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VIABILITY OF HYDROGEN ELECTRICITY STORAGE

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Nykymaailman tarvitsemat energiajärjestelmät perustuvat pääasiassa fossiilisten polttoaineiden ja uusiutumattoman energian käyttöön. Uusiutumattoman energian katsotaan olevan ekologisesti kestämätöntä, polttoaineen loppuessa tuotannoltaan epävarmaa ja arviolta yksi suurin syy ilmastonmuutokseen. Eurooppa on riippuvainen fossiilisten polttoaineiden maahantuonnista, erityisesti öljyä ja maakaasua tuodaan epäluotettavista lähteistä. Fossiiliset varannot nähdään epävarmoina ja erityisesti öljyvarantojen huomattava väheneminen on odotettavissa ennen vuosisadan puoliväliä.

Opinnäytetyöni tutkii, kuinka varastoida sähköenergiaa vedyksi. Vety säilötään ja muunnetaan takaisin sähköksi vedyllä sähkön- ja lämmön yhteistuotantolaitoksessa, kun energian markkinahinnat ovat korkealla. Kaasuturbiinista syntynyt hukkalämpö käytetään hyödyksi ja syötetään kaukolämpöverkkoon.

Muuntoprojektin ensimmäisenä tarkoituksena on ratkaista uusiutuvan energian varastointi ja tasainen tuotanto kysynnän mukaan. Toiseksi on ratkaistavana varastoidun vedyn muuntaminen sähköksi ja syöttö sähköverkkoon, kun hinta on korkealla.

Vety, Sähköenrgia varastointi vedyksi

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ABSTRACT

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In these days the energy systems are still based on the use of fossil fuels and nonrenewable energy in a high percent of the world total energy needs. Nonrenewable energy is considered to be unsustainable and liable to suffer from the insecurity of supply and is also considered one of the main cause of climate change. Europe is dependent on the imported fossil fuels especially oil and natural gas from non-reliable sources. The rest of the fossil reserves is considered insecure, although noticeable reduction of oil would be expected before mid-century.

This thesis examines how to store electrical energy as hydrogen gas. Electricity from a renewable energy source, for example wind is converted into hydrogen, the hydrogen is stored and later converted back to electricity using a CHP when the Elspot market prices are high. The waste heat produced in the CHP is fed into a district heating grid. There are two main reasons for this thesis. The first reason for conversion is to solve the storage problem of renewably generated energy, so that the electricity generation meets the electricity demand at any moment. The second reason is converting the stored hydrogen back to electricity and feed it to the power grid when the electricity market price is high.

Energy storage, electricity to hydrogen conversion, wind to hydrogen feasibility

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LIST OF ABBREVIATIONS

m^3	Cubic meter
m^2	Square meter
MWh	Megawatts per hour
MJ	Mega joule
kW	Kilowatt
km	Kilometre
w	watt
cm	Centimetre
PEM	Proton exchange membrane
CHP	Combined heat and power
H2	Hydrogen
Pa	Pascal
kPa	Kilopascal
mPa	Mega pascal
AC	Alternating current
DC	Direct current
A	Ampere
Co2	Carbon dioxide
°C	Celsius
ppm	parts per million
K	kelvin
kg	kilo gram
%	percentage
m/s	meter per second
GW	gigawatts
TWh	terawatt per hour
mm	millimetre

SO3	sulfur trioxide
hv	high voltage
NO	nitrogen oxides
CO	carbon monoxide
O2	oxygen
LNG	liquefied natural gas

1 INTRODUCTION

As the world turns to renewable sources, such as solar energy and wind energy to meet it is energy demand experts found a problem, which is how to balance the supply and the demand in an electricity grid when power sources naturally fluctuate. How can we harness clean energy and still balance the electricity grid? One of the solution is converting the electricity to energy storage. The production of the renewable energy is converted into hydrogen, which is the principle component of natural gas. This hydrogen is fully compatible with the currently existing infrastructure and it can be injected into any existing natural gas pipe and stored for a time and can be also transported geographically to be used elsewhere.

The project main targets are to convert the renewable electricity generated by the wind source into hydrogen, the hydrogen is stored and converted back to electricity using a CHP plant when the spot market prices are high. The waste heat produced in the electrolysis is fed into a district heating grid. Other possible hydrogen applications for example:

- Hydrogen fuel station for vehicles.
- Biogas fuel station for vehicles.
- Produced hydrogen/biogas can be fed to the Finnish gas grid, nearest injection point is in Tampere.
- Finnish metal factories that uses high heat in metal manufacturing process.
- Input material for chemical processes.

1.1 Project Overview

The world’s energy demands are ever increasing, and to fulfill the demands, engineering solutions needs to be searched, such as conversion of energy from one form to another. The purpose of converting one form of energy to another is to get a convenient form to use the energy in a better way. There are engineering solutions and technologies to use the fossil fuels to produce electricity, then it could be converted to hydrogen form but in that way we pollute our environment faster. One kilowatt hour of converted energy from coal produces almost 0,98 kg CO2 into the environment. In comparison to renewable technologies which cause less pollution and damage to the environment, but there are also limitations regarding the poor efficiencies. Here it comes to the right selection of technology conversion regarding the protection of our environment. It is important for energy and environmental engineers to balance between the factors of sustainable development, energy and environment /1, 83-84/.

To be efficient, economical and sustainable, the production of hydrogen should be from a renewable energy source, which is wind energy. Since hydrogen can be produced directly from renewable water and wind power that makes the technology more successful and economic viability and that would be the suitable technology to solve both energy and environmental problems for the future /1, 27/.

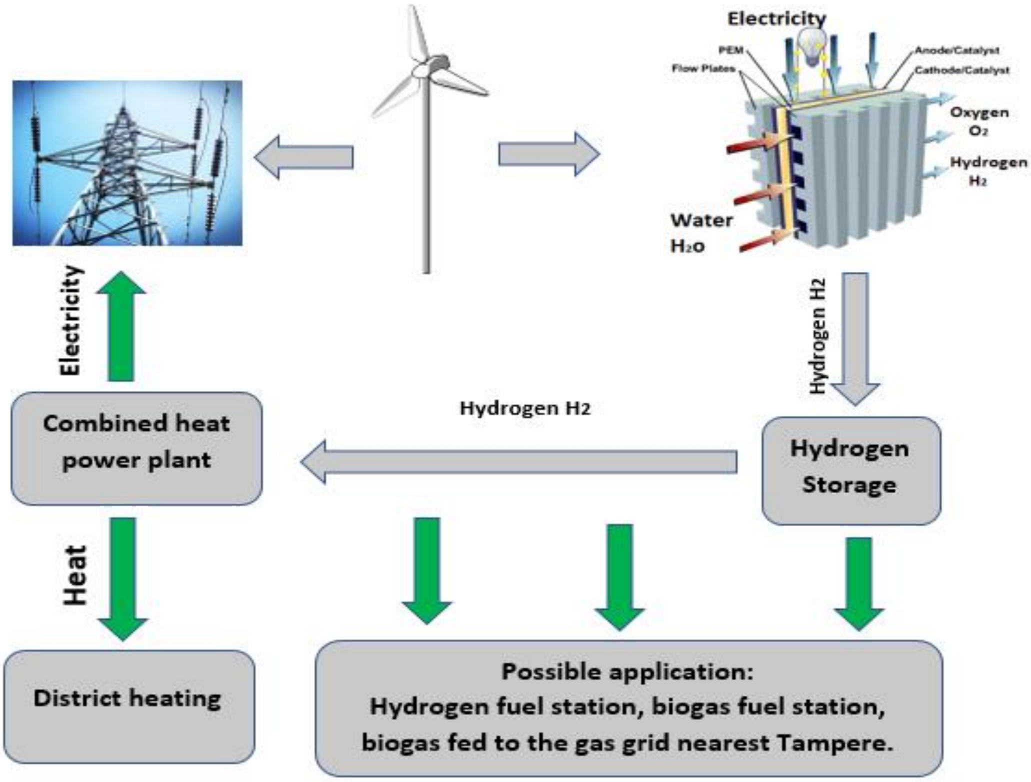


Figure 1. Project mind map

Figure 1 shows a diagram of the project, aiming to convert the renewable wind power plant energy into hydrogen. The hydrogen is stored and converted back to electricity using a CHP plant when the spot market prices are high. The residual heat released from the electrolysis and gas turbine is fed into a district heat grid. Hydrogen can be used in different applications. The aim to take the advantages and benefits of clean renewable energy source, by lowering CO2 emissions and more independency from the fossil sources and add to that the increase of the energy production with the storage ability. These advantages and benefits will be investigated in the project.

Project applications are possible if there is a need for example:

- Hydrogen fuel station for vehicles.
- Biogas fuel station for vehicles.
- Biogas can be fed to the Finnish gas grid, nearest injection point is Tampere.

This solution result would be a high overall integrated system efficiency. The usages of the storage can be running applications as industry, heating and refuelling stations for vehicles.

1.2 Methodology

The project scope is to evaluate in a theoretical way the technology involved in the project and calculate the efficiency and economic viability of the power plant.

The key points of the project are as follows:

- To study the theoretical technology for each plant and component involved in the project such as wind power plant. hydrogen electrolysis, storage and applications, gas turbine, Nord pool electricity market, Finnish gas network and the gas market.
- Applying the conversion in a study case to evaluate the disadvantages and the advantages of the project.

- Establish economic and efficiency analyses for the project conclusions.

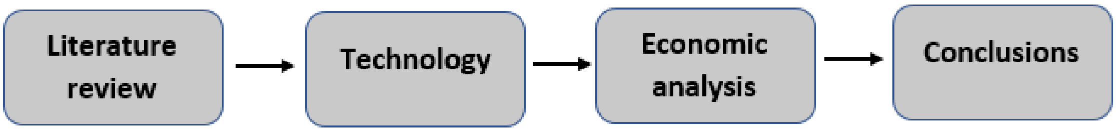


Figure 2. The project methodology

Figure 2 hows the idea of the project and how it is going to be literature reviewed in order to explain and understand the system operations as the technology, then the system efficiency. In the final steps the economic analysis of the project is presented mean-while the valuable conclusions will be generated.

1.3 Outline of the Thesis

Chapter 2 explains the wind power in Finland, and how the wind power affects the balancing of the power grid. The wind power demands and storage are also reviewed.

Chapter 3 gives information on the conversion technology from electricity to hydrogen. The types of electrolysis and hydrogen storages is reviewed, and how to store the hydrogen. The hydrogen conversion projects in Europe and the possible off grid applications for hydrogen will be reviewed.

Chapter 4 presents the gas turbine as it is the main converter of stored hydrogen to electricity and the possible usage of heat loss coming out from the process to take it as advantage and higher the efficiency.

Chapter 5 explains the electricity market in Finland and how the price of electricity is decided. The future target for the electricity in Finland and the Finnish feed in tariff system are also discussed, as well as the Finnish gas network and its interconnection points. The new gas pipeline project between Finland and Estonia and the trading of the gas market in Finland and the pricing of the natural gas are also presented.

Chapter 6 discusses and analyses the viability to convert stored hydrogen to electricity in Finland using a gas turbine in combined heat power plant.

In Chapter 7 the conclusion of the research is generated and summarized.

2 WIND POWER PLANTS

The idea of storing electricity produced by a wind power plant is storing the electricity when there is over production. The focus in this thesis especially is to study the possibility to store electricity when the electricity market price is low and sell or convert back the stored electricity when there is need for the electricity when the market price is high.

The wind varies according to the day and the seasons, that makes is that the wind power production varies according to the weather. The predictability of the weather in short term is possible but impossible for the long term.

Wind as renewable energy source is considered as a source of the solar energy but indirectly, and it has variability problem depending on the location, offshore wind generator expected to run on nominal power during 30% of it is life time and 20% of it is life time when the generator located onshore. The best capacity factor that is expected between 25% - 35%. This means wind farms require a backup system /7, 65/.

In the following chapters information will be given regarding the wind and electricity in Finland, and how the wind plays a vital role in the electricity production in Finland. Some of the wind turbine components will be discussed in order to understand that the wind turbine components play a big role in better energy production. The design of the components is also discussed for example aerodynamics prevent the wind from damaging the turbine.

