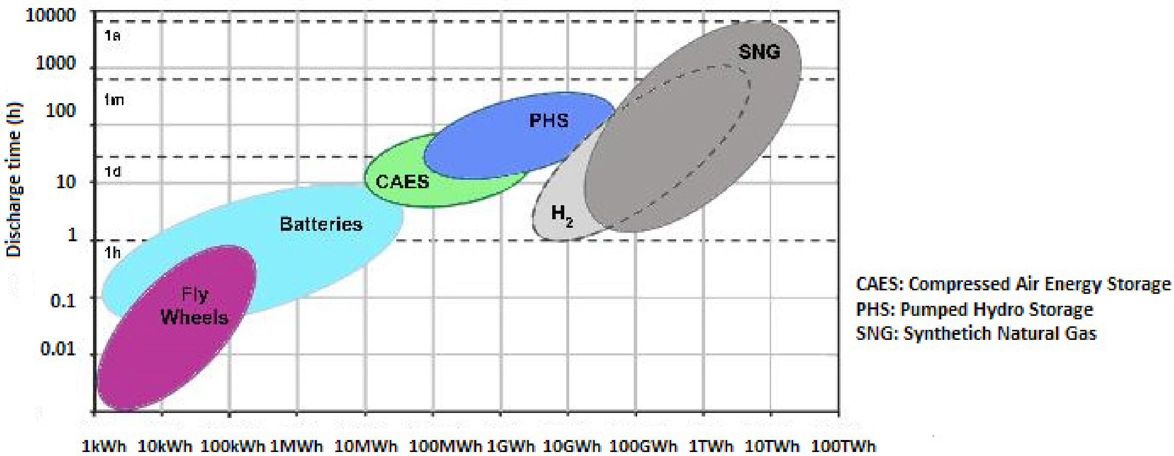


Figure 4. Comparison of energy storage options in terms of capacity against discharge time (Schiller 2014)

4.1 PHYSICAL STORAGE AS COMPRESSED GAS OR CRYOGENIC LIQUID

The most mature storage system for hydrogen is physical storage as compressed gas. Depending on storage size and used applications, there are several types of storage systems available. Because of hydrogens low density, its storage needs high pressure or extreme low temperatures. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014) At a pressure of 20 MPa, the energy density of hydrogen gas is comparable to that of a lithium-ion battery. (Buck & Webel 2016) Usually, at nowadays hydrogen is pressured up to 35 MPa or 70 MPa because of current fuel-cell applications. Theoretically pressuring will affect negatively 11 - 13 % of the hydrogens energy content. (Jumppanen 2009) Due to the fact that hydrogen is the simplest element, small amounts of it will leak out over time from any vessel due to high pressure.

The most common type of storage vessels for merchant hydrogen are made of steel or aluminum. These are really heavy solutions and example for automotive application fully impractical. Lighter solution is a composite vessel wrapped with carbon fiber, but the costs of manufacturing will rise significant compared to steel or aluminum vessels. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.) Al thought, researchers and developers are trying to find solutions for cheaper materials and ways to make vessels that are more practical.

Pressured hydrogen could be also stored in large underground storages, caverns of salt domes if storing time is long or the hydrogen amount is significant. On calm or cloudy days when solar and wind power are not so effective, hydrogen could then be retrieved from caverns and burned in combined-cycle power plant that generates electricity. At the moment, there are no turbines that can burn pure hydrogen, but in the year 2018, these could be reality. For example, Siemens is developing that kind of turbines. (Buck & Webel 2015.)

Another method for physical storage is liquid. Storage of hydrogen as liquid increase its density. At its normal boiling point of 20K, liquid hydrogen has a density of about 71g/L, which is about 1.8 times the density of 70 MPa hydrogen at 288K. Liquid hydrogen requires cryogenic temperatures because of its low boiling point, as depend on used cooling technology, it takes 25 - 27 % of the energy content of hydrogen. These low temperatures require specialty double-walled vessels with good insulation systems to minimize heat leakage. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.) Cryogenic pressure vessels are more compact and lighter than pressured hydrogen vessels, also they offer some safety advantages. Liquid hydrogen is suitable only for applications that requires high energy density despite of high price, example space and automotive applications. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.)

4.2 TRANSITION METAL HYBRIDS

Metal hybrids are the most technological solution to store hydrogen. In metal hybrid vessel hydrogen molecules bonds into metal hybrids (like water to sponge) under moderate temperature and pressure. That makes the system safer than other solution because hydrogen cannot leak out by itself or explode. As a disadvantage, these vessels are heavy. (Heung 2003.)

Metal hybrids are one of the most promising solution to store hydrogen due good storage efficiency and it also has high volumetric energy density. Storage energy consumption of 15 MJ/kg of hydrogen was presented for metal hydride storage (when waste heat is used for desorption). This equals 89.6 % efficiency related to the heat of combustion for hydrogen (120 MJ/kg). Similar way calculated energy efficiency results for compressed gas at 35 MPa is 70 % and for liquid hydrogen 65 %. (Pasonen, Mäki, Alanen, & Sipilä 2012.)

There are currently some companies (McPhy, Pragma industries, Hydrexia), which have commercial solutions currently or early 2017 on the market. Metal hybrid storage systems range from 60 Wh to 10 MWh. As Hydrexia will launch commercial solutions in early 2017, they promise that system will have about half of the capital cost, three to four time better storage density and superior safe advantages as compared to current compressed gas storage systems have. There is still limited data about metal hybrid storage systems in use, but if there is a little truth in sales pitch, it looks pretty promising. (McPhy 2017; Pragma industries 2017 & Hydrexia 2017)

4.3 AMMONIA

Storing hydrogen to methanol or ammonia has been studied. Ammonia has been identified suitable hydrogen carrier due great hydrogen storage capacity 17.8 mass percentage and the volumetric hydrogen density is 1.5 - 2.5 times of liquid hydrogen. Reforming ammonia produces hydrogen without pollutants. As we know Ammonia is a one the most used industrial chemicals in the world, so there is set up production and distribute networks already. (Kojima 2014.)

4.4 POWER-TO-GAS

Unlike other storage options, power-to-gas includes storage and transport of energy. It links the power grid with the gas grid by converting surplus power to gas. As there is around the world massive capacity of natural gas grid, the power-to-gas is the considerable solution for storing surplus energy. There are two methods to utilize gas

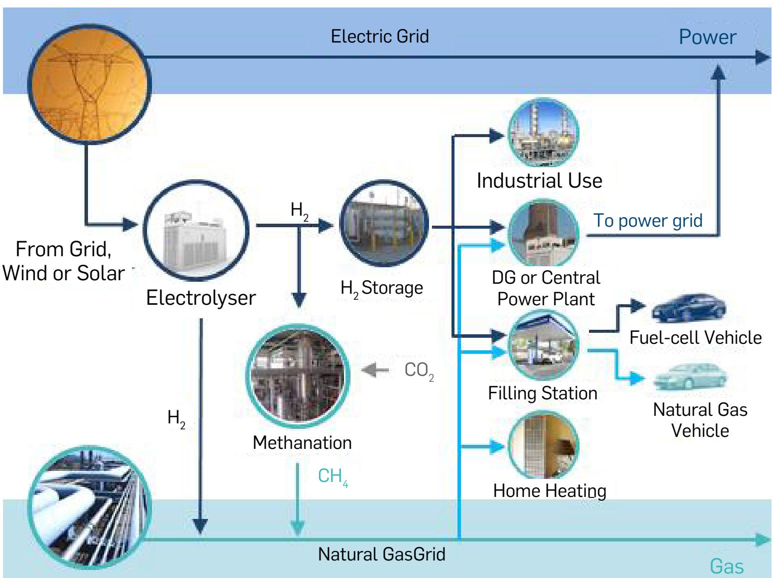


Figure 5. Power-to-gas concept (California Hydrogen Business Council 2015)

grid for hydrogen. (California Hydrogen Business Council 2015) Concepts of methods are shown in figure 5.

Hydrogen could be blended into natural gas and be stored and transported in natural gas pipelines. Because of different physical and chemical properties with hydrogen and natural gas, the permissible hydrogen fraction is limited. Research studies have suggested that volume fractions could be up to 20 %, but at the moment highest limit in Europe is 12 % (Netherlands) with most standards are below 5 %. (California Hydrogen Business Council 2015.)