2.1 The Wind Power in Finland

From the wind turbine point of view, in Finland it is mostly windy during the winter months and clearly less wind during the summer months. Finland's wind conditions are significantly affected by its geographic location and mainly from the Atlantic to Finland by low pressure and its routes. /26/

Due to these, the large scale average wind speed at a kilometer (geostrophic wind) is comparatively high (9 to 9,5 m/s), which is considerably higher than in southern Europe (7-8,5), on the other hand smaller than closer to the North Atlantic in the British Isles (10-12 m/s), the Norwegian coast (10-11 m/s) or Denmark (10-10,5 m/s) and the North Sea coast (10-10.5 m/s). /26/

The Finnish climate is characterized by human observation altitude and the average height of the weather stations at the altitude of the windmill, the clear variations in wind speeds in seas, coasts, while in the inland the average monthly wind speed varies quite little. The average annual wind speed measured in inland weather stations is considerably lower than that measured at aerial stations. /26/

The speed of the wind increases as the height rises. The rate of increase depends on the altitude difference between the terrains, the roughness of the terrain. The change in wind speed in the vertical direction is much smaller in the boundary than in the open sea area. On the other hand, the change in speed in Lapland during the winter months is considerably higher than on the south coast, due to the higher number of pin versions, that is thermally stable situations. At the top of the cross section, the change in speed can also be influenced by the lower atmosphere jet flow. /26/

2.2 Electricity demand

The electricity demand differs from country to country depending on the time of the day. That is why countries have different generation portfolios. The differences from country to country make it difficult to define general conclusions and recommendations for the optimum method for balancing production and demand of electricity and for integration of renewable energy resources. Demand for electric energy changes continuously, depending on the time of day, day of the week and the season. After midnight, the demand generally decreases because of reduced human activity. In the morning, when people wake up, they switch on appliances, railway systems intensify running, and factories increase their power demand. That creates the morning ramp up. /7,81-82/

2.2.1 Power Demand in Finland

Finland is a North European country with high living standards based on industrial activity. Due to its high latitude, winters in Finland are very cold. Electricity provides 27% of the country's final energy use while 53% of all electric energy supplied is used in industry. Much industrial activity, a cold climate and a high wealth level together bring Finland in the group of countries with top electricity demand per capita (16,4MWh / capita in 2008). Electric heating in many homes as well as the low level of sunlight raises winter base load by some 60% above that in summer. Power demand based on annual electricity consumption and averaged over the year amounted to 9,9 GW for the year 2008. The relatively large year-round base load of 7 GW makes Finland very suitable for nuclear and coal fired power plants. These plants have maximum economic performance for high utilization factor. Since the Finnish system is part of the Nordel network, the system balancing is mainly done with its own hydropower with support from Norwegian and Swedish hydropower. /7, 88/

2.2.2 Effect of Wind Power Variability on Balancing the Power System

Many policymakers and citizens consider electricity generation using wind turbines as the ultimate solution for providing the world with sustainable energy. However, electricity production based on wind has characteristics that differ substantially from those of fuel-based generation. Weather events determine the output of these renewable sources, resulting in a poor dispatch ability. Their intermittent and to some extent unpredictable character therefore puts an additional burden on matching electricity production with demand. Many information sources suggest that interconnecting renewable electricity sources from over a wide area would smooth the variability in output, thus solving most problems of intermittency. /7, 93/

Wind variability gives rise to serious balancing problems. It depends on the situation and the moment load of the power grid, if all the generated electricity from the wind turbines can be exported or the observed increase in wind output is accommodated by a decrease in output of hydropower, gas fueled combined cycles and steam-based power plants. In case of fail in predicating the high winds, the winds are late for example 2 hours, in that case, the power resources other than wind would have had to compensate for the difference. Other case is, what would happen because of incorrect wind speed predications when a wind capacity is installed that cover 25% of electricity needs in that country. It will be clear that rapidly deployable back-up power is essential for accommodating much wind power. /7, 152/

Rapid back-up power is very much needed if during times of high winds, wind speed suddenly exceeds the maximum value allowed for wind turbines. Such events happen especially in areas of much wind, a large portion of wind turbines has to be switched off. This results in a high ramp up rate of reserved capacity, meaning an increase in output from zero up to almost full load within a period of one hour. Steam based power plants can never perform such a task alone. /7, 152/

2.3 Wind Power Plants in Finland

Wind power is a relatively new form of electricity production in Finland, the construction of which has started well in recent years. However, Finland's wind power capacity can be significantly increased from the present. At the end of 2017, there were 700 wind turbines operating in Finland with a total capacity of 2044 MW. They generated about 5.6 percent of the electricity consumed in Finland in 2017. /27/

Today, the largest plants in Finland are 5 MW. In the future, the size of individual wind farms, especially in the sea, will increase so that the power plants can be more than 7 megawatts. /27/

In 2017, 153 new wind farms were built in Finland. At the end of the year wind turbines manufacturers produced 700 wind turbines in Finland. Wind power capacity grew by 516 MW in 2017, with a combined capacity of 2044 MW. Electricity wind power produced 4.8 TWh, covering 5.6% of Finland's electricity consumption. /27/

According to an inventory of wind power projects carried out annually, by the beginning of April 2018, wind power projects were published in Finland for almost 15,500 megawatts (MW). The planned projects for the sea are about 2000 MW. /27/

2.4 Storage of Renewable Energy

It would be attractive if renewable energy could easily be stored so that peaks and valleys in the demand could be smoothed and temporary excess output from renewable sources could be stored for later use. Opting for storage of renewable energy and selecting the optimum storage system require knowledge of the time-based patterns of the electric energy to be charged and discharged. These patterns determine which key performance indicators are relevant for the storage system. To cover a contingency such as the sudden loss of a generator or a load, rapid release or absorption of energy is crucial. This means that in this case the power of the storage system expressed in MW is important. For covering a few hours of peak demand each day from storage, both power (MW/GW) and energy (MWh/GWh) are relevant. For saving energy harvested in summer for use in winter, storage of large amounts of energy, preferably in the range of TWh, is important. /7, 116/

2.4.1 Smooth Down Wind Power Output

The energy output from wind turbines appears to be very variable. Short duration high peaks are interspersed with periods of moderate output and sometimes up to 10 days without any output at all. To cover 10 days of no output from wind by energy storage, much energy has to be stored. High peaks of short duration in wind output allow only a short time for energy storage, while releasing the stored energy back into the grid might take a much longer time. However, the opposite can also be true. /7, 116/

2.4.2 Wind Stored Energy Based on Gas Compared with Other Techniques

Gas, natural gas and biogas, where methane is the major constituent, when stored at 70 bar pressure, have an energy density close to a hundred times higher than that of compressed air. Therefore, only a fraction of the compression energy and storage volume is needed for gas-based energy storage compared with that of compressed air. In a fully sustainable world, using stored biogas for peaking power, for covering contingency demand and for bridging differences between seasons seems to be the most economical solution. Until that point is reached, sufficient natural gas is available as a buffer. Using hydrogen as a storage medium is much less attractive than methane-based gas because of the losses involved in producing it, its much lower volumetric energy density than natural gas as well as the safety aspects. The energy density of hydrogen is lower than that of methane by a factor of 3,6 while the turnaround efficiency of using hydrogen as a medium is less than 40%, and in practice reaches about 25%. /7, 126/

2.5 Wind Turbine Components

By using rotor blades, the wind kinetic energy is transformed into mechanical energy to move the generator and generate electricity. The wind turbine consists of many components that help to generate the electricity in as efficient way. For that reason, it is important to study and represent the main components of the wind turbine and realize the whole process of the energy conversion /6, 25/.

Ensuring the maximum power output, there is a relation between the wind speed and the blades that capture the energy from the wind. The blades are playing a big roll to control the speed and torque of the wind generator. These controls are important to protect the wind turbine not to be damaged and pollutant the environment /6, 25/.

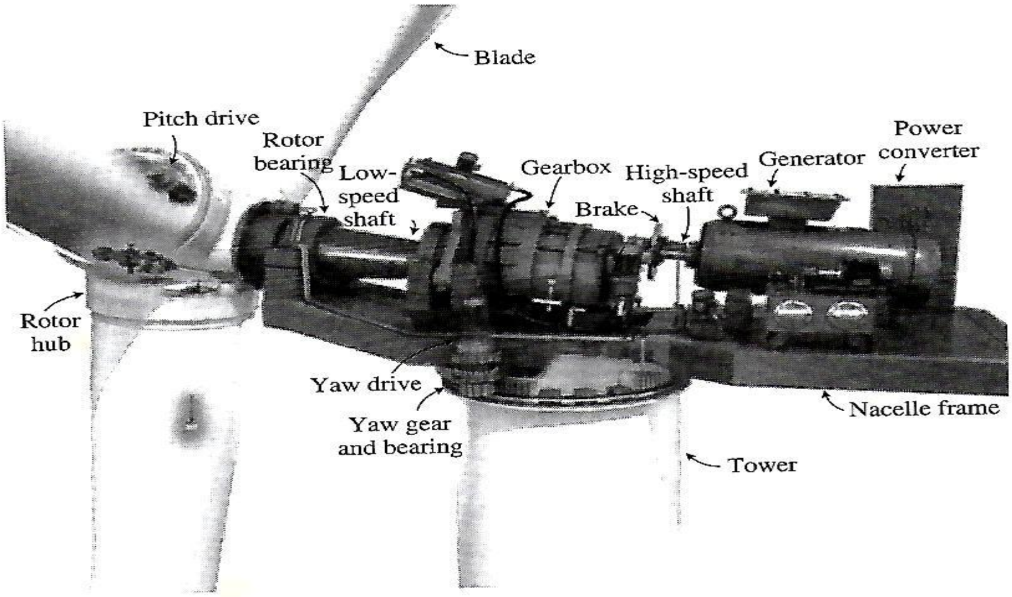


Figure 3. Wind turbine components /6, 26/.

Figure 3 shows the wind turbine components and parts. The blades on the rotor hub transform the kinetic to mechanical energy. The rotor hub is installed on the main shaft. The mechanical force moves via the drive train which consists of shafts, gearbox, bearings and then to the generator that converts the mechanical energy to power. The conversion process is done with the power converter system that transfer the generated electricity to the grid. Other components that help in controlling and protecting the system in an efficient way are direction and wind speed sensors, yaw system, pitch system, electric cables, mechanical brake, the lightning protection system and heat exchange system. There are constructive components such as the foundation, turbines tower, nacelle frame. There is a backup system for the pitch drive and for the brakes in order to control the system in case of interruption operation of the previous parts /6, 27/.

3 THE CONVERSION AND STORING OF ELECTRICITY TO HYDROGEN

In this chapter detailed information for the conversion technology from electricity to hydrogen will be given. The types of electrolysis and hydrogen storages is reviewed, and how to store the hydrogen. The hydrogen conversion projects in Europe and the possible off grid applications for hydrogen will be reviewed.

3.1 Introduction

The unsustainable energy, uncertainty of the reserves and non-security of fossil supply challenges, puts the efforts to look after a solution.

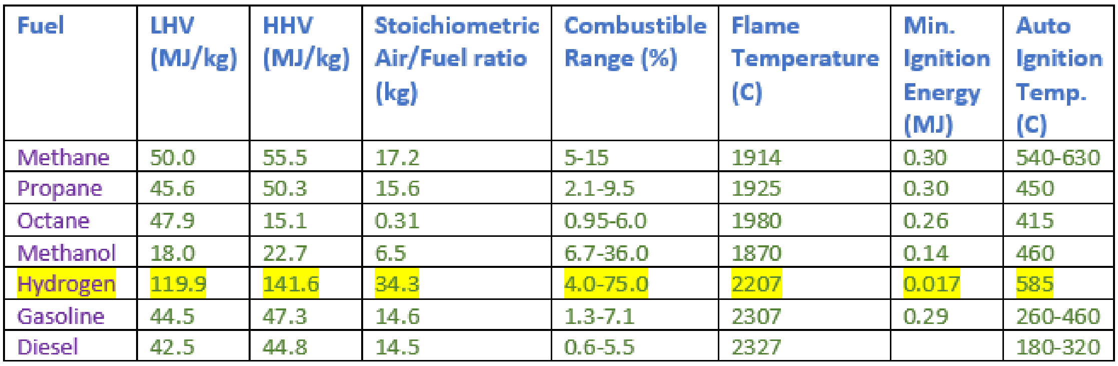
The expected solutions need to be studied from the technological and method options which is considered a wide package. One of the suggested part of this package is hydrogen technology, which is positively focusing on two important matters: 1. Storage of occasional energy sources. 2. Fuel option for transportation.

There are many renewable energy sources and energy technologies to produce electricity and heat, such as solar photovoltaics, small hydropower, concentrating solar system, geothermal, biomass and wind energy source. Despite the fact of available and clean energy, still there is a major problem facing these renewable sources. Due to the fact of fluctuation of the power generated from the renewables that integrated in the electric grid would be needed, to storage electricity with large quantities still an unsolved major problem. A hydro power plant can solve that major problem but only when geographically possible, other solution is electric cars for the electric storage considered to be in the future more common, but this solution is still uncertain. For that comes hydrogen considered as energy storage for the excess electricity with different forms as gas or liquid and also can be as used as another form of energy supply to many other applications. It can also be transported through out pipelines, truck, tanks, rail, add to that can be converted back to electricity or heat with no emissions. / 3, 8/.

3.2 Why Hydrogen?

Hydrogen is considered to have the highest energy amount per unit mass in comparison to any other fuel. The following table compare the hydrogen to other fuels from a various combustibility property:

Table 1 Hydrogen in compare to another fuels / 3, 9/.