Another method to use natural gas pipelines is to methanize the hydrogen prior to injecting it by combining the hydrogen with carbon dioxide to create methane. Methanation could be done by catalytic or biological way. The efficiency of both methanation processes are limited by the Sabatier reaction to a maximum of 80 %. The resultant methane is interchangeable with conventional natural gas and can be stored, transported and used without any restrictions. (California Hydrogen Business Council 2015 & Benjaminsson, Benjaminsson, & Boogh Rudberg 2013.)

5 Hydrogen conversion

Hydrogen as an energy carrier can be converted into different forms by internal combustion engines or fuel cells, such as heat, steam or electricity. Combusting with pure oxygen generates steam, catalytic combustion generates heat and electrochemical conversion (fuel cell) to electricity. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.)

Hydrogen-powered internal combustion engines are about 20 % more efficient than comparable gasoline engines. However, using hydrogen results 15 % power loss due the lower energy content in a stoichiometric mixture in the engines cylinder. Major advantage is that hydrogen will emit far fever nature than gasoline. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.)

Combustion with pure oxygen results steam. A compact hydrogen/oxygen steam generator has been made commercially. This generator consists of the ignition, combustion and evaporation chamber. It is almost 100 % efficiency, since there are no emissions other than steam and small amounts nitrogen oxides and almost no thermal losses. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.)

Hydrogen can be combined with oxygen in a fuel cell. The electrochemical reaction produces direct-current electricity. It is basically reversed electrolysis, so burning product is water. Depending on the used electrolyte, there are several types of fuel cells, such as alkaline fuel cell, polymer electrolyte membrane fuel cell, phosphoric acid fuel cell, molten carbonate fuel cell and solid oxide fuel cells. (Sheriff, Yogi Goswami, Stefanakos & Steinfield 2014.) Each type has own advantages and challenges that are shown in table 1.

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluorosulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2; [i] 40% reformed fuel [ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1-100 kW	60% [iii]	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a porous matrix	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane	40% [iv]	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/ or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50% [v]	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60% [vi]	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

Table 1. Comparison of fuel cells. (U.S Department of Energy 2016)

As table 1. shows that PEMFC and AFC are operating in lower temperature than other fuel cell types it makes them not as suitable for combined heat and power (CHP) applications as high temperature fuel cells. Similar to electrolysers, the fuel cell has a trade-off between efficiency and power output. Efficiency is highest at very low loads and decreases power output and the higher temperatures gives better efficiency. For stationary operation, the focus is on higher efficiencies at higher loads, what makes high temperature fuel cells better suited in that case. (U.S Department of Energy 2016)

PEMFC has lots of development ongoing in the stationary application sector, but currently lifetime up to 60 000 hours is low and the capital cost are not significantly lower than what other high temperature fuel cells have. In addition, the low temperature limits the use in CHP applications. Because of the low operating temperature, cold start is possible and this makes is suitable to be used in the fuel cell vehicle sector. Other low temperature fuel cell, alkaline fuel cell, has a long development history, but it does not have much commercial interest due it requires pure oxygen along with pure hydrogen. (Körner 2015.)

Phosphoric acid fuel cells (PAFC) are mature technology, it operates at high temperature (200 degree Celsius) what makes it suitable for CHP applications, as a result of high temperature it could be fueled with lower purity hydrogen. As disadvantage PAFC's have lower efficiency (30 - 40%) than other high temperature fuel cells, also phosphoric acid is highly corrosive material, which increase maintenance and material costs. (Körner 2015.)

Molten carbonate fuel cell (MCFC) operates above 600 degree Celsius, which allow it operate with natural gas, biogas or coal based syngas. As MCFC have efficiencies more than 60 % (HHV) and if resulting high temperature waste heat is recovered, the overall efficiencies could be around 85 %. As disadvantages for MCFC, there is not so much cost reduction potential in the future and it is challenging to avoid electrolyte being corroded. (Körner 2015.)

One of the most potential fuel cell for stationary applications is solid oxide fuel cell with operating temperature of up to 1000 degrees Celsius. As it can reform the gaseous fuel to hydrogen internally, it can be fueled with natural gas, biogas, and syngas. As stack lifetime is longer and capital costs are lower than other high temperature fuel cells have, it dominates the markets for high temperature fuel cells. As disadvantages the very high operating temperature needs a time for heating-up process, which reduces its flexibility. In addition, rapid changes in power flow could produce temperature gradients in the material, which makes SOFC not suited for power shaving applications. (Körner 2015.)

Much research has been carried out for an equipment, which include both electrolyser and fuel cell. This reversible fuel cell (RFC) could operate, as a reverse mode to perform electrolysis and it would lower the capital costs as it could do both operations. There have been questions about that could RFC also reach same efficiencies that separate systems. (FuelCellToday 2013) At 2016, first reversible Solid Oxide Fuel Cell (50 kW) was delivered by Boeing for U.S. Navy to be tested. Combined with a solar photovoltaic array, a SOEC system generates electricity, potable water, and heat with only two inputs, sunshine and seawater. (FuelCellsWorks. 2016.)

6 Producing hydrogen from renewable sources

Around the world, there are approximately 4000 remote communities, which are typically small, isolated sites with unstable grid connectivity. These communities generate much or all of their electricity by diesel generators, which have high operating costs and low efficiency. Hydrogen based systems would definitely be a good option for these communities. (Glandt 2012.)

As mentioned earlier producing hydrogen from renewable energy source via water electrolysis is a great way to reduce greenhouse gas. Hydrogen storage systems are ideal for all renewable energy, especially for large-scale wind or multi energy source system. (Astiaso Garcia, Barbanera, Cumo, Di Matteo & Nastasi 2016) It makes the whole system stronger if two or more renewable systems are combined together. Wind and solar could support each other well, because it can be windy in off-sunshine periods and vice versa. Alternatively, geothermal heat can be used as high temperature electrolysis. (Dincer & Joshi 2013) Produced decarbonized electricity could be supplied directly to the transmission grid or to an electrolyser to produce hydrogen. (Astiaso Garcia, Barbanera, Cumo, Di Matteo & Nastasi 2016) Figure 6. shows how a renewable hydrogen storage system would work.

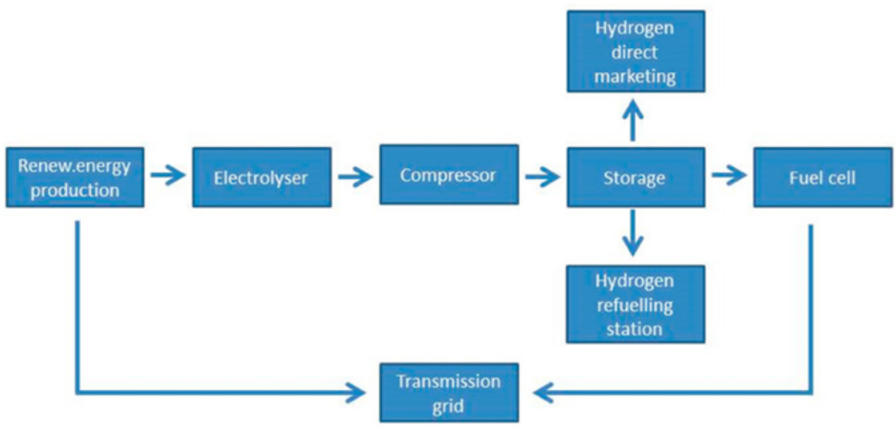


Figure 6. Hydrogen storage system for renewable energy (Astiaso Garcia, Barbanera, Cumo, Di Matteo & Nastasi 2016)

Produced hydrogen is stored in compressed form and can be directly marketed as a commodity or re-electrified on demand using fuel cells or combustion engines. Considering energy production for stand-alone systems it is better to have more than one energy source by integrating wind plants with solar- or bioenergy plants. Storage capacity should be sized by main purpose of the system. (Astiaso Garcia, Barbanera, Cumo, Di Matteo & Nastasi 2016)

In an electricity system with high levels of variable renewable energy, it is expected that supply will outstrip demand in some periods of the day. That is the time to generate hydrogen and store it. These surplus periods will occur only for a limited amount of time and because electrolysers has high investment costs, which means that they will only be cost effective if they are operated for a sufficient time of the year, it creates challenges. Firstly, it is challenging to reach cost effective capacities with these surplus periods, so it is likely that electricity of some value needs to be used as hydrogen production. The second challenge is that every conversion step from electricity to hydrogen process will cause losses, nevertheless losses are minor importance if input electricity cannot be used for any other applications. (International Energy Agency 2015.)