Fuel	LHV (MJ/kg)	HHV (MJ/kg)	Stoichiometric Air/Fuel ratio (kg)	Combustible Range (%)	Flame Temperature (C)	Min. Ignition Energy (MJ)	Auto Ignition Temp. (C)
Methane	50.0	55.5	17.2	5-15	1914	0.30	540-630
Propane	45.6	50.3	15.6	2.1-9.5	1925	0.30	450
Octane	47.9	15.1	0.31	0.95-6.0	1980	0.26	415
Methanol	18.0	22.7	6.5	6.7-36.0	1870	0.14	460
Hydrogen	119.9	141.6	34.3	4.0-75.0	2207	0.017	585
Gasoline	44.5	47.3	14.6	1.3-7.1	2307	0.29	260-460
Diesel	42.5	44.8	14.5	0.6-5.5	2327		180-320

Source: Adapted from hydrogen fuel cell engines and related technologies, college of the desert, palm desert, CA, 2001.

As it is declared in the table hydrogen has almost 3 times the energy value of gasoline (141,60 MJ/kg versus 47,3 MJ/kg). As for the volume the situation changed to 8,491 MJ/m$_3$ compared to liquid hydrogen 31,150MJ//m$_3$ to gasoline. Here comes the main problem for the low volumetric density of hydrogen which is the storage for automotive application. A bigger tank would be needed to stock hydrogen for longer operational time to the vehicle. That would be depend on the physical content of the fuel, liquid or gas and the pressure. One of the most desirable character of hydrogen is electrochemical property that can be benefited in a fuel cell. The efficiency of the fuel cells is between 50 to 60% and lifetime up to 3000 hours. That would give an output power from 50-2500W and a current output from 440-1720 A/m$_2$ / 3, 8-10/.

As for the ignition of the hydrogen the energy amount needed is about 0,02 MJ, which is 10 times less than the gasoline needs 0,24 MJ. That means a fast ignition even for a little mixture. The main challenge in here is how to run an engine with hydrogen that has hot gases or even hot spots on the cylinder that would be a source of ignition and a problem that to a flashback and early ignition / 3, 10-12/.

The extinguish distance for the hydrogen is smaller than that of the gasoline (0,64 mm to 2 mm). This means the flames of the hydrogen travels closer to the cylinder wall before extinguishing compared to the other fuels / 3, 10-12/.

The cause of the hydrogen embrittlement in different materials is the continuous exposure to the hydrogen, the results can be leakage or failures in metal components and non-metal components. Pressure, moisture content, concentration, temperature are factors that could affect the level and rate of impact for the hydrogen embrittlement / 3, 10-12/.

The attractive benefits for the hydrogen help to build up more interest to invest in the technology, some of these benefits:

- Hydrogen can reduce the CO2 emissions and is environmental friendly because the production process for the water involves the oxygen and hydrogen without gas emissions.
- The production of the hydrogen can be done on the production location with the possibility for transporting it without any loss.
- Hydrogen can be transported in liquid or gas form with the benefit of light weight, hydrogen is not considered toxic if leakage happens.
- Hydrogen can be used in the internal combustion engines as a fuel add to that the usage to produce electricity and also as a fuel for vehicles and energy carrier. All these would make the hydrogen the candidate to replace the fossil fuels.

Nonetheless, there are a few disadvantages that hydrogen technology has:

- Hydrogen production requires a higher amount of common fuel than from renewable sources that leads to a lower overall hydrogen efficiency.
- A high amount of energy is needed in order to store the hydrogen / 1, 1-5/.

3.3 Converting the Electricity to Hydrogen

The wind power plant attached to a PEM electrolysis system, the electrolyzer is connected to a water feed. The produced hydrogen is stored into a tank, the tank pressure can be of the electrolyzer pressure or compressed to a higher pressure with the use of gas compressor. The storage instrument for the system can be metal hydride, in order to store or convert and also does not interrupt the load consumption of the plant. An auxiliary power supply needs to be installed for the energy security reasons. The auxiliary power supply unit can be a fuel cell or a hydrogen combustion engine. In this thesis the conversion from hydrogen to electricity with a hydrogen combustion engine is discussed. The second security reason for having the auxiliary power supply is when the storage tank is full, the unit is able to convert the excess of the hydrogen to electricity. The power plants are running as autonomous, when the price of electricity is low the conversion from produced wind energy to hydrogen is done, and when the price of electricity is high the conversion from hydrogen to electricity is done. /3, 174-175/

The first step of converting the renewable electricity to renewable gas process is splitting of water into hydrogen and oxygen. This is done by chemical process known as electrolysis. Energy is required to split the water stored in the chemical bonds of the hydrogen molecules, then the hydrogen is catalytically reacted with carbon dioxide to yield methane. This reaction accurses to a biological process inside a single cell microbe named ARCHAEA which were among the first living organism on earth. /11/.

A company named Hydrogencis has created a new and the world’s smallest and powerful PEM electrolyser single stack which converts 3 megawatts of power to 1,3 metric tons of hydrogen per day. The stacks can be connected and build up electrolysis plant for up to 100 megawatts power to gas system /11/.

The company’s chief technology officer discussed the uses for the power gas. Due to the instability of the wind that blow on and off creates the instability issues and also there is a need for a large scale of energy storage. That is why the power to gas plays a role as advantage that can storage a large amount of energy. For example when the wind blows in the evening and when electricity is needed least, the grid operator ends up with excess amount of electricity in the grid and that is considered as a problem to the grid operator. Therefore the power to gas is a tool to help the grid operator to help to control the grid so when there is excess electricity on the grid, the grid operator is able to turn on the power to the gas plant and adsorb all the excess electricity and convert it into hydrogen that can be used to power buses, cars, trains or to be injected to the natural gas network to be used at later time. There are new projects and cooperation with local transport companies in California at the moment to make a new stage of development in hydrogen fuel extension /11/.

The company hydrogencis is delivering 1000 fuel cells for buses in China that would reduce the emission which is caused by the diesel applications in the streets, and force the Chinese government to remove these applications from the streets and reduce the emission level dramatically. There is a new target to build 100 stations in Korea, Japan, California, Germany in the future /11/.

3.3.1 Water Electrolysis

On earth there are enormous resources and water is considered as one of the most important resources. Splitting the water by electricity into oxygen and hydrogen is known as water electrolysis / 4, 155/.

The water electrolysis has many different technologies but one common process, is applying the water to an electrochemical cell. By supplying enough high voltage above zero current cell potential E_0, the hydrogen generates at the cathode and oxygen generates at the anode. The ions are moved through electrolyte and a diaphragm verify the separation of the generated oxygen and hydrogen / 4, 155/.

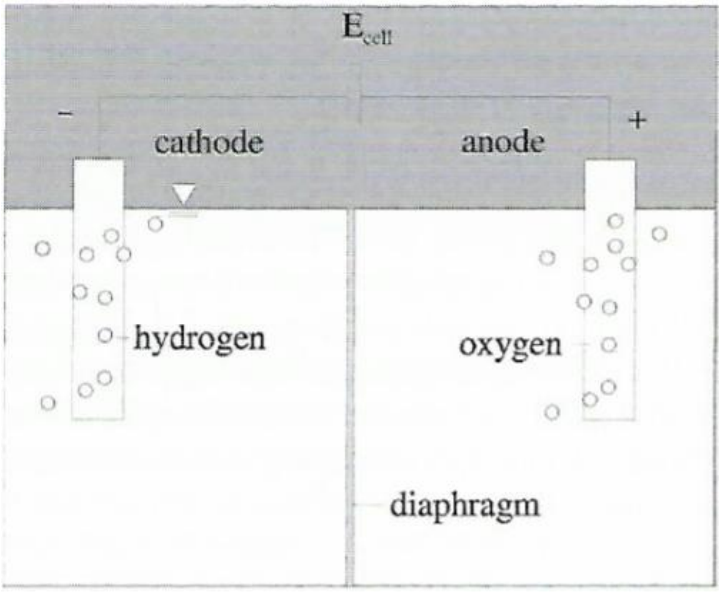


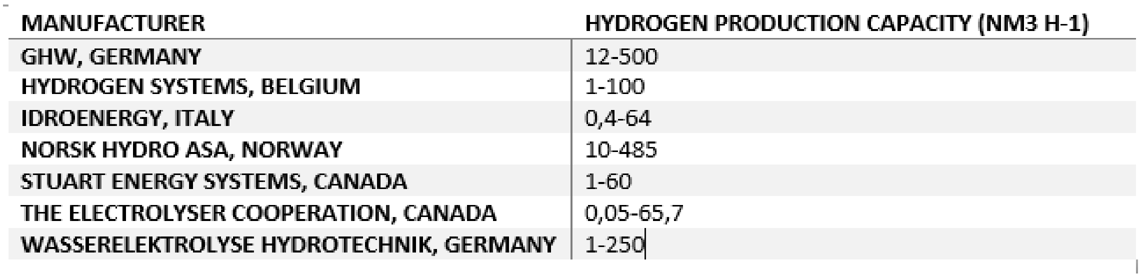
Figure 4. Principle of an electrolysis cell / 4, 156/.

3.3.2 Alkaline Electrolysis

Alkaline electrolysis is a common technique and universally used. An alkaline solution is used is the electrolyte. Most of electrolysis plants operate 20 – 40 % potassium hydroxide aqueous solution as an electrolyte. The material used for diaphragm that divides the two gases is asbestos and these days the material is replaced with polysulfone polymers or nickel oxide. The operating temperatures are between 80-100 degrees Celsius. Raney nickel is used as an electrode material / 4, 158/.

Singles cells are connected in order to construct electrolyser unites. When cells are connected electrically in parallel and open to the ambient this concept is called unipolar and used for uncomplicated installation. Handling the high current is a must and the operation cannot be at high pressure. This unipolar concept is used by a few manufacturers such as the electrolyser cooperation in Canada, but the rest of industrial manufacturers of electrolysers use a bipolar concept, where one electrode serves the anode and cathode in the same time. A stack is called for this type of cells arrangement because the single cells are stacked on each other. The currents need to be low and high voltages must be controlled / 4, 158/.

Table 2. Alkaline electrolyser manufacturers / 4, 158/.



MANUFACTURER	HYDROGEN PRODUCTION CAPACITY (NM3 H-1)
GHW, GERMANY	12-500
HYDROGEN SYSTEMS, BELGIUM	1-100
IDROENERGY, ITALY	0,4-64
NORSK HYDRO ASA, NORWAY	10-485
STUART ENERGY SYSTEMS, CANADA	1-60
THE ELECTROLYSER COOPERATION, CANADA	0,05-65,7
WASSERELEKTROLYSE HYDROTECHNIK, GERMANY	1-250

As for the feed water, the process is handled by deionization to stop the dirt to reach the system. An automatic water feeder is important in this process to add water automatically after the decomposition of the water. The lye controlling device handle the alkaline electrolyte concentration inside the electrolyser system. The output form of the energy is AC electricity, to provide direct current for the needed voltage level would require a transformation station / 4, 158/.

3.3.3 Solid Polymer Electrolysis

There has been many attempts to develop and replace the liquid alkaline and acidic with solid electrolyte, in order to decrease corrosion. In the alkaline system the concentration needs to be controlled but the solid system would not need that control. A solid electrolyte is able to operate at the same time as a diagram. The ion exchange membranes used as the material for the electrolyte / 4, 160/.

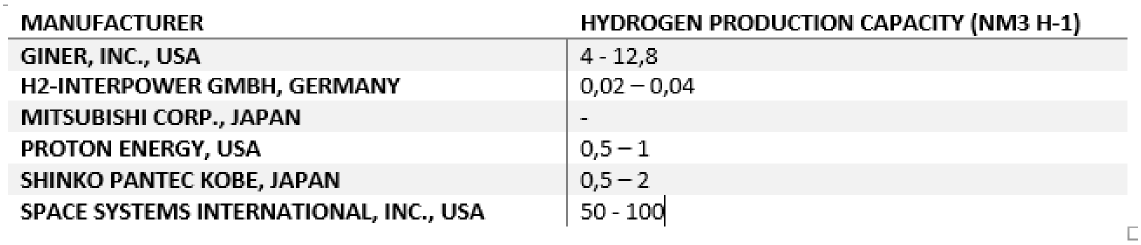
In 1967 the electrolysis was developed and “perfluorinated sulfuric acid polymer” was used. Both the anode and the cathode are used straight into the membrane as a fine ply, and the circulation of the cell done by the deionized water. At the anode, the water dissolves into oxygen and protons which is hydrogen ions. The hydrogen ions move as hydrated compounds via the membrane operating with fixed SO3- category in order to move. The result is that the hydrogen is shaped in the cathode / 4, 160/.

Compared to the alkaline electrolysis, the alkaline uses the cathode and anode as a catalyst. In the cathode side the carbon assisted platinum is used to stimulate the hydrogen progress in order to minimize the costs, which cannot be done with the anode because the progress of the oxygen would oxidize the carbon material in not a long period / 4, 160/.