As for all long-term, large-scale storage systems, annual full-load hours are limited. While technology components remain expensive, it is suitable to explore markets for use of all by-products, such as oxygen and process heat to get more profit. (International Energy Agency 2015)

According to Ballard Power systems Inc., hydrogen energy storage and using renewable energy sources and electrolyser technology combined with the fuel cell system for power production can enable remote communities to meet all or a significant proportion of their power demands in an economic manner. Fuel cells have higher efficiency at all power levels than conventional technologies, such as diesel generators. For disadvantages, the hydrogen energy systems have much higher capital cost than diesel engines, but the levelized energy cost is lower. As compared to diesel, annual savings of over $900,000 from renewable hydrogen storage system were obtained in a study of hypothetical remote community. (Glandt 2012 & Motay 2016.)

What it comes up to renewable energy sources, it depends a lot with current locations. Different type sources are stronger in different areas. Coastal and sub-coastal areas have typically strong wind power potential and solar power is stronger in areas where the sun will shine sufficient time of the year. Locations along the river have potential to use hydropower to generate hydrogen and areas, which have good geothermal resources, could use it in hydrogen production.

6.1 REAL WORLD PROJECTS

The first full-scale wind power and hydrogen plant was realized in Utsira, a small island of Norway, in 2004. This off-grid test site aimed at making it self-sufficient ten household community with renewable energy. This plant included two 600 kW wind turbines (one for the external grid and other to stand-alone system), 55 kW hydrogen engine, 10 kW fuel cell, 10 /h electrolyser with 48 kW a peak load, 5.5 kW hydrogen compressor, 2400 hydrogen storage (200 bar). The system also included 5 kWh flywheel, 50 kWh battery and master synchronous machine to balance voltage and frequency. Plant worked for years without problems or complaints, but it concluded that the technology was not commercially competitive with other solutions at the time of completing project. (StatoilHydro 2017.)

In a Danish Island called Lolland, which produce 50 % more energy that they can consume, started hydrogen project at 2006. It have been successfully producing hydrogen via wind power since 2007. It uses 8 kW electrolyser, 10.5 kW fuel cell and 25 hydrogen storage tank. Produced hydrogen is used to generate electricity when demand exceeds and the by-product oxygen is used for wastewater cleaning process. To increase efficiency, fuel cells (2 kW) were installed in 35 residential homes to be used as a combined heat and power generation. These cells ended up being more efficient and have higher energy security than conventional boilers. (Jasmine 2010 & Du & 2014.)

6.2 NORDIC REGION POTENTIAL

Based on expert opinions in Finland potential renewable hydrogen storage system would locate to coast cities like Pori, Tampere, Oulu and Helsinki where offshore wind power is an option. Furthermore, Finland has also bioenergy resources, which could be utilized for hydrogen production. In Norway, there is a large potential for widespread micro-grid, particularly small-scale hydro power plants with production and storage. However, Norway has strong grid and huge magazine hydropower (50 TWh), so it is out of the question to store surplus energy as hydrogen and re-electrified it. Produced hydrogen would go for the fuel cell vehicle sector, cause Norway set the target of 100% of the new car sales to be zero-emission vehicles starting in 2025. In Sweden, preferred locations on a larger scale are close to the wind farms located in the north of the country. On a smaller scale, off-grid places in the mountains or in the archipelagos that currently have diesel-generators. (Garcia, Barbanera, Cumo, Di Matteo & Nastasi 2016.)

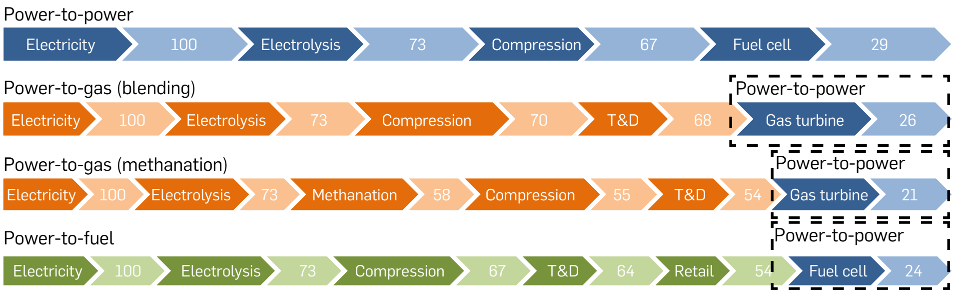
7 The system performance and costs

The system performance stats and costs are shown in table 2.

Application	Power or capacity	Efficiency	Investment cost	Lifetime	Maturity
Steam Methane Reformer (SMR)	150 - 300 MW	70 - 85 % (LHV)	400 - 600 USD/kW	30 year	Mature
SMR, small scale	0,15 - 15MW	51 % (LHV)	3 000 - 5 000 USD/kW	15 years	Demonstration
Alkaline electrolyser	Up to 150 MW	65 - 82 % (HHV)	850 - 1500 USD/kW	60 000 - 90 000 h	Mature
PEM electrolyser	Up to 1 MW	65 - 78 % (HHV)	1 500 - 3800 USD/kW	20 000 - 60 000 h	Early Market
Solid Oxide electrolyser (SOEC)	Lab Scale	> 90 %	NA	1000 h	Deveplopment & Research
Pressurised Hydrogen Tank	0,1 - 10 MWh	Almost 100 %	6 000 - 10 000 USD/MWh	20 years	Mature
Liquid Hydrogen Storage	0,1 - 100 GWh	Boil-off loss 0,3 %/d	800 - 10 000 USD/MWh	20 years	Mature
Underground Storage	GWh To TWh	90 - 95 %	~ 8000 USD/MWh	30 years	Deveplopment & Research
Alkaline Fuel Cell (AFC)	Up to 250 kW	60 % (LHV) 50 % (HHV)	200 - 700 USD/kW	5 000 - 8 000 h	Early Market
PEM Fuel Cell (PEMFC)	1-100 kW	60 % (LHV) 32 - 49 %	3 000 - 4 000 USD/kW	60 000 h	Early Market
Solid Oxide Fuel Cell (SOFC)	1 kW - 2 MW	60 % (LHV) 50 - 70 %	3 000 - 4 000 USD/kW	Up to 90 000 h	Deveplopment & Research
Molten Carbonate (MCFC)	300 kW - 3 MW	50 % (LHV) >60 % (HHV)	4 000 - 6 000 USD/kW	20 000 - 30 000 h	Early Market
Photophosporic Acid (PAFC)	Up to 11 MW	40 % (LHV) 30 - 40 %	4 000 - 5 000 USD/kW	30 000 - 60 000 h	Mature

Table 2. The system performance and costs (Körner 2015 & U.S Department of Energy 2016)

As a conclusion of tables, costs are currently relatively high and roundtrip (electricity to hydrogen and back to electricity) efficiencies are relatively low (figure 7.).



Note: The numbers denote useful energy; except for gas turbines, effeciencies are based on HHV; the conversion efficiency of gas turbines is based on LHV.

Figure 7. Conversion efficiencies (International Energy Agency 2015)

8 Commercial hydrogen generation systems and fuel cells

Followed tables 3. & 4. shows some examples of current commercial hydrogen generation or fuel cell application.

Examples of Commercially Available Hydrogen Generation Systems 2015			
Manufacturer	**Product**	**Type**	**Hydrogen Production**
Air Products and Chemicals, Inc. U.S.	PRISM®	Reformer	11,600 kg/day
Element 1 U.S.	H-Series	Reformer	9.7 – 19.5 kg/day
	S-Series	Reformer	1.9 – 4.5 kg/day
Hydrogenics Canada	HySTAT	Alkaline electrolysis	8.6 – 1,080 kg/day
	HyLYZER	PEM Electrolysis	2.4 – 4.8 kg/day
HyGear Netherlands	HyGEN Series	Reformer	10.8 – 225 kg/day
ITM Power U.K.	HGas	PEM electrolysis	25 – 462 kg/day
Linde Germany	HYDROPRIME	Reformer	713 – 2,160 kg/day
McPhy France	McLyzer	Alkaline electrolysis	2.2 – 43 kg/day
	Large H2 production units	Alkaline electrolysis	216 – 865 kg/day
Nuvera Fuel Cells U.S.	PowerTap	Reformer	Up to 500 kg/day
Osaka Gas Japan	HYSERVE series	Reformer	64.8 – 648 kg/day
Proton OnSite U.S.	H Series	PEM electrolysis	4.3 – 13 kg/day
	C Series	PEM electrolysis	21.6 – 64.8 kg/day
	M Series	PEM electrolysis	Up to 1,000 kg/day
Siemens Germany	SILYZER Series	PEM electrolysis	48 – 5,400 kg/day
Verde LLC U.S.	Portable Hydrogen Generators	Alkaline electrolysis	0.39 – 64.8 kg/day
	Hydrogen Generating Plant	Alkaline electrolysis	4.3 – 1,080 kg/day

Table 3. Examples of commercial available systems (Curtin & Gangi 2015)

Examples of Commercially Available Stationary Fuel Cells 2015 - Prime Power and m-CHP			
Manufacturer	**Product**	**Type**	**Output**
Ballard Power Systems (Canada)	ClearGen	PEM	Multi-500 kW power banks
Bloom Energy (U.S.)	ES-5700	SOFC	200 kW
	ES-5710	SOFC	250 kW
	UPM-570	SOFC	160 kW
	UPM-571	SOFC	200 kW
Doosan Fuel Cell America (U.S.)	PureCell System Model 400	PAFC	400 kW
Elcore GmbH (Germany)	Elcore 2400	SOFC	300 W
ENEOS CellTech (Japan)	Ene-Farm	PEM	250-700 W
FuelCell Energy (U.S.)	DFC 300	MCFC	300 kW
	DFC 1500	MCFC	1,400 kW
	DFC 3000	MCFC	2,800 kW
	DFC-ERG	MCFC	Multi-MW
Fuji Electric (Japan)	FP-100i	PAFC	100 kW
Hydrogenics (Canada)	MW power plant	PEM	1 MW
Nedstack (the Netherlands)	HP	PEM	2-10 kW (scalable)
	XXL	PEM	2-9.5 kW (scalable)
Panasonic (Japan)	Ene-Farm	PEM	200-750 W
Toshiba (Japan)	Ene-Farm	PEM	250-700 W
	H2One™	PEM	N/A

Table 4. Commercial available fuel cells (Curtin & Gangi 2015)

9 Summary of hydrogen technologies

There is definitely lots of potential of using hydrogen as an energy carrier in the future, but there are also many ifs. Hydrogen has been talked about for decades now as an clean energy for the future, but it is still under question marks in what timeframe hydrogen based systems will realize own potential.

Such as wind and solar are unpredictable energy sources so off-peak energy could be stored as hydrogen. As for the electrolysis system, there are a couple of options. AEL is the most mature technology and it has lower cost and longest lifetime expectation of the other electrolyser types. It is not as flexible as PEM and also the efficiency is lower, but due the capital cost and lifetime, it is currently better solution in an economic manner.

Preferred storages today are vessels or tanks for compressed form, or if communities have salt domes, it could be potentially the cheapest way to store hydrogen into them. As metal hybrid storages are coming on markets, they could offer some superior advantages as compared to other solutions. Hydrogen storage systems are a good way to store energy for long periods and convert it back to electricity by fuel cells during peak times. Preferred fuel cells types are PEM and SOFC.

Hydrogen based energy systems are a suitable option for communities, which have high renewable energy source surplus, such as wind, solar, hydro or bio. Especially islands, where wind turbines are overproducing energy, could use hydrogen as energy storage. Islands with high variable renewable energy production could even become an energy exporter. Bigger communities, which have natural gas infrastructure could use power-to-gas solutions to store and deliver hydrogen in natural gas pipelines.

Hydrogen systems have a high capacity to store energy, but relatively low round trip efficiency and high capital cost, but operating costs are lower than what diesel engines have. At the moment, there is a chicken-egg standoff situation. Hydrogen system prices are too high because there is not enough demand, but there will be no more demand because costs are too high. Due to the time, when prices of fossil fuels will rise, and renewable energy will have a higher penetration of the energy markets, hydrogen could promote on a bigger scale as worlds energy carrier. As European Commissions are driving towards low-carbon economy, sooner or later manufacturing prices could drop a lot due the strong policies, which could make hydrogen systems attractive for a broad customer base.

10 Battery storage system

A battery is a well-known technology to store energy as we use them in every day in our equipment's. When the battery is charged, electrical energy is converted by chemical reaction to electrochemical form and when it is discharged, it converts energy back to electricity. This round trip is called a cycle. The battery lifetime is determined by how many cycles it could last, before it loses considerable performance. (IRENA 2015.)

The idea of the battery is that two different chemicals within a battery cell have different loads and they are connected to a negative and a positive electrode. When connected to an appliance the negative electrode (cathode) supplies a current of electrons that flow through the appliance and are accepted by the positive electrode (anode). (Obenhofer & Meisen 2012.)

There are many different kinds of batteries with different chemicals, which have own unique attributes. Depth discussion about market leading batteries such as lithium-ion, sodium-sulphur, lead-acid and flow batteries is coming in following chapters.

As the energy storage point of view, batteries can mitigate fluctuation of renewable energy from seconds to hours. Batteries can be connected together and create multi-megawatt storages which reacts fast to electricity demand, but they are generally not suited to medium and longer-term or seasonal storage unlike hydrogen based systems. Batteries can be used as bulk storage, ancillary services, transmission and distribution infrastructures and customer management services. (IRENA 2015.)

The battery storage system includes several primary components along with the battery, monitoring system, control systems and a power conversion system. These systems ensure the safety aspects and maximize performance. Some battery types needs also thermal monitoring and control systems due to the risk of overheating. (IRENA 2015.)

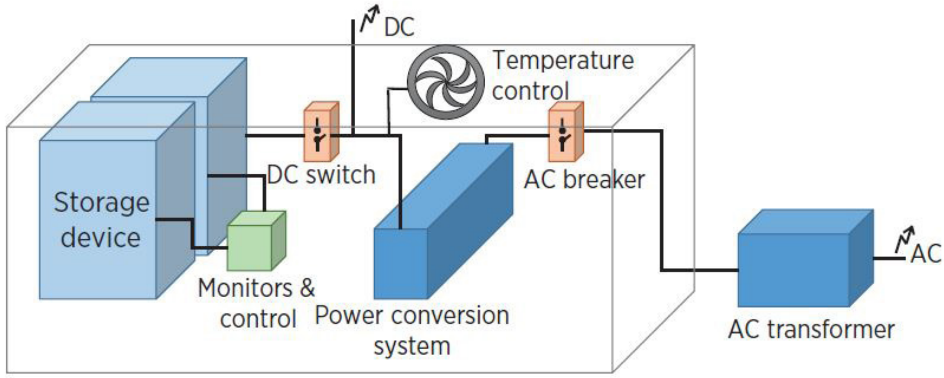


Figure 8: Battery storage systems and key components (IRENA 2015)

Several factors need to be considered before choosing battery type for the system. As generally energy storage systems are displayed on the basis of power in MW and/or energy in MWh, set against discharge time. However, there is other aspects such as safety, capital costs, space limitations, performance in variable ambient temperature etc. which need to be taken into account. Important considerations for battery selection are shown in figures 9. and 10.