The solid polymer electrolysis material has high cost and the technology depends on very good quality of the gas and produced high pressure, on the other hand alkaline solution has good sealing possibility. The solid polymer electrolysis application are used mostly on the site of the production because it produces small amounts of hydrogen to be used for example in aerospace purposes. Alkaline has more forward technology than solid polymer. The efficiency of solid polymer is 85% - 93% / 4, 160/.

Table 3 shows the manufacturers of the solid polymer systems

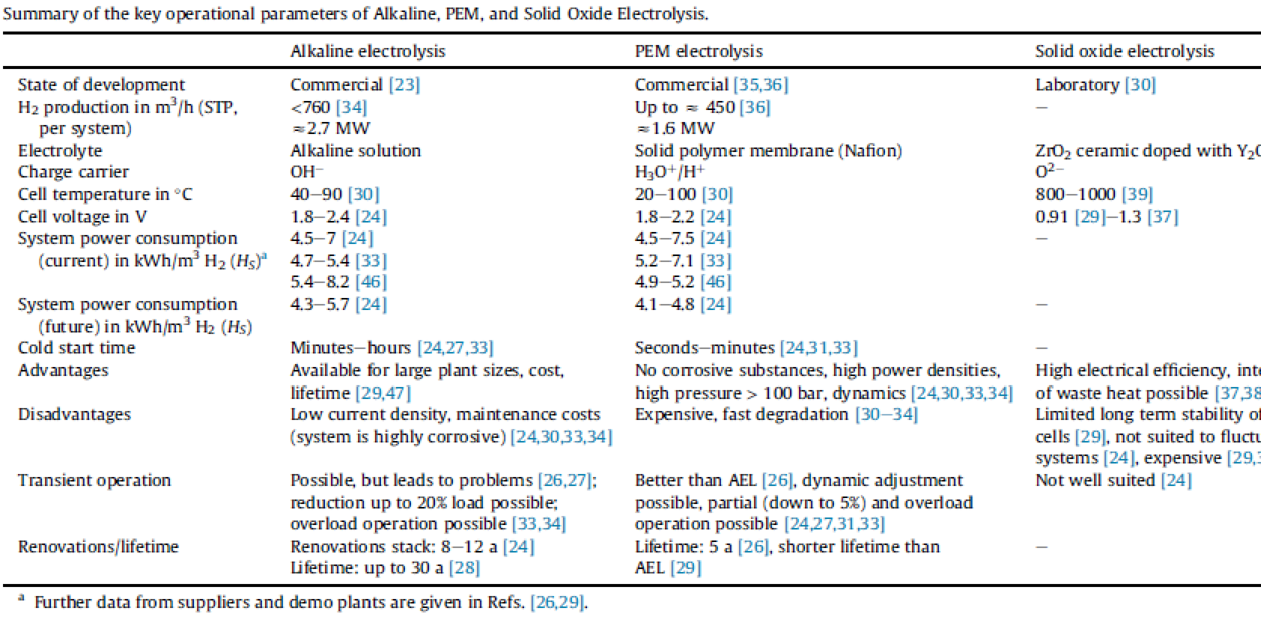
Table 3. Solid polymer systems manufacturer / 4, 160/.



MANUFACTURER	HYDROGEN PRODUCTION CAPACITY (NM3 H-1)
GINER, INC., USA	4 - 12,8
H2-INTERPOWER GMBH, GERMANY	0,02 – 0,04
MITSUBISHI CORP., JAPAN	-
PROTON ENERGY, USA	0,5 – 1
SHINKO PANTEC KOBE, JAPAN	0,5 – 2
SPACE SYSTEMS INTERNATIONAL, INC., USA	50 - 100

The following table compare the operational parameters for Alkaline, PEM and solid oxide fuels cells.

Table 4. Operational parameters for fuel cells /10/.



Summary of the key operational parameters of Alkaline, PEM, and Solid Oxide Electrolysis.

	Alkaline electrolysis	PEM electrolysis	Solid oxide electrolysis
State of development	Commercial [23]	Commercial [35,36]	Laboratory [30]
H_2 production in m^3/h (STP, per system)	<760 [34] ≈2.7 MW	Up to ≈ 450 [36] ≈1.6 MW	–
Electrolyte	Alkaline solution	Solid polymer membrane (Nafion)	ZrO_2 ceramic doped with Y_2
Charge carrier	OH^-	H_3O^+/H^+	O^{2-}
Cell temperature in °C	40–90 [30]	20–100 [30]	800–1000 [39]
Cell voltage in V	1.8–2.4 [24]	1.8–2.2 [24]	0.91 [29]–1.3 [37]
System power consumption (current) in kWh/m^3 H_2 (H_S)[a]	4.5–7 [24] 4.7–5.4 [33] 5.4–8.2 [46]	4.5–7.5 [24] 5.2–7.1 [33] 4.9–5.2 [46]	–
System power consumption (future) in kWh/m^3 H_2 (H_S)	4.3–5.7 [24]	4.1–4.8 [24]	–
Cold start time	Minutes–hours [24,27,33]	Seconds–minutes [24,31,33]	–
Advantages	Available for large plant sizes, cost, lifetime [29,47]	No corrosive substances, high power densities, high pressure > 100 bar, dynamics [24,30,33,34]	High electrical efficiency, inte of waste heat possible [37,38
Disadvantages	Low current density, maintenance costs (system is highly corrosive) [24,30,33,34]	Expensive, fast degradation [30–34]	Limited long term stability of cells [29], not suited to fluctu systems [24], expensive [29,
Transient operation	Possible, but leads to problems [26,27]; reduction up to 20% load possible; overload operation possible [33,34]	Better than AEL [26], dynamic adjustment possible, partial (down to 5%) and overload operation possible [24,27,31,33]	Not well suited [24]
Renovations/lifetime	Renovations stack: 8–12 a [24] Lifetime: up to 30 a [28]	Lifetime: 5 a [26], shorter lifetime than AEL [29]	–

[a] Further data from suppliers and demo plants are given in Refs. [26,29].

3.4 The Efficiency and Heat Loss of Hydrogen Rlectrolysis

"Common industrial electrolyzers have a nominal hydrogen production efficiency of around 70%. High power dissipation value is the most important drawback of such systems since electric power expense has the largest share in the price of electrolytic hydrogen. The electrical impedance of an electrolysis cell causes a fraction of the applied energy to be wasted as heat while the electric current passes through it". / 4, 159/.

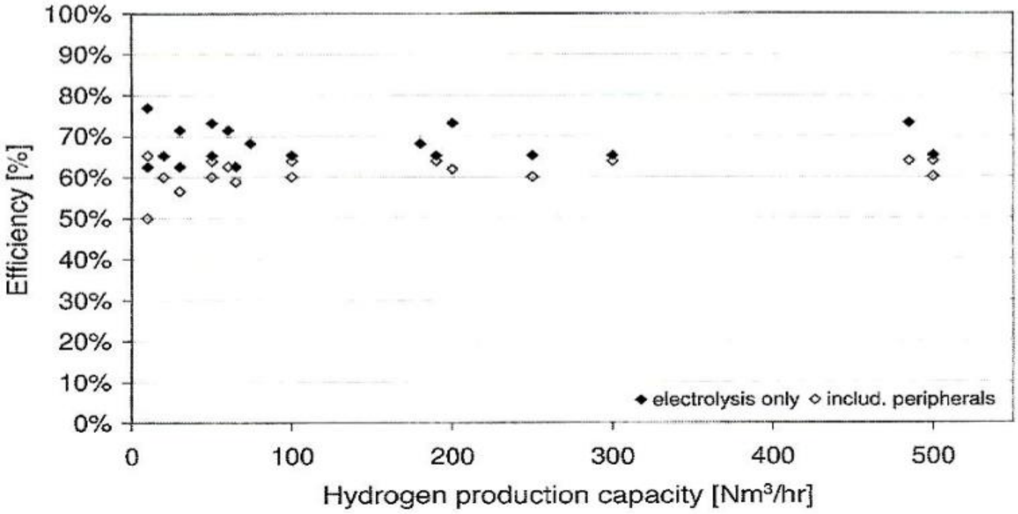


Figure 5. The efficiency of alkaline systems in compare to various plant sizes / 4, 159/.

The efficiency of alkaline system can be seen in Figure 5, the efficiency percentage versus the production capacity of the plant also depends on the technology used and the end usage of the plant. The percentage varies from 60% to 79%. / 4, 159/.

The heat loss from the conversion process of electricity to hydrogen will be 29%, “the heat losses reflect the energy losses and maybe described by comparing the cell voltage with the higher heating value voltage”. / 4, 159/. Figure 18 in Chapter 6 shows the heat losses percentages during all the conversion processes.

The heat loss is 29% from the electrolysis process, during the process will be heat released from the cell between 20 – 100 °C. The cell temperature for alkaline system seen in Table 4. The heat temperature is not high during this process, and it cannot be a benefit to be used as a heat source for the district heat network.

3.5 Storing of hydrogen

The hydrogen is similar to natural gas in way of moving it and that would be accomplished by injecting the hydrogen into the hydrogen pipelines. There are hydrogen pipe networks for the hydrogen in Europe which consists of 1500 km and in United States of America 720 km. There is one old pipe network that has been operated in Germany for about 50 years. The pipes are made from steel and have a diameter between 25 cm to 30 cm. The function pressure in the pipes are 10 bars to 20 bars. Hydrogen to be moved through the pipes that would require 2,8-time bigger flow than natural gas because the volumetric hydrogen energy density is 36% compared to volumetric energy density of the natural gas. The viscosity of natural gas is $11{,}2.10^{-6}$ Pa which is higher than that of hydrogen has $8{,}92.10^{-6}$ Pa. The following is the equation is to calculate how much power needed to pump the gas through a pipe:

$$P = 8.\pi.l.v^2.\eta \qquad (1)$$

P=Power L=pipe length v=velocity η=viscosity

The transmission power per energy unit is 2,2 times bigger for hydrogen in compare to natural gas. The total energy loss during the transportation of hydrogen is around 4% from the energy content. The system pipes volume, length and pressure can cause a big effect on the amount of hydrogen within the pipe. For that reason, the pipes are used to deal with the changes in demand and supply, preventing the cost of building a storage at the location / 4, 165/.

Renewable energy converted to renewable gas storage has many benefits

1. High energy storage capacity.
2. Flexibility in use.
3. Long distance energy transmission.

The following figure shows how the hydrogen is stored, just the physical storages will be discussed:

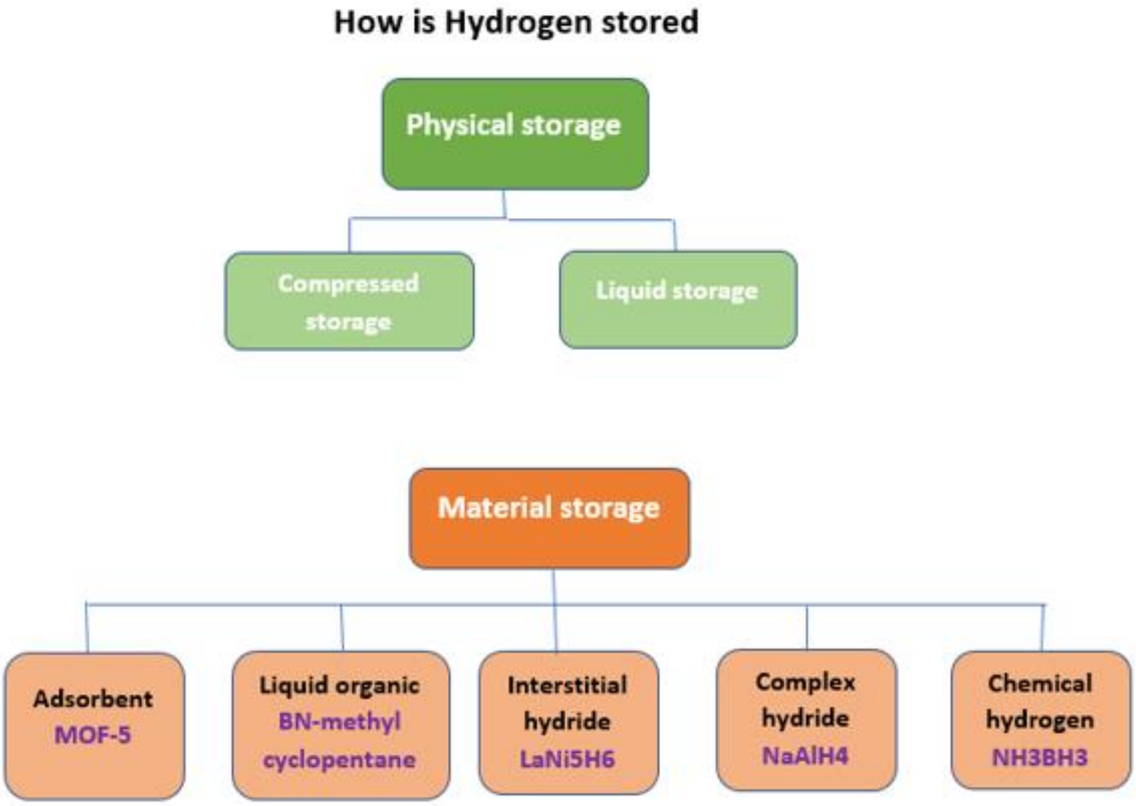


Figure 6. Hydrogen storages. /22/

3.5.1 Compressed Storage

To reach the needed storage density, the pressure should be between 50 MPa to 70 MPa. There are also tanks available with 35 MPa and as for the hydrogen steel cylinders that are used in laboratories the pressurization would be around 20 MPa. For the cylinders to be able to resist a high pressure like that would be made from carbon fiber reinforced composite. The compression, pressure control mechanisms, safety issues during the process and after, are considered the highest cost for this technology. One main problem with the compressed cylinders is their round shape and that would create a possible hazard. The stability of tanks framework would cause difficulties to transportation applications due to the space availability / 5, 250/.