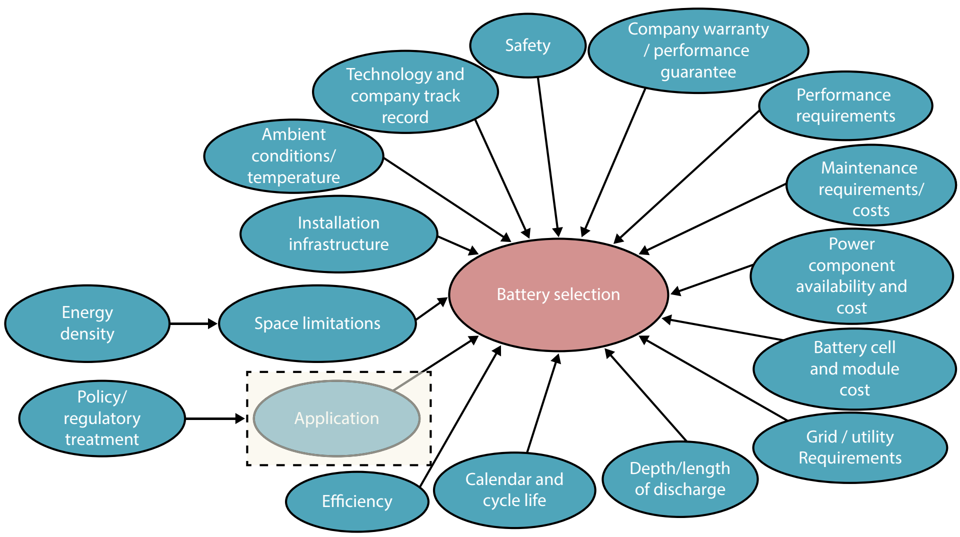


Figure 9: Important factors for battery selection (IRENA 2015)

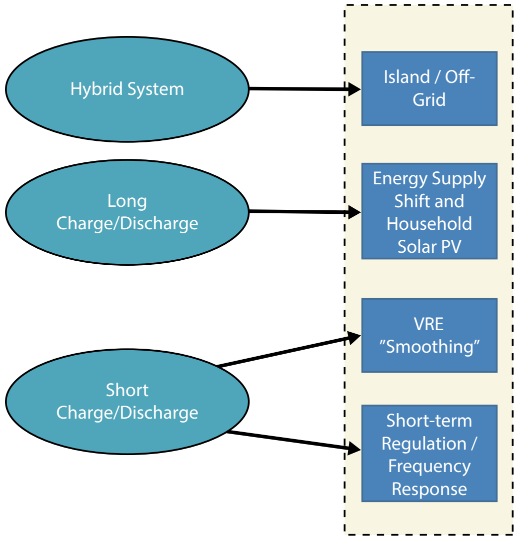


Figure 10: Important factors for battery selection by application (IRENA 2015)

10.1 LITHIUM-ION BATTERY

Lithium is the lightest metal with the highest potential due to its reactive behavior, which makes it a suitable compound for battery. Li-ion battery construction have three layers, where the first is an anode made of lithium compound, the second is a cathode, usually made of graphite and between them there is a separator which allows Li-ions to pass through. Separator can be made of various compounds. (Obenhofer & Meisen 2012.)

As high reactivity gives advantages to changing supply and demand fast it also raises some safety measurements. The temperature control system needs to be included, because lithium can burst into flames. In addition, the control system for discharge is required, because a complete discharge would destroy the cells. (Obenhofer & Meisen 2012)

Due to its high energy density combined with low weight, it means that Li-ion batteries are relatively small and lightweight. As an example, standard size, 6-meter container, stacked with Li-ion batteries could provide close to 1 MWh of energy with power capability of up to 2 MW. (McDovall 2017)

Li-ion batteries are suitable for storing large amounts of energy because it has a good roundtrip efficiency around 83 % to 98 % and self-discharge is only 5 % per month. As disadvantages for large-scale systems is the high cost, although the lithium-ions price has decreased a lot in recent years. The investment costs are high due to all control systems required. (Sánchez Muñoz, Garcia. & Gerlich 2016.)

Due to Li-Ion batteries high scalability and flexibility in power and energy, they are used in a large variety of applications: supporting distribution grids, ancillary services for transmission grids, supporting large-scale renewable energy generation voltages and frequencies. (EASE 2016a)

Lithium-ion battery prices have decreased radically in recent years, Tesla have slashed actively costs down. Currently Tesla's Powerpack system for utility services, price-range is somewhere around 390 – 450 / kWh including inverters and controllers. (Lambert 2016)

10.2 SODIUM-SULPHUR BATTERY

A Sodium-Sulphur (NaS) battery is based electrochemical reaction between molten sulphur cathode and molten sodium anode. The electrodes are separated by a solid ceramic, sodium beta alumina. The battery temperature is kept between 300 and 350 Celsius to keep electrodes as molted state. This requires independent heaters as part of the battery system, which raises annual operational costs and makes system only suitable for large-scale stationary applications. Therefore operational costs would be significant bigger, if they are placed in very cold environment. In addition, high temperatures raises safety requirements. (EASE 2016b.)

As the main advantages for the NaS are highest rated capacity than other batteries, almost zero self-discharge and inexpensive materials with high recycling rate. With these attributes, NaS battery is considered as one of the most promising candidates for high power electrical energy storage applications. NaS batteries are currently used in peak shaving applications. (Sánchez Muñoz, Garcia. & Gerlich 2016.)

10.3 LEAD-ACID BATTERY

The lead-acid batteries are the most widely used rechargeable batteries. Cathode is made of lead dioxide (PbO_2) and the anode is made of Pb. Used electrolyte is sulphuric acid. (Sánchez Muñoz, Garcia. & Gerlich 2016) The lead-acid batteries have fast response time of some milliseconds, long discharge time, small daily self-discharge rates and low capital costs and they can be implemented in the large-scale storage. Therefore, there are some barriers such as it has a limited cycle life and they often need ventilation systems. Technology is used in nearly all applications except small portable and mobile systems. Due to long discharge time, lead-acid batteries are commonly used in a large backup power supplies for telephone and computer centers, grid-connected energy storages and off-grid household power systems. (Sánchez Muñoz, Garcia. & Gerlich 2016 & EASE 2016c.)

10.4 FLOW BATTERY

A flow battery is a type rechargeable battery, which use two liquid electrolytes. Liquid electrolytes are contained in separated tanks and circulated through two independent loops to the cell stack. Stack consist two electrolyte flow compartments separated by ion-selective membranes. The membrane allows selected ions pass and complete chemical reaction under charging and discharging conditions. The flow batteries energy capability depends from the amount of the electrolytes used and the capacity of the tanks. The power rate is determined by the active surface of the membrane and by hydraulic pumps management. (Sánchez Muñoz, Garcia. & Gerlich 2016 & EASE 2016d)

Flow batteries can be classified into the categories with redox flow batteries and hybrid flow batteries. The main benefits of the both are the very small self-discharge due to electrolytes being stored in sealed tanks. Great flexibility due to power and energy ratings as they could be tailored for applications, quick response time, low maintenance and they can be almost instantly recharged by replacing the electrolyte liquid. As drawbacks of flow batteries have relatively high manufacturing costs and requirements of sensors, pumps, and flow and power management. (Sánchez Muñoz, Garcia. & Gerlich 2016)

10.5 ZINC-AIR BATTERY

Zinc is one of the most abundant metals on earth, and it is much cheaper than lithium. Al thought there have been challenge to create rechargeable batteries due to electro corrosion. However, in recent years there have been success, a company called Eos solved the corrosion problem by using a propriety coating that creates conductive and non-corrosive surface. (St.John 2015)

Eos has made megawatt-scale battery called Aurora. It is a cargo-container sized box, filled with a complex air and aqueous electrolyte solution battery cells, which absorb and discharge electricity via the interaction of air and zinc hybrid cathode, “Znyth®”. (St.John 2013)

The main advantages of Znyth® technology are low cost, long lifetime (5000 cycles) and that it is safe due to non-toxic materials. In addition, energy density is great, as 4MWh could be stored in 12-meter container. As a disadvantage, round-trip efficiency is 75%. Suitable applications for Znyth® batteries are peak shaving and management, renewable integration and frequency regulation applications. (Eos Energy Storage 2017)

11 Comparison of battery technologies

Battery energy storage systems can be used in many different applications. In order to solve global environmental problems, renewable energies will be widely used, which have created new trends in applications: storing renewable surplus energy, smart grids, smart microgrids, smart houses and electric vehicles. (IEC 2011)

Installed capacity and investment in battery storage are increasing in two main areas: renewables integration support in small or isolated grids, and grid support services for larger-scale distribution and transmission grids. In both cases, battery storage can offer faster solutions than conventional fossil fuel plants for services such as frequency response, voltage regulation and ramping support. (Houlding 2016.)

As prices of solar panels have decreased a lot, it has increased the number of installed PV systems for residential buildings. To provide a consumer-friendly storage system at low cost, the maintenance costs need to be low. The most important factor for stationary batteries is the price per kWh. Lead-acid batteries are common due to low investment costs, but as Li-ion batteries are generally better in efficiency and number of cycles, they would provide better solution. (EASE 2016d.) As Li-ion batteries investment costs are coming down fast and levelized costs are already smaller than what lead-acid have, it will take the markets for the smart house sector. (PowerTech Systems 2015) The development of Li-ion batteries has made it the most common battery type for small grid orientated storage systems. As it looks like, that the decrease of prices will continue in recent years, Li-Ion batteries will get a good foothold in the markets. (Ivanova 2015)

Largest battery energy storage systems for wind and solar farms are mostly using sodium-sulphur batteries due to high energy density and long discharge time. The NaS batteries could be used in applications for peak shaving, power quality, load leveling along with renewable energy management and integration. The flow batteries could be used as renewable energy farms to helping average out of the production as they could have extremely large capacities if electrolyte tanks are big enough. (Poullikkas 2015.)

Operating temperatures are an important aspect of batteries. Most of the batteries operate best at room temperature or slightly below. Heat is the worst enemy of most of the batteries, not include NaS or other high temperature batteries. Also cold temperatures decrease performance of the batteries and most batteries stop functioning at -20 Celsius. Although, Li-ion can operate at -40 Celsius but only at reduced discharge rate. (Battery University 2016.)

As for conclusion, the key performance attributes are shown in table 5. suitable applications in table 6. and some examples of current grid/utility-scale battery storage systems in table 7.

Type	Lithium-ion	Sodium-Sulphur	Lead-acid	Flow	Zinc-Air
Power range	1kW to 50 MW	0.5 to 50 MW	Some MW	Several kW to Some MW	Up to 10 MW
Energy range	Up to 10 MWh	Up to 350 MWh	Up to 10 MWh	100 kWh to some MWh	Up to 40 MWh
Discharge time	10 min to 4 hours	6 - 7 hours	Min to > 20 hours	Some hours	4 hours
Cycle life	2000 - 10 000	2 000 - 5 000	500 - 3 000	> 12 000	5000
Life duration	15 - 20 years	< 15 years	5 - 15 years	10 - 20 years	15 years
Reaction time	Some millisec	Some millisec	Some millisec	Some millisec	Some millisec
Efficiency	90 - 98 %	75 - 85 %	75 - 85 %	70 - 75 %	75 %
Energy density	120 - 180 Wh/kg	100 - 120 Wh/kg	25 - 35 Wh/kg	10 - 25 Wh/liter	
CAPEX: energy	390 - 1 300 €/kWh	400 - 600 €/kWh	100 - 200 €/kWh	100 - 400 €/kWh	160 - 250 €/kWh
CAPEX: power	150 - 1 000 €/kW	3 000 - 4 000 €/kW	100 - 500 €/kW	500 - 1 300 €/kW	1000 €/kW

Table 5: The key performance data of battery technologies (EASE 2016a; Lambert 2016; EASE 2016b; EASE 2016c; EASE 2016d; Eos Energy Storage 2012 & Eos Energy Storage 2016)

Battery type	Application
Lithium-ion	Residential and commercial buildings: time-shifting of locally produced PV energy Distribution grids: voltage, capacity and support of smart grids Transmission grids: ancillary services, namely frequency regulation Renewable generation: smoothing and shaping functions associated with voltage and frequency support to ensure better integration of large renewable plants into the electricty system
Sodium-Sulphur	Stabilisation of wind farms and solar generation plants Peak shaving Time-shifting
Lead-acid	Stationary stand-ups & UPS Motive power applications Starter batteries requiring high power at low temperatures Backup power supplies for telephone and computer centers Grid-connected energy storage, and off-grid residential electric power system
Flow battery	Large-scale non-mobile energy storage applications Peak shaving Energy time shifting
Zinc-Air Battery	Peak shaving and management Renewable integration Frequency regulation

Table 6: Suitable applications for battery types (EASE 2016a; Lambert 2016; EASE 2016b; EASE 2016c; EASE 2016d; & Eos Energy Storage 2017)

Manufacturer	Product	Battery type	Power	Energy
Alevo Group S.A.	The Alevo GridBank™	Lithium-Ion	2 MW	1 MWh
American Vanadium	CellCube FB 400-1600	Redox-Flow	400 kW	1.6 MWh
Eos Energy Storage	The Eos Aurora® 1000│4000	Zinc hybrid cathode	1 MW	4 MWh
NGK Insulators, Ltd.	Container type unit	Sodium-Sulphur	800 kW	4.8 MWh
Sumitomo Electric Industries, Ltd.	Container type unit	Redox-Flow	125 kW	500 kWh
Tesla Motors, Inc.	Powerpack	Lithium-ion	50 kW	210 kWh / pack
ViZn Energy, Inc.	GS200	Zinc/iron Flow	1 - 1.4 MW	3 - 4.2 MWh
Younicos Inc.	Y.Cube	Lithium-ion	250 - 500 kW	Up to 920 kWh

Table 7: Examples of commercial/utility scale battery storage systems.

Operating in cold temperatures is one of the most important aspects in arctic environments. Tesla's Powerpack operating temperature is from -30 Celsius to 50 Celsius, due to internal heating/cooling system. (Tesla Motors 2017) Temperature range is significantly better than what Eos's Zinc-Air battery have, which range from 10 to 45 Celsius. (Eos Energy Storage 2017) In addition, a French company, Saft, has delivered lithium-ion battery storages to Alaska, where ambient temperature can drop to -50 Celsius. Even though lithium-ion battery have large operating range, in the very cold temperatures, storage containers needs insulations and heating systems to ensure that the temperature stays ideal. (McDovall 2017.)

Lead-Acid battery is another type that operates well in cold temperatures, but as mentioned before lithium-ion is more suitable than it, due to longer lifetime and better energy densities and efficiencies. At current state of art, it looks that lithium-ion batteries will be the winning technology. Market status of lithium-ion batteries will be discussed later.

12 Market status report

Following chapters will discuss about current market status of electrolysers, hydrogen storages, fuel cells and lithium-ion batteries.

12.1 HYDROGEN ECONOMY, BOOM OR BUST?

Hydrogen has been on the discussion table for decades now. There is a potential, that is a clear thing, but will the potential ever be realized, it have been another question. The main vision of a hydrogen economy is that hydrogen would replace all fossil fuels in every sector where it is used today such as industrial, transport, residential and commercial. It is an ambitious vision, but there are still many question marks, how to make hydrogen competitive solution for the globes energy system.

Due the Paris agreement, United Nations have agreed to cut CO2 and greenhouse gas emissions. Target is to limit global warming below 2 Celsius as close to 1.5 Celsius as possible. (United Nations Framework Convention on Climate Change 2017) This agreement boosts markets for renewable energy and energy storage systems. According United Nations Emission Gap Report it means that CO2 emissions need to be reduced at net zero by 2060-2075 to stay on target. (United Nations Environment Programme 2015) This opens the doors for renewable, emission free solutions, such as hydrogen economy.

Hydrogen energy storage systems have been struggling years with low roundtrip efficiencies and high capital costs. Over 90 % of total hydrogen demand is produced by steam reforming process, which uses fossil fuels as resource, only a fraction of demand is covered by renewable hydrogen production via water electrolysis. (Future Market Insights 2017)

12.2 DRIVING TOWARDS TO THE HYDROGEN ECONOMY

As it looks like, fuel cell vehicles will be the forerunners of the hydrogen economy, as many major car manufacturers such as Toyota, Nissan, Honda, Hyundai, etc. are developing fuel cell vehicles. It is expected that transportation sector will be the fastest growing market due demand of hydrogen powered cars in North America and Europe. (Global Energy News 2017.) Transportation segment looks also attractive for battery based electric vehicles (EV). EVs are also reducing emissions and they are more attractive for consumers due smaller capital costs. Even tough, FC-vehicles can run up five times longer and have faster recharge time than electric vehicles. Anyhow, transport-related fuel cell markets doubled capacity to 280MW in 2016 comparing as 2015. (Mace 2017.) There is still a little chicken-egg problem because the limitations of hydrogen refueling stations, but if the demand of FC-vehicles are high enough it will make wheels rolling in the whole hydrogen industry.