3.5.2 Liquid Storage H_2

The liquid hydrogen has a temperature of around 21 K at ambient pressure and the proper storage density of 70,8 kg.m-3 which is a little more than that of solid hydrogen 70,6 kg.m-3. Though, the whole process considered as costly, due to energy and evaporation loss. The systems must be air ventilated due to heat transferred within the tanks and the ventilation would stop the hazard of producing pressure up to 104 bar, which could cause the boil off of the hydrogen. A solution for fuel loss problem is to collect the boil off with help of hydrides or add better thermal insulation to the storage / 5, 251/.

3.6 Hydrogen Applications

The main purpose of producing hydrogen from renewable sources is to open a new field for the electrolysis to produce hydrogen and to be used as storage and to be used later during the periods where the renewables are not producing energy. The hydrogen electrolysis plants are mainly build in countries where electricity is a cheap and very good quality of gas is available. The following are examples of off grid applications in small scale / 4, 161/.

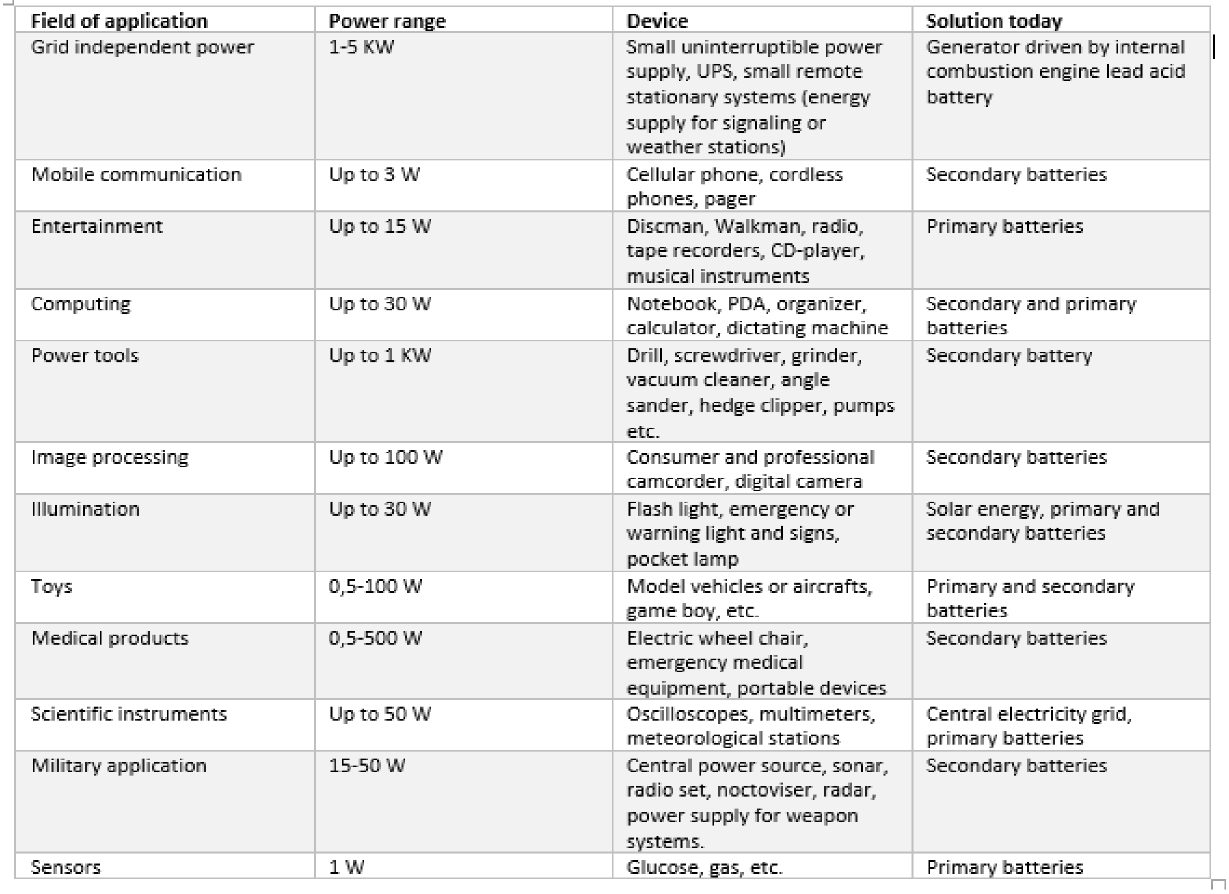
3.6.1 Off grid Applications

The purposes of use are to power cottages or houses, telecommunications terminals, railway junctions. The energy need to power the targets is low from 100W to 10kW but the idea that the power has to be available all the time. The power supply from renewable sources is not guaranteed all the time so the hydrogen production and storage is needed. Battery storage solution is for short time and regarding the renewable for example solar or wind production, there are differences in capacities in summer time and in winter time. The energy available also depends on the size of the hydrogen plant to guarantee that the extra produced energy from renewable is stored and is enough to supply the power to the application while there is no energy production from the renewables. In this case in the small application it is preferred to use the solid polymer system, compared with the alkaline system there are no quality differences in gas and no need for the lye control. Just deionized water needs to be supplied with ion cartridges. The operation temperatures for most of the hydrogen electrolyses is 333,15K – 353,15K. The electrolyser has a possibility to connect directly to a DC power supply with the help of a DC / DC converter for example a solar panel, an AC to DC converter is needed in case the energy is produced from the wind source / 4, 161/.

3.6.2 Hydrogen Fuel Cells Applications

The following table introduces several types of fuel cells applications

Table 5. Fuel cells applications / 4, 356/.



Field of application	Power range	Device	Solution today
Grid independent power	1-5 KW	Small uninterruptible power supply, UPS, small remote stationary systems (energy supply for signaling or weather stations)	Generator driven by internal combustion engine lead acid battery
Mobile communication	Up to 3 W	Cellular phone, cordless phones, pager	Secondary batteries
Entertainment	Up to 15 W	Discman, Walkman, radio, tape recorders, CD-player, musical instruments	Primary batteries
Computing	Up to 30 W	Notebook, PDA, organizer, calculator, dictating machine	Secondary and primary batteries
Power tools	Up to 1 KW	Drill, screwdriver, grinder, vacuum cleaner, angle sander, hedge clipper, pumps etc.	Secondary battery
Image processing	Up to 100 W	Consumer and professional camcorder, digital camera	Secondary batteries
Illumination	Up to 30 W	Flash light, emergency or warning light and signs, pocket lamp	Solar energy, primary and secondary batteries
Toys	0,5-100 W	Model vehicles or aircrafts, game boy, etc.	Primary and secondary batteries
Medical products	0,5-500 W	Electric wheel chair, emergency medical equipment, portable devices	Secondary batteries
Scientific instruments	Up to 50 W	Oscilloscopes, multimeters, meteorological stations	Central electricity grid, primary batteries
Military application	15-50 W	Central power source, sonar, radio set, noctoviser, radar, power supply for weapon systems.	Secondary batteries
Sensors	1 W	Glucose, gas, etc.	Primary batteries

Fuel cells which uses the air and hydrogen would convert the fuel chemical energy to electricity with a high efficiency compared to hydrogen combustion engine, and water is produced after the process without emissions. The benefit of using it will increase the renewable share. The overall consideration of producing electricity from renewables and hydrogen fuel cells as complex would be a solution for mobile electricity generation. The fuel cells can be run with several fuels / 4, 335/.

As for the fuel cell efficiency it is not more than 60%, because the kinetic losses as heat. One example for the efficiency is 1kw of fuel cell has 50% of efficiency rate and which evaporates 1kw of heat. The low rate of efficiency is expressed as slow electrode kinetics and electrolyte resistance / 4, 340-341/.

3.6.3 Internal Combustion Engines as Application

Hydrogen is considered as the future expected fuel regarding the transportation field, because of the possibility of production from several energy sources without producing emissions. By feeding the hydrogen into internal combustion engines would give great advantages to transportation field for example the vehicles / 4, 372/.

Dual fuel engines are underdevelopment as hydrogen / gasoline engine. The, BMW group developed the technology with Hydrogen 7 dual fuel engine / 4, 379/.

3.6.4 Space Applications

The hydrogen could serve the spacecraft as a rocket fuel, as “cooling scientific instrument and detectors to cryogenic temperatures in the operation of electric power systems example nickel hydrogen batteries and fuel cells”. The production and storage of the liquid hydrogen is done on the site where there are the spacecraft for military, communications and other space missions / 4, 382/.

Regarding the future development of hydrogen for space applications, one scenario could be to produce oxygen from CO_2 in the Martian atmosphere and also produce fuel. Mars in need for oxygen and water to have humans living on it, hydrogen is ideal for that purpose / 4, 406/.

3.7 Actual Electricity to Gas Projects in Europe

There are electricity to gas projects in Europe which are operational or planned at this moment. The following map shows the locations of the projects and the produced gas type.

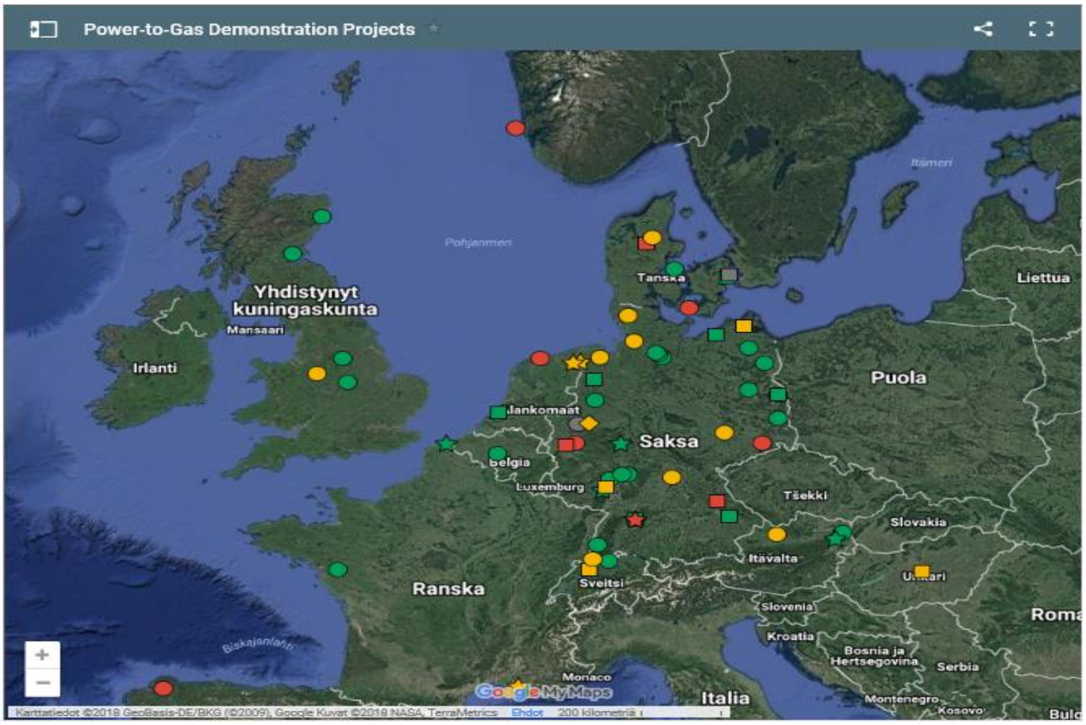
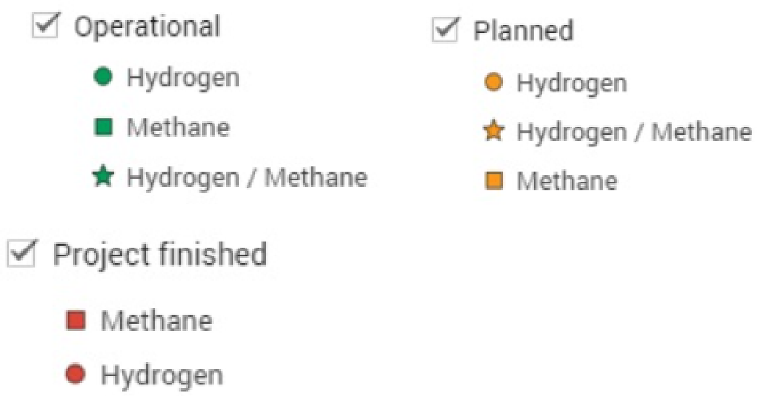


Figure 7. Electricity to gas projects in Europe /12/.



There are many actual projects which are already operating in Germany as follows:

- Germany / Reussenköge, GP Joule GmbH /13/.
- Germany / Prenzlau, Vattenfall GmbH /14/.
- Germany / Werlte, Audi AG and Etogas GmbH /15/.
- Germany / Ibbenbüren, RWE /16/.
- Germany / Frankfurt, ITM power /17/.

3.7.1 Stratos Fuel Company

Stratos uses the wind and solar energy to convert to hydrogen and to be used in Merchant and automotive use. There are hydrogen stations inside and outside of California State and the company is in development to extend the stations during the next five years /18/

As for the efficiency of the hydrogen fuel cells which are 2 to 3 times extra efficient than combustion engines, the company believe in the electrochemical processes because the car can drive as far as you drive normal with $\frac{1}{3}$ of the fuel /18/.

The storage of the hydrogen can be done as compressed gas and to be stored on the ground at the tanking stations. The hydrogen can be produced onsite or delivered to the gas station by a tanker truck /18/.

3.7.2 Fuel Cells of Hydrogen in Electric Cars

The following figure shows the principle of hydrogen fuel cell in an electric car.

Figure 8. Hydrogen fuel cells cars /18/.

The electricity is created from the fuel cells as follows, the PEM (proton exchange membrane cell) operates the oxygen and the hydrogen as the reactants. The hydrogen flows from the car tank into one side of the fuel stack and into the air side. As the hydrogen and oxygen are attracted in the air so the hydrogen moves to the oxygen through the stack, then the proton and electron produced by the catalyst. The electron travels to the anode and the proton travels through the membrane. The electricity is created and drift into a power unit, which spreads the electricity into the electric motor that applies the force to the car’s wheels. The power unit provides electricity also to the air conditions, sound systems, and other devices that requests electricity. The electrons and proton are together again in the cathode, then oxygen and hydrogen come together to create the emission which is water.

- One-time hydrogen fill can drive about 418 to 502 kilometres.
- Filling time at the station is about 3 to 5 minutes /18/.

3.7.3 Alstom in transport sector

The Alstom company has 14 hydrogen fuelled trains in Germany that has zero emissions by using the hydrogen fuel cells technology as explained in the previous chapter. The president of Alstom product and innovation says the company owns trains which are very silent to the customers inside the trains and no sound emission to the environment. The train can run with one single fuel filling up to 1000 km. The president of the company is convinced that hydrogen technology for the transportation is the technology for the future. Alstom has cooperation and partnership with Hydrogencis Company to develop the projects. The president mentioned that is a free competition market /11/.

4 THE CONVERSION OF STORED HYDROGEN TO ELECTRICITY

This chapter will discuss the conversion technology from stored hydrogen to electricity and heat. The electricity will be sold when the electricity price is high, and the heat will be used as a heat source to the district heat network, and also will be sold.

4.1 The Gas Turbine

The first gas turbine patented was for John Barber in 1791. The first gas turbine that gave net power which build by the Norwegian Elling in 1903, the output power was 11hv equal to 8,2 kw. The gas turbines have been used after the Second World War as aircrafts engines and to power the military vessels. The first gas turbine power plant was constructed in Switzerland in 1939 /9, 204/.

The gas turbine is a heat engine in which the turbine uses the hot gas. The gas turbine itself converts the fuel energy into a heat and the heat as a mechanical energy, without the need of a boiler. The gas turbine consists of three main parts as shown in Figure 9:

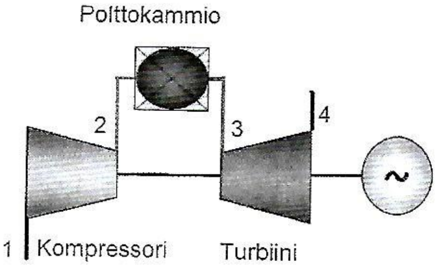


Figure 9. The process of gas turbine

- Compressor (1&2) which produce high air pressure into the combustion chamber.
- Combustion chamber (2&3) where the fuel burns and the formed hot gases expands in the turbine.

- The turbine (3&4) where the expanded hot gases develop effective power and the power required for the own use of the gas turbine.

  Only about a third of the power generated by the turbine is gained out from the effective power. Approximately the same power is needed to operate the generator and the compressor /9, 204/.

  Gas turbines are considered as the best prime mover due to its advantages that are required in a smart power generation system, examples of these advantages are fast start and generation of electricity in 5 minutes from start the engine, the efficiency of the engine, very quick in reducing the generated power it can take 2,5 minutes to stop the power generation and the engine. The net fuel efficiency is 46%. Gas engines are mostly used in ships, trucks and vehicles /7, 166/.

4.2 The Heat Recovery and Efficiency of the Gas Turbine

The exhaust produced from the gas turbine process is much, which means the loss is great. The economy of the gas turbine can be improved by extracting the heat of the exhaust gases. The exhaust heat of the gas turbines can be used as drying for certain product or other use in the industrial processes. Heat from the exhaust gas is recovered in a heat recovery boiler that generates steam or hot water. The overall efficiency will increase to about 75%, of which steam will account 45%. The efficiency is so much better than the efficiency of the gas turbine process itself, so such facilities are also used in basic load utilization. The temperature of the exhaust after the turbine is generally at least 450 °C, which determines the maximum temperature and pressure. The plant type is ideal for industrial plants that require electricity or steam or hot water. The heat recovery boiler can also be built as a water heat exchanger for the district heating network. The following figure shows the heat recovery boiler in the process /9, 208/.

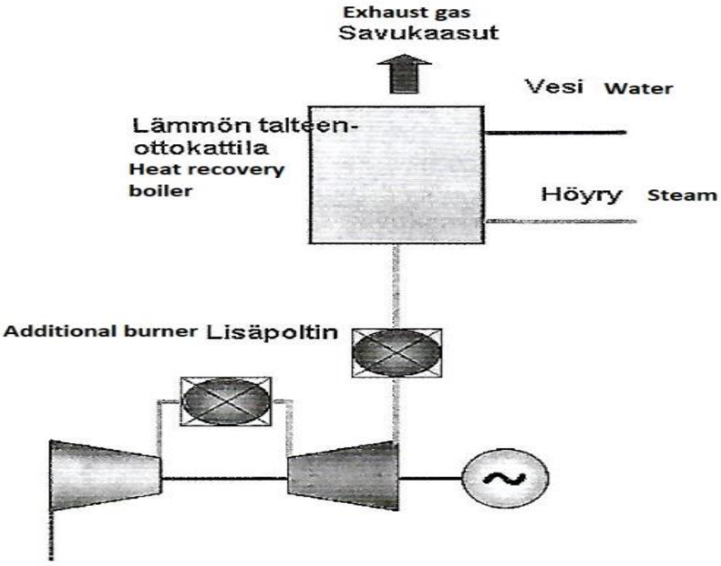


Figure 10. System with heat recovery boiler in the process /9, 208/.

In Figure 11 shows a hot water boiler added to the system, which makes electricity development to a certain extent independent of heat generation while maintaining good efficiency. The efficiency can be further improved by providing the boiler with additional burners that use the gas turbine exhaust as combustion air. The gas turbine itself uses more air than is needed for burning. The amount of air is high because a high amount of air is used to cool down the exhaust gases that goes inside the turbine, especially the wings of the turbines to prevent it is damage. The exhaust gas residue O_2 is 14-15%, which is a triple amount compared to the amount required for combustion. When all the heat energy can be used, the total efficiency can be about 90%. /9, 208/.

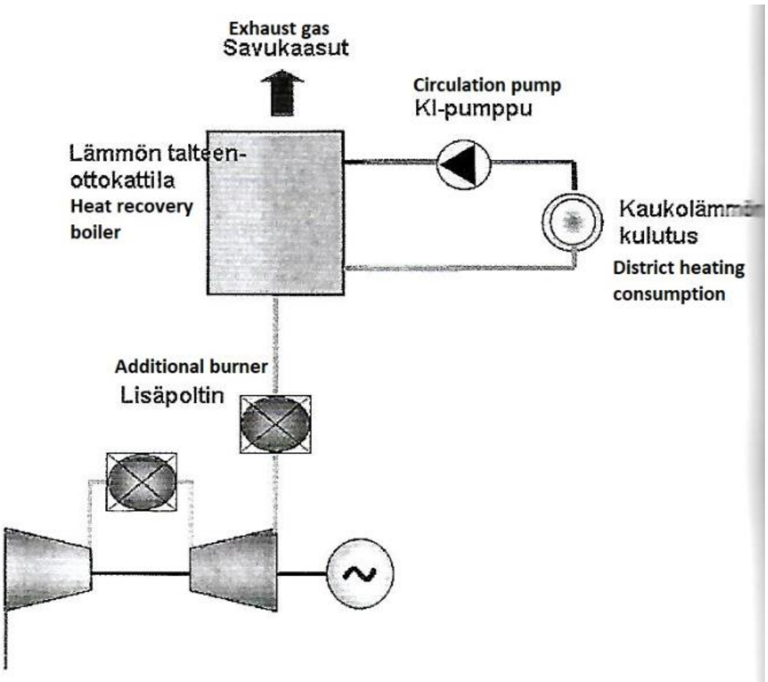


Figure 11. District heat system with a heat recovery boiler. /9, 208/.

4.3 The Processes of Gas Turbines

4.3.1 Open Gas Turbine Process

As Figure 9 shows, the air is sucked from outside (point 1) and pass the exhausts after the turbine back into the outside air (point 4). The efficiency of a gas turbine process is about 36%. The open gas turbine process used as a backup power and peak load facility which is used not much during the year. The investment costs for the open gas turbine process is low therefore the usage duration is short. /9, 204/.

4.3.2 Closed Gas Turbine Process

In the closed gas turbine process, the same gas (air or other gases such as helium) circulate all the time in the closed system. The heat is brought to the system externally by means of a heater. Solid fuels can also be used as fuel, because exhaust gases do not go through the turbine, so it cannot get dirty. The closed gas turbine process is complicated and more expensive than the open gas turbine process. /9, 207/.

4.3.3 Multi Shaft Gas Turbine

The efficiency of a single axle gas turbine falls considerably when running on partial loads, as the air volume cannot be adjusted. When power turbine and compressor use the turbine parts, they are on a different axis, the efficiency is with a partial loud higher, since the turbine part rotating the compressor is independent from the speed of the turbine. The potency of the turbine can be improved structurally by compressing the air in several stages and by cooling it between the compression stages. Cooling after the low-pressure compressor reduces air volume, so the high-pressure compressor handles a smaller volume and takes less power from the turbine. In this case there is more mechanical work in the gas stream to deliver to the turbine. In fact, the intercooling effect does little, because the heat delivered in the intercooler must be recycled to the combustion chamber immediately after the high-pressure compressor. The turbine can also be built in multiple stages, so that the gas can be heated in between the stages. /9, 207/.

4.4 Emissions of the Gas Turbine

Gas turbines forms emissions such as nitrogen oxides NO_x which called NO_x emissions and unburned gas emissions, for example carbon monoxide CO. The NO_x emissions can be at the level of 20 ppm (O_2 = 15%). Emission produced by the gas turbine has more nitrogen dioxide other than any incinerator. Lowing the temperature of the flame would cause the increase of unburned gas. To hold high enough temperature of the flame can be helped by adjusting the dilution air system. The carbon monoxide can be at the level of 10 ppm (O_2 = 15%) when the gas turbine at a normal work load. /9, 219/.

4.5 Efficiency of Hydrogen-electricity Process

From the fuel used in a gas turbine the energy efficiency about 25-35% can be collected and heat energy from exhaust about 35 – 45%. By using district heat about 80% overall efficiency can be achieved. Running the turbine with partial load lower the efficiency considerably, especially with one axel gas turbine where you cannot adjust the air.