In the terms of refueling Japan, Germany, UK, Norway and California are increasing deployment of hydrogen stations. Now it looks like, that Norway will be the first country to have hydrogen-refueling stations in every major cities. (4th Energy Wave 2016) Norway set the target of 100% of the new car sales to be zero-emission vehicles starting in 2025. A complete emission free transport sector is estimated to demand 7 TWh for battery electric vehicles and 20 TWh for hydrogen production for fuel cell vehicles. (Garcia, Barbanera, Cumo, Di Matteo & Nastasi 2016.)

12.3 BIG IN JAPAN

Japan is the only nation currently, which is steadily moving forward to hydrogen society. They are developing long term and stable local fuel cell industry with clear policies. Most of the fuel cells that they are developing are PEM-type stacks and systems. (Hydrogeit 2017.) Due these reasons Japan is viewed currently as king of the fuel cell, as the country has around 200 000 stationary units in people's homes. (Mace 2017) Government of Japan had an ambitious plan, project Ene-Farm, to get 1.4 million stationary fuel cell application in homes by 2020. Currently, the project is facing hurdles, due the sales of residential CHP application are not increasing as expected. Therefore, they start building new towns where every house has a fuel cell, solar panels and energy storage system. (4th Energy Wave 2016.) The government also set the target of having majority of new homes built in 2020 to be net-zero energy. (Ward 2016)

12.4 PEM WILL DOMINATE MARKETS

As it expected that hydrogen by water electrolysis will be a viable option for energy storage beyond conventional power-to-power systems. Due the multiple possibilities to use hydrogen as a transport fuel, re-electrified back to the grid, injecting into natural gas or hydrogen grid or use it as feedstock for chemical industries, there is growing markets for it. Due the growing renewable energy demand, there will be lots of surplus energy to use for hydrogen production. Market for electrolytic hydrogen could be several tens of GW in the next 10 to 20 years and become even larger until

2050 if GHG emission reductions remains as worldwide goal. (Smolinka, Thomassen, Oyarce. & Marchal 2016)

Both, alkaline and PEM electrolysers, will have its market share, but it seems to be clear that PEM will be favored at least for distributed and decentralized hydrogen production with the need for higher pressure required from applications. (Smolinka, Thomassen, Oyarce. & Marchal 2016)

In the fuel cell sector, there will be also large markets available so all electrolytes will have own share, if they can be commercialized. Therefore, it is a clear that PEM FC and SOFC will form the majority market share going forward. Reason for the dominance of these two are broad spread markets, the largest number of developers globally, largest amount of funding for research and modular power ranges. Of these two, PEM have even larger market due as it is used in transportation applications. (4th Energy Wave 2016.)

12.5 MARKET GROWTH PREDICTIONS

The global hydrogen generation market is forecast to cross 180 billion USD by 2024 according to *Global Markets Insight*. Strict policies to reduce sulfur contents and carbon footprints drives the global hydrogen generation markets forward. (Globe Newswire 2017)

According to *Research and Markets* report, the hydrogen storage market was valued at 415.8 million USD in 2015 and it is projected to reach 969.6 million USD in next 9 years. China and Asia-Pacific seems to be the biggest market for hydrogen storage in next 10 years, due the rise of demand of methanol-based gasolines and ammonia-based fertilizers. (Global Energy News 2017.)

The fuel cell industry is estimated to be worth a total 3.6 billion USD in 2016 and it is expected to skyrocket into 25.5 billion USD by 2024, according to research from *Global Markets Insight*. The key driver for growth of the fuel cell industry is demand for clean energy. Stationary fuel cell applications are projected to have steady demand, as key driver for market growth is expected to be increasing back up power installations in commercial and residential buildings. (Globe Newswire 2016.)

Despite the growth of the fuel cell industry in recent years, the market looks like a pyramid. At the top of it, there is worldwide about 30 stack and system manufacturer, which have commercial products. In the middle of it, there are less than 60 companies, which are close to become commercial and the rest of the industry makes the base of the pyramid. Therefore, the majority of the industry is still in research and development stage. (4th Energy Wave 2016.)

12.6 ENERGY CARRIER OF THE FUTURE HAS FINALLY BECOME AVAILABLE

Thirteen leading industry, automotive and energy companies have joint the forces and create the global initiative called the Hydrogen council. The international companies in the Hydrogen Council are: Air Liquide, Alstom, Anglo American, BMW GROUP, Daimler, ENGIE, Honda, Hyundai Motor, Kawasaki, Royal Dutch Shell, The Linde Group, Total and Toyota. They share united vision and long-term ambition to promote hydrogen as the key solution of the worldwide energy transition. (Healy 2017.)

In the first meeting they had in January, 2017 they stated that industries need to scale up support for these ambitions, but it cannot be done alone. Governments need to back up hydrogen with actions through large-scale infrastructure investment schemes. The key ambition of the Hydrogen Council is to accelerate the investments in the development and commercialization of the hydrogen and fuel cell sectors. Because notable progress in the whole chain of hydrogen industry in recent years, it is now up to industry, policy makers and customers to use the full potential of the hydrogen. (Healy 2017.)

12.7 LITHIUM-ION, RISE OF ENERGY DENSITIES AND FALLING COSTS

Just like hydrogen economy, battery market growth is highly depended on demand of electric vehicles, which decreases manufacturing costs. Transition to electric transportation is a big leap. There are many indications of a paradigm change. As seen in 2016, record number of Tesla's latest car model in pre-orders. Model 3 collected 180 000 pre-orders in a day, which is the single-day sales record for any product in the world according to the Tesla's CEO Elon Musk. Three months later, the number of pre-orders exceeded 325 000 copies though Model 3 Tesla will be available no earlier than the end of 2017. (Shankleman 2016.) The above-mentioned electric cars in production volumes requires lithium-ion an unprecedented number. To achieve required battery capacity Tesla is building a lithium-ion battery plant in the Nevada desert, the Gigafactory. The plant is in full production in 2020 and will thus double production of lithium-ion batteries in the world. (Lienert 2016.)

European car manufacturers are responding to Tesla's plans. The first information on Volkswagen's own billion-battery factory was given in May 2016. (Fehrenbache 2016) Also, LG Chemical is looking to build a battery factory for electric vehicles due to the growing demand in Europe. LG is one of the largest suppliers of batteries among Panasonic and Samsung SDI. (Handelsblatt 2016)

The increase in industrial production of batteries is a result of the growing demand, which leads to reduction of the prices (figure 11). The battery technology development is driven by electric vehicles. Car manufacturers bring to the market also to household-size battery packs as well as larger properties targeted battery solutions, such as the Tesla Powerwall and Powerpack. Mercedes Benz has also brought similar products to market. (Baisden & Glendinning 2016)

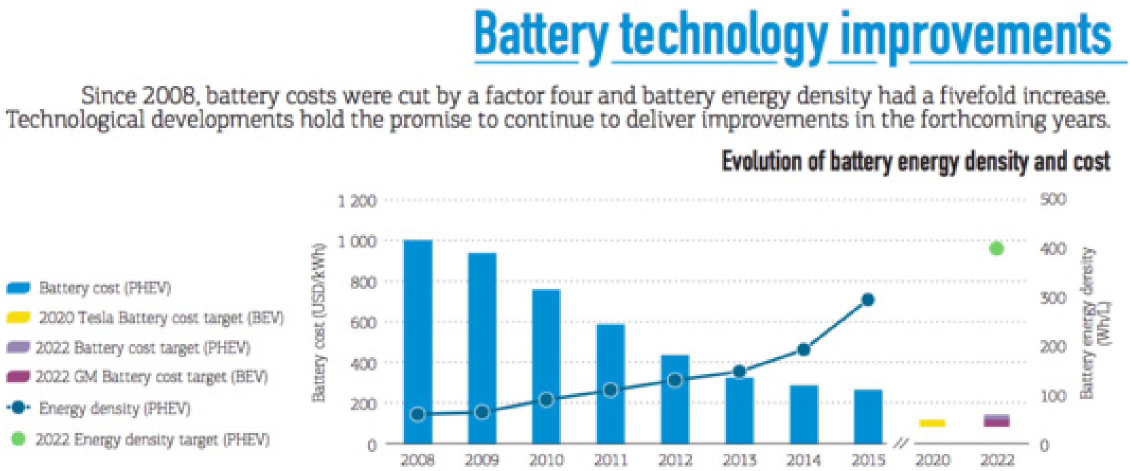


Figure 11: Battery technology development and price trend (Pressman 2016)