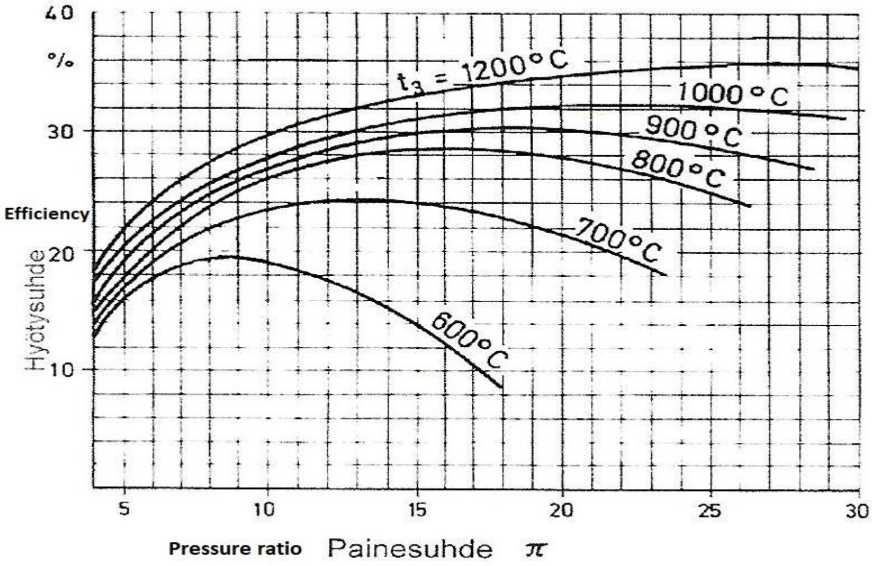


Figure 12. Gas turbine process efficiency. /9, 219/.

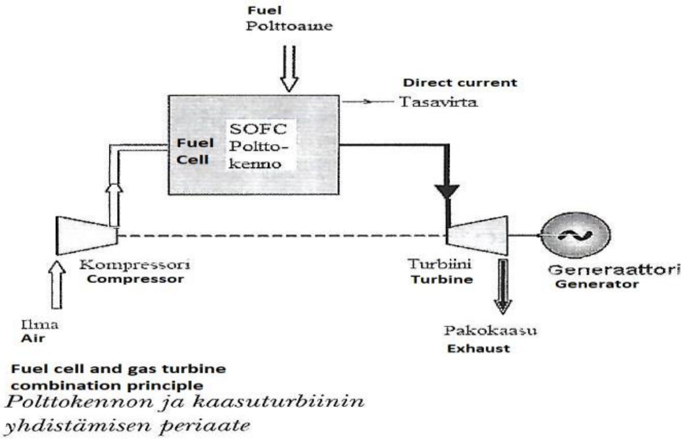
Figure 12 shows how, the efficiency is depending on the pressure ratio and temperature after the chamber. /9, 219/.

4.6 Gaseous Fuels

Fuels used in gas turbines can be in liquid form or gases. Solid fuels can be used in a closed system. Some gas turbines have double fuel system, where the main fuel for example gas changes automatically to another fuel when the turbine is working on the fuel load. The other fuel can be for example oil. This makes the turbine function normally even the main fuel suddenly runs out. /9, 220/.

4.7 The Conversion Process from Hydrogen to Electricity

Figure 17 shows how the fuel cell is integrated to a gas turbine



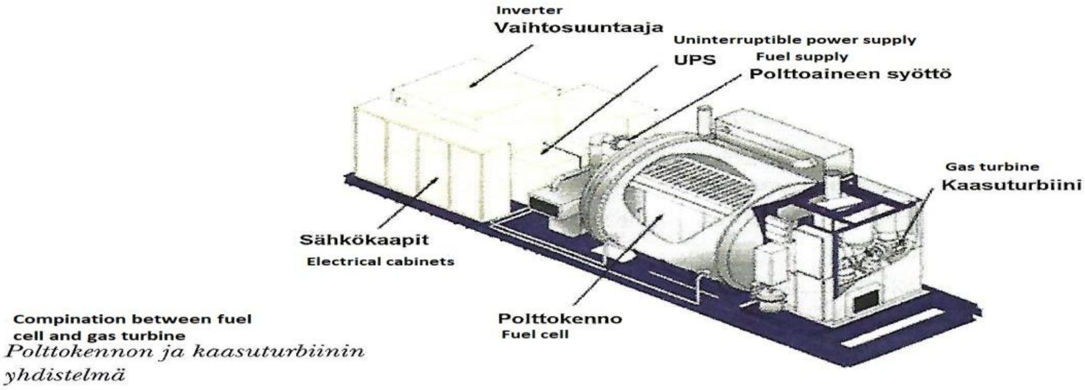


Figure 13. Combination of fuel cell and gas turbine. /9, 232/.

In the fuel cell the chemical energy of the fuel is converted directly into electric and heat. Hydrogen or fuel containing hydrogen is led to anode of the fuel cell. Oxygen or air led into cathode. Voltage is formed between the electrodes because the oxidation and reduction reactions. Voltage can be used to produce electricity. The fuel cells are divided to multiple types based on the electrolyte. Not all fuels are reacting in the fuel cell so the coming out gas should be led to the combustion chamber and use the unburned substance energy production of the gas turbine. In the process, the pressurized air is fed with the compressor of the gas turbine to the cathode of the fuel cell. The air is heat with preheater and mixed with hot gas from the cathode. The mixture of reformed fuel and water vapor is led to the anode of the fuel cell. Electricity is produced when the hot air and fuel reacts. The electricity production of this combination can have efficiency up to 70%, and from the power energy production 70% is from the fuel cell and 30% from the gas turbine. The overall efficiency is about 90% if all the heat energy can be used. /9, 231-232/.

5 ELECTRICITY AND GAS IN FINLAND

This chapter explains the electricity market in Finland and how the price of electricity is decided. The electricity market is a vital principle regarding the variety of the electricity prices to be considered as advantage in this thesis. The future target of the electricity in Finland and the Finnish feed in tariff system.

The Finnish gas network and it is interconnection points are also discussed for example. The new gas pipeline project between Finland and Estonia. The gas trade in Finland and the pricing of the natural gas is looked into as well.

5.1 Nord pool electricity market

Electricity is a commodity which can be sold or bought through an electricity market where the buying and selling bids happens. The bids happen with help of supply and demand to set the price. /19/.

Norwegian Nord Pool is a trading market that has been used by Nordic and Baltic countries including Finland. The power market prices are decided hourly and based on the electricity supply and the need of the Nordic and Baltic market. This done easily with the benefits of the electric network between these countries. /19/.

There are direct electric connections between Finland and the Nordic countries and also Finland with the Baltic countries with a connection to European electricity network, which gives the possibility of electricity transfers between these countries in order to get the most benefits of supply and need concurrently. /19/.

Nasdaq OMX merchandise is where the electric transactions take a place for the Nordic countries. There is a protection system against the risk related to the sudden changes in the hourly price. /19/.

Nord Pool offers a service for day-ahead market which is a short-term deliverable and intraday markets of which the day-ahead is considered as the major need for the power trading market. The intraday market (pay as you bid prices) which add and complete to the day-ahead markets and considered the way to secure and balance between the supply and demand. /19/.

Nord Pool a method of security to check that the customers are able to pay for the entered contracts. /19/.

5.2 The Electricity Market for the Future

The main target for the coming year is to increase the renewable electricity production by taking into consideration the cost effective and continues supply of energy from the renewable sources. The increase of renewable electricity production is done with the help of the consumers by means of integrating the renewable generators at homes and also by increasing the use of electric vehicles. /24/

The sale of electricity in the future will be closer to the consumption hour. The price of electricity is determined in the market, where the market price reflects its value, which varies at each moment. In the short term, the market price will guide electricity production and consumption. In the long term, it will enable and guide investments both to production and consumption, as well as to transmission lines and storage. It has traditionally been relatively easy to predict electricity production and consumption in the short term. Weekdays are generally very similar, on weekends saunas are heated up at around the same time, and as the mercury drops, more electricity is used for heating. At any given time, an exact amount of electricity is produced to meet demand. /24/

Electricity must be generated and consumed precisely the same amount as there a demand for at every moment. If the generation outweighs the demand, the frequency rises. Correspondingly, if there is not enough generation, the frequency drops. Excessive frequency disturbances can cause problems such as defects in electrical equipment and, in the worst-case scenario, a considerably lengthy blackout. Electricity production has traditionally been flexible, matching consumers' needs. With the change in the electricity market, flexible generation capacity that has the ability to regulate has been replaced by weather-dependent generation. An increased amount of weather-dependent generation calls for increased power system flexibility. /24/

In Finland, big industry has for some time been active in the electricity market and, guided by price signals, has adapted its electricity consumption. With a green electricity system, this alone is not sufficient: an increasing number of electricity consumers will have to be able to adapt their electricity consumption to weather-dependent generation. Since the price of electricity guides and reflects the need to adapt consumption, active and flexible electricity consumers benefit financially through their participation in the electricity market. /24/

Fingrid's, the Finnish national electricity transmission grid operator, goal is to enable a full-scale use of the potential of the power system to adapt in the electricity and real-time markets. The aim is to eliminate barriers to market entry so that every consumer can have the opportunity to influence and benefit from the change taking place in the electricity system, either directly or through a service provider. At the same time, Fingrid is especially improving transparency in the real-time markets and increasing the availability of electricity market data. /24/

Fingrid aim to develop electricity balance pricing to increase financial incentives for active electricity market operators. When the value of flexibility in a green electricity system grows, it will also mean that inflexible electricity producers and consumers will have to correspondingly pay a larger share of the overall costs to balance the power system. Active electricity consumers, however, will benefit from the change. /24/

The future of the electricity, the energy system, and the electricity system that forms a part thereof, will be green and low carbon. In this green electricity system, electricity is generated diversely through, e.g., hydro and wind power, nuclear power, biomass and solar energy. In addition, homes make use of microgeneration and stored power. /24/

5.3 The Finnish Feed in Tariff

Finland has a feed in tariff scheme for electricity regarding wind power plants, biogas plants, wood-fueled plants and, timber chip plants. The EU has a demand to increase the renewable energy production in Finland to 38% by 2020. The feed in tariff is 83.50€/MWh and to be paid for 12 years period. The feed in tariff applies to a wind power plant the production power of which is above 500kW. The wind power producer has right to choose the buyer of the produced energy which it can be sold to the power market or by contracts.

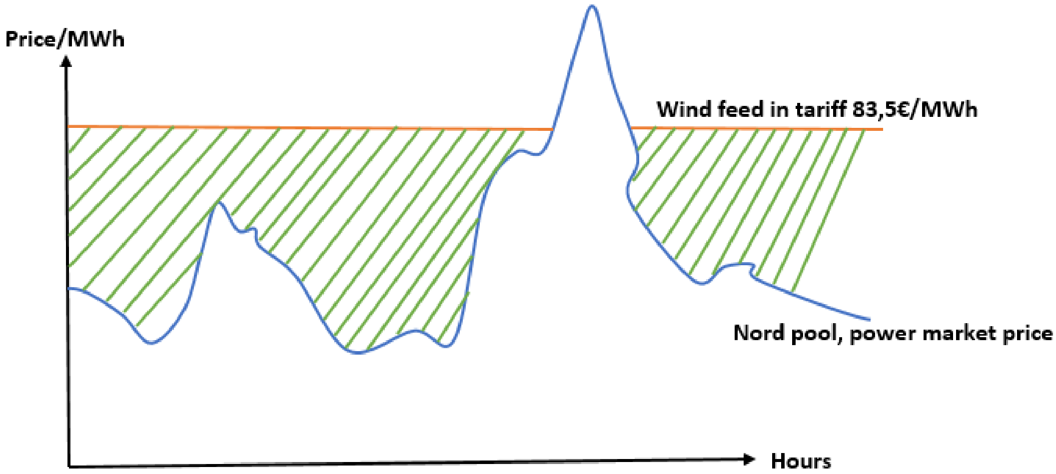


Figure 14. Wind electricity feed in tariff and Nord Pool market prices.

Figure 14 explains the Finnish feed in tariff system which is called a guarantee price. The wind power producer gets guaranteed payment of the different price between the market price and the guarantee price which is marked in green color lines. If the market price is higher than the guarantee price, then the wind power producer gets paid just for the market price which is marked in blue color line.