Bloomberg Energy Finance forecasts lithium-ion battery production roughly doubles every two years and the price is reduced to approx. 15-20 % over the same period. The forecast is based on the learning curve that industrial production refers to the theory of the production volume doubled, the production cost will fall by 10-20 %. It is not just a result of the industrial production scaling, but the learning curve is the result of the development of the knowledge and know-how in the field of technology. (Pressman 2016)

12.8 LITHIUM-ION - WINNING TECHNOLOGY?

The cost of energy storing can be estimated with LCOE analysis (Leveled Cost of Energy) which observes the costs over the entire life cycle. Energy source's LCOE-price consist of the price of the production equipment, cost of capital, management and maintenance costs, fuel costs, and the amount of energy produced. (Naam 2015.) In the German market the battery systems for household-use (5 kW nominal power) was analyzed with LCOE. The cheapest LCOE-price for electricity was 0.39 €/kWh. The comparison also revealed the fact that the investment cost of the most expensive system turned out to be cheapest for during its life cycle. It should be noted that the household- scale battery systems in the market are still 1300-2300 €/kWh price range, although the automotive industry is below 200 €/kWh. Domestic market size class systems are still marginal compared to the vehicle industry. (Finsolar 2016) In general, 500 €/kWh price is considered mass-market breakthrough precondition.

German state-owned KfW bank grants cheap loans to household's battery solutions. Through the funding program has been funded 19 000 battery purchases between 2013-2015. Lithium-ion prices decreased by 18 % during 2015. (IRENA 2015) Germany Trade and Invest (GTAI) predicts a massive growth on energy storage market in 2016-2017. It is expected annual sales up to 50 000 battery system by 2020. The forecast is based on GTAI's statements that integrated solar power production with battery system will reach grid parity in between 2016-2017 as seen in figure 12. (PV Magazine 2016.)

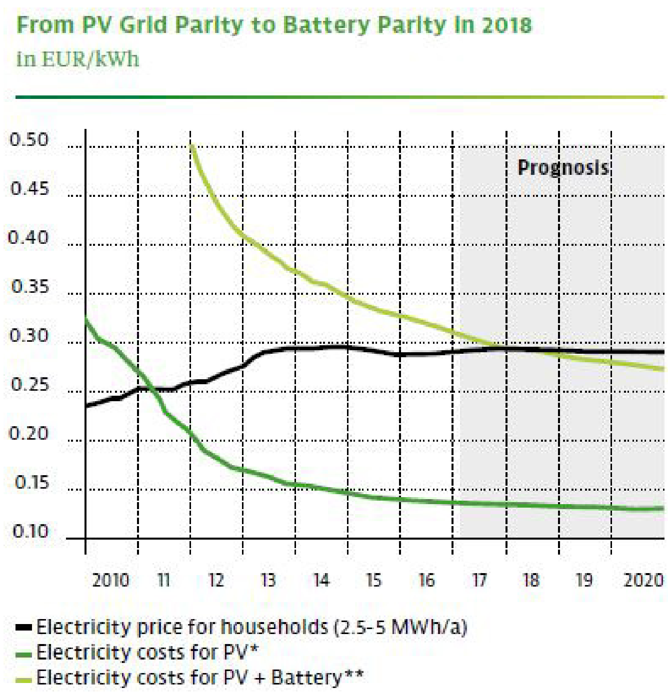


Figure 12: Calculation of the battery system's competitiveness compared to grid. Prices are forecasted to be the same in 2017. (Bräutigam, Rothacher & Staubitz 2016)

US energy storage market tripled in 2015. The biggest growth was in small-scale or household size category, which increased by four times. Lithium-ion batteries have 96 % market share of new systems. The market is expected eight times by 2020 and to increase investment of 2.5 billion dollars. (Bräutigam, Rothacher & Staubitz 2016)

Household size class battery systems are reaching marketability. The big players such as Tesla, LG, Enphase, Panasonic, Samsung and Sonnen have introduced a battery product in a household category recent years. (Roselund 2016) According to Sonnenbatterie managing director, their price of the system has fallen by 80 % in six years, and according to him, similar price drop will be in the next four years. (Parkinson 2016) Sonnenbatterie is the market leader in household-scale systems worldwide.

12.9 BATTERY ENERGY STORING IS IN ITS INFANCY IN FINLAND

In Finland, the price of electricity is still inexpensive and there is no incentive to invest in order to save electricity. In Denmark, the price of energy is twice as high in Finland and Germany even higher, about 0.3 €/kWh. In addition to Germany, other Nordic countries have the electricity feed-in tariff, which will be paid to small producers of surplus energy produced in the power grid. Feed-in tariff raises the price of electricity but it also increases the local production of renewable energy. On the other hand, more expensive electricity prices encourage to investment in the energy performance. (Bade 2016)

From an economic point of view, energy storage is not yet profitable to households in Finland. Battery energy storages have not reached market maturity in Finland, though Helsinki energy company Helen Ltd have the largest megawatt-scale li-ion battery system in the Nordic countries. (Kurnitski 2016.) However, energy production system based on renewables according to the Paris agreement requires the use of energy storage methods. In Finnish conditions which are emphasized by long distances and low population density, regional energy storage solutions have its place in the mix.

In Lapland, there are many small villages with local raw materials available for energy production. Agricultural waste, forest-based bioenergy and even the use of solar energy ensure autonomous, grid independent production. The construction of such island grids will also require energy storage solutions and intelligent management of the electricity grid to balance consumption and production. The integration of remote residential areas to the grid may not be commercially profitable compared to off-grid solution.

13 Hydrogen or batteries for energy storage?

As every storage technology has own advantages and disadvantages. The technologies have a range of different performance characteristics based on their energy capacity and discharge time at rated power.

The battery storage systems have lower energy capacity and shorter discharge time than hydrogen and are therefore more suited for short-term storage. In other hand, batteries has better efficiency, faster response time than hydrogen and are more mature technology. In addition, batteries have public acceptance over hydrogen because of the Hindenburg disaster, which is still in people's minds.

Hydrogen-based systems have higher energy capacity and longer discharge time at rated power, than batteries, what makes them suited storing large amounts of energy, which could be discharged over long periods. In addition, hydrogen is flexible fuel because it can be used as fuel for transportation sector and it can be used as raw material in the chemical industry. However, hydrogen based storages are still less mature technology and high capital costs with poor roundtrip efficiency does not look good for broad customers. Even though, it is expected that prices of electrolysers and fuel cells will decrease a lot in the future, but the same will happen with battery technologies.

Probably both solutions will have own role in our sustainable energy system in the future, due to the need of seasonal and short-term storage. Anyway, it can be expected that battery based systems will have bigger market share in near and medium term due to earlier mentioned reasons. However, as we know, there is an unlimited amount of hydrogen, unlike rare metals, which are used in batteries, the long term sustainable energy solution could be the hydrogen. Anyhow, it is a long road ahead for the hydrogen economy, which have many barriers to overcome.

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The purpose of this publication is to update the state of the art research and future sights for hydrogen and battery based energy storage systems. Even though batteries are well known technology and hydrogen have been called energy carrier of the future for decades now, the development of large-scale electrical energy storages has been challenging. This study takes a look at the current situation of energy storage markets.

In this report, there are described current technologies to generate, store and convert hydrogen back to electricity, and furthermore common battery technologies are presented. It includes current market status reports for both storage technologies and comparison between them.

This publication is part of cross-border project Artic Energy - Low Carbon Self-Sufficient Community. The goal of the project is to create a model for self-sufficient, low carbon community using local renewable energy sources in the arctic region. Developed model can be used as a planning tool for all regions, which have the same circumstances than the project area to follow EU- and national level climate and energy strategies. The project is funded by EU-program Interreg Nord, Regional Council of Lapland, Länsstyrelsen Norbotten and Interreg-program in Norway.

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