5.4 The Finnish Gas Grid

Gasum is the transmission system operator in Finland. Gasum owns the gas network pipelines and all equipment needed for the gas transmission. Finland has a high-pressure transmission pipeline network of 1300 km. There are valve stations for the safety reasons installed along the transmission network, the valve stations are installed 8-32 km apart. Link stations are installed together with the valve stations. The transmission system of the data consists of 15 link stations. The Finnish gas network has compressor stations which are used to higher the gas pressure, the benefits of these stations is to increase the gas transmission network capacity. The locations of the compressed stations located are Kouvola, Imatra and Mäntsälä, which consist of the total of nine gas turbine operated turbo compressors. /21/

Figure 15. The Finnish gas transmission network. /21/

Figure 15 shows the Finnish gas transmission network which has nine main points. There is a physical interconnection point in Imatra with Russian Gazprom. There are 116 interconnections for the distribution networks. There are four points to inject the biogas into the network which are Mäkikylä biogas facility in Kouvola, Suomenoja biogas facility in Espoo, Kujala biogas facility in Lahti and Riihimäki biogas facility in Riihimäki. /21/

5.5 Gas Pipeline between Finland and Estonia

There is a project to build a gas pipeline and two compressor stations between Finland and Estonia. The project involves pipeline in Finland for 22 km DN500 (80 bar), in Inkoo-Siuntio, there will be also a metering and compressor station. From Inkoo there will be a pipeline to Kersalu Estonia which is 78 km long and DN500 (80 bar) under the sea with the capacity injection of 7.2 million m3/day. A pipeline from Kiili to Kersalu (Paldiski) Estonia is 54 km long and the size of DN700 (54 bar) and has a metering and compressor station. /25/

The start date of the project is December 2020 with the cost estimation of 250 million euro. The project aims to connect physically the Finnish with the Baltic gas infrastructure. This opportunity gives the Finnish gas market possibility to access the Latvian underground gas storage and Klaipeda LNG terminal and the gas coming from central Europe through the GIPL. /25/

5.6 The Gas Markets

The Finnish gas market offers around the clock, every day of the year, an open market for natural gas after market. The trading method is gas physical forward, which means that the transaction is based on physical natural gas supply. The trading period is one hour, and trading can be used 1 hour – 30 days before the physical delivery time of the gas supply. Transactional parties issue orders through Gasum's gas market by the Online Service and will be automatically incurred when the purchase and sale orders are met. /21/

The trading party can enter into bilateral gas after-market trading. In this case, the parties agree trade between them and report the target period of the transaction and the amount of energy to the Gas Exchange Online service. Information on the web service is still communicated to the system responsible and the natural gas system operators. /21/

5.7 The Cost of Natural Gas

The price of natural gas consists of the energy sales and transmission price, just like the electricity price. The reasonableness of natural gas pricing is monitored by the Energy Agency, which defines the allowable return on natural gas. /21/

The energy price of natural gas is tied by price indices for crude oil and international coal prices and the domestic energy price index published by Statistics Finland. The price of natural gas is revised on a monthly basis, maintaining its relative position to other forms of energy. /21/

The pricing of natural gas transfer is based on the capital invested in the transmission network and the costs of operating the transmission network. The price of the transfer is also affected by the per-capita consumption. /21/

The steadier the use of gas, the cheaper the gas will be. Stable gas usage affects both natural gas transfer and sales price. /21/

The pricing of wholesale gas prices is based on the public pricing system M2017. The low-cost tariff is intended for customers with a gas consumption of less than five million cubic meters per year and a buyer's contract power of less than 40 MW. /21/

6 HYDROGEN ELECTRICITY VIABILITY

The purpose of this thesis research is to study and examine, if it is viable to convert stored hydrogen to electricity in Finland using a gas turbine in combined heat power plant.

In order to determine the viability of the conversion, the electricity and heat sales revenue has to cover the fixed and variable costs such as the electricity purchase costs and equipment depreciation.

The following figure explains the methodology of how to determine the break-even analysis, which only takes the losses of the process in account:

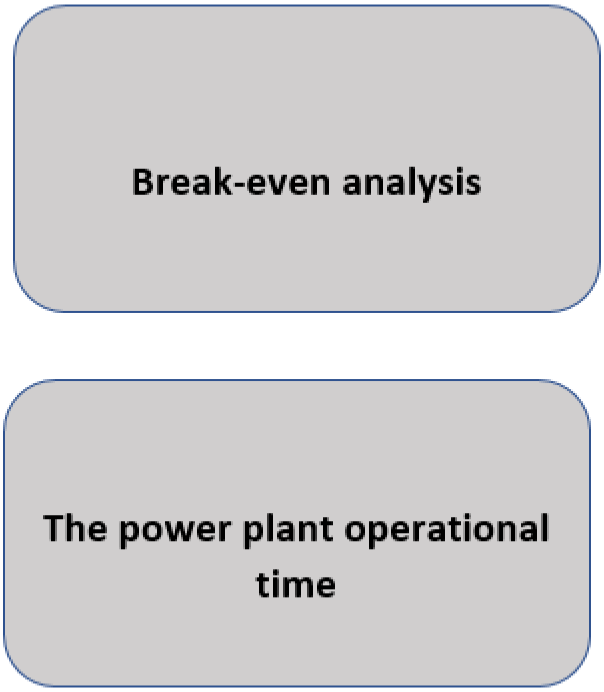


Figure 16. Methodology of determine the break-even analysis.

To find out the electricity sale price/MWh, electricity and heat sales revenues must cover variable and fixed costs such as electricity purchase costs and equipment depreciation, add to that should return a profit.

The following equation is used to get the electricity sale price/MWh:

$$\textbf{The electricity sale price/MWh} \geq$$

$$= \frac{(\text{Electricity purchase} \frac{\text{price}}{\text{MWh}}) - (\eta\text{Hyd. Dist x sales price of district heat in } \frac{\text{euro}}{\text{Mwh}})}{\eta\text{el} - \text{Hyd} - \text{el}} \tag{2}$$

$\eta_{\text{Hyd-Dist}}$ is the efficiency in district heat conversion, $\eta_{\text{el-Hyd-el}}$ is the conversion efficiency of electricity-hydrogen-electricity.

In order to define the electricity sale price/MWh the following needs to be defined:

- The efficiency rates of the power plant.
- Electricity purchase price/MWh.
- District heat sale price/MWh.

The efficiency rates of the power plant is calculated from data of the manufacturer company of hydrogen electrolyser called Hydrogencis. /11/. The efficiency rates of the gas turbine in a combined power plant is obtained from reference book. /9,219/.

The electricity purchase price/MWh is obtained from Nord Pool Elspot hourly price data year 2017 in Finland. /20/.

The district heat sale price/MWh is obtained from Vaasa sähkö Oy, the price is 54 euro/MWh. /23/.

The second step is an Excel file of collected data, calculations and chart created to determine the break-even viability without costs from the following data, electricity sale price/MWh, electricity purchase price/MWh and district heat price/MWh.

The third step is to obtain the power plant operational time, how many hours in year 2017, can sell electricity (convert from hydrogen to electricity) and how many hours in year 2017, can buy electricity (convert from electricity to hydrogen).

After getting the power plant operational hours for selling and buying electricity, then the selling and buying operational hours are compared to the hours of the whole year. The power plant operational time helps to determine if the power plant has enough operational hours in order to break-even and to be profitable, and also to find out if it is worth to go further for cost calculations or if it is clear enough to take a decision.

The following are detailed descriptions of the previous mentioned steps to determine the viability to convert from stored hydrogen into electricity in Finland using a gas turbine in combined heat power plant.

6.1 Electricity Sale Price

As shown in Figure 17 during the conversion from stored hydrogen to electricity there will be a heat loss which will be utilized as a heat source and be sold to the district heat grid. The heat loss caused by the conversion process from stored hydrogen to electricity will raise the overall efficiency of the power plant and will be considered as a district heat sale. The economic outcome from the overall efficiency is to increase the total revenue.

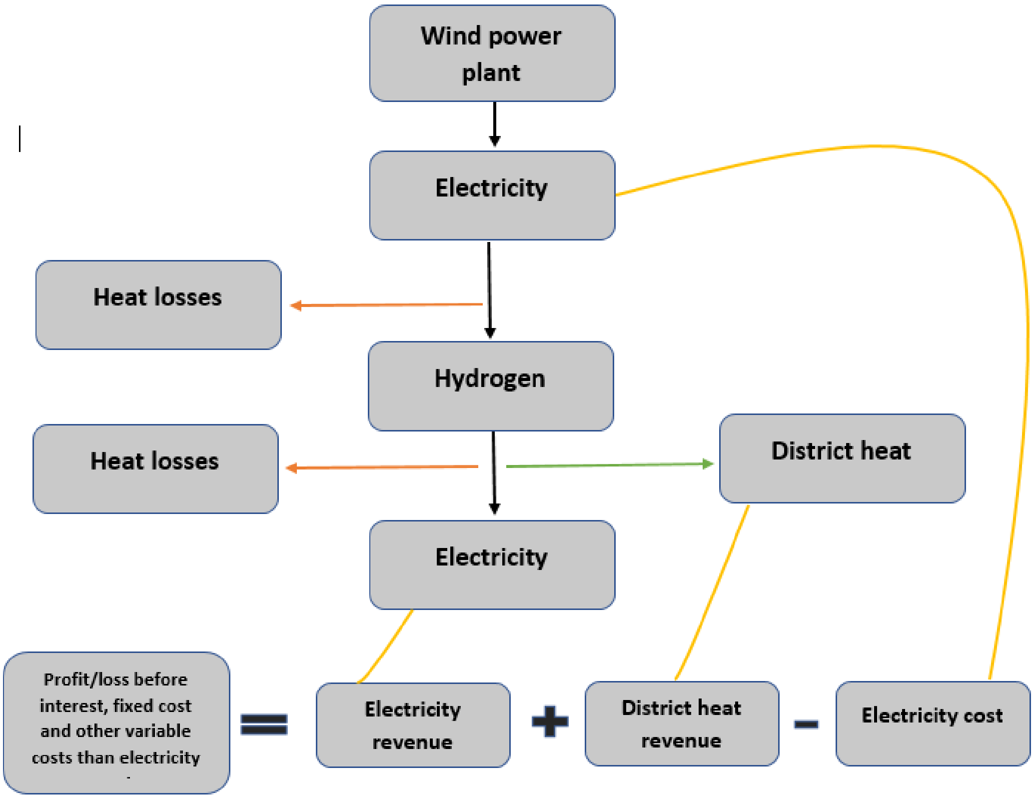


Figure 17. Viability analysis of the project.

The profit/loss before interest, fixed and variable costs and other variables than electricity takes into account just the electricity cost and the revenue of district heat and electricity, and also the conversion efficiencies. The fixed costs, and such will not be taken into account in this project or in the following calculations.

Electricity energy cost < electricity energy revenue + district heat revenue (3)

The point of interest in this project is to know how much the sale price should be euro/MWh in order to be viable. The selling price can be obtained from the following calculations.

Electricity revenues = electricity energy cost – district heat revenues (4)

Equation 4 is to calculate the electricity revenues by deducting the electricity energy cost from the district heat revenues. The electricity and district heat revenues are different revenues from each other, each has its own efficiency and own price.

Electricity energy cost = purchased electricity energy in MWh **x** cost e/MWh when buying electricity. (5)

Equation 5 is to calculate the electricity energy cost which is the cost of the purchased electrical energy times the cost of energy. The purchased electricity cost depends on the cost at the time of purchase.

Electricity revenues = Sold electricity energy in MWh **x** the revenue when selling electricity. (6)

Equation 6 is for calculating the sold electricity as energy times the revenue of electricity at the moment of selling, results of the electricity revenues.

District heat revenues = district heat energy **x** district heat cost (7)

Equation 7 is for calculating the district heat energy times district heat price results of the district heat revenues.

Sold electricity energy in MWh = purchased electricity energy in MWh **x** $\eta_{\text{el-Hyd}}$-el (8)

$\eta_{\text{el-Hyd}}$-el is the conversion efficiency of electricity-hydrogen-electricity.

Equation 8 is for calculating the sold electricity energy amount after deducting the conversion efficiency from the purchased amount of electricity.

Sold district heat in MWh = purchased electricity energy in MWh x ηHyd-dist (9)

$\eta_{\text{Hyd-dist}}$ is efficiency of hydrogen to district heat.

Equation 9 is the purchased electricity energy time the conversion efficiency from hydrogen for district heat resulting in sold district heat energy.

The equations are put in order to obtain the electricity selling price in euro as follows.

(Purchased electricity energy in MWh) x ($\eta_{\text{el-Hyd}}$) x (the cost in MWh when selling electricity) = (purchased electricity energy in MWh) x (the cost in MWh when buying electricity) – (purchased electricity energy in MWh) x ($\eta_{\text{Hyd-Dist}}$) x (District heat revenues) (10)

$\eta_{\text{el-Hyd}}$ is the conversion efficiency of electricity-hydrogen, $\eta_{\text{Hyd-Dist}}$ is the efficiency in district heat conversion

$$\textbf{Electricity revenue} \geq$$

$$= \frac{(\text{Electricity energy cost}) \; - (\eta \text{Hyd. Dist x district heat revenue})}{\eta \text{el} - \text{Hyd} - \text{el}} \tag{11}$$

$\eta_{\text{Hyd-Dist}}$ is the efficiency in district heat conversion, $\eta_{\text{el-Hyd-el}}$ is the conversion efficiency of electricity-hydrogen-electricity.

Equation 11 is to obtain the electricity revenue which is equal or not less than the cost of electricity subtracted from the sales price of district heat, taking in consideration the district heat efficiency and all divided to the conversion efficiency of electricity hydrogen electricity.

6.1.1 The Efficiency

Finland has a cold climate during the winter period and the heat source is important. The electricity price is high during the winter period where the need of district heat is high. The heat loss from the conversion process in the combined power plant is an economic value in Finland and considered as an advantage in the project case.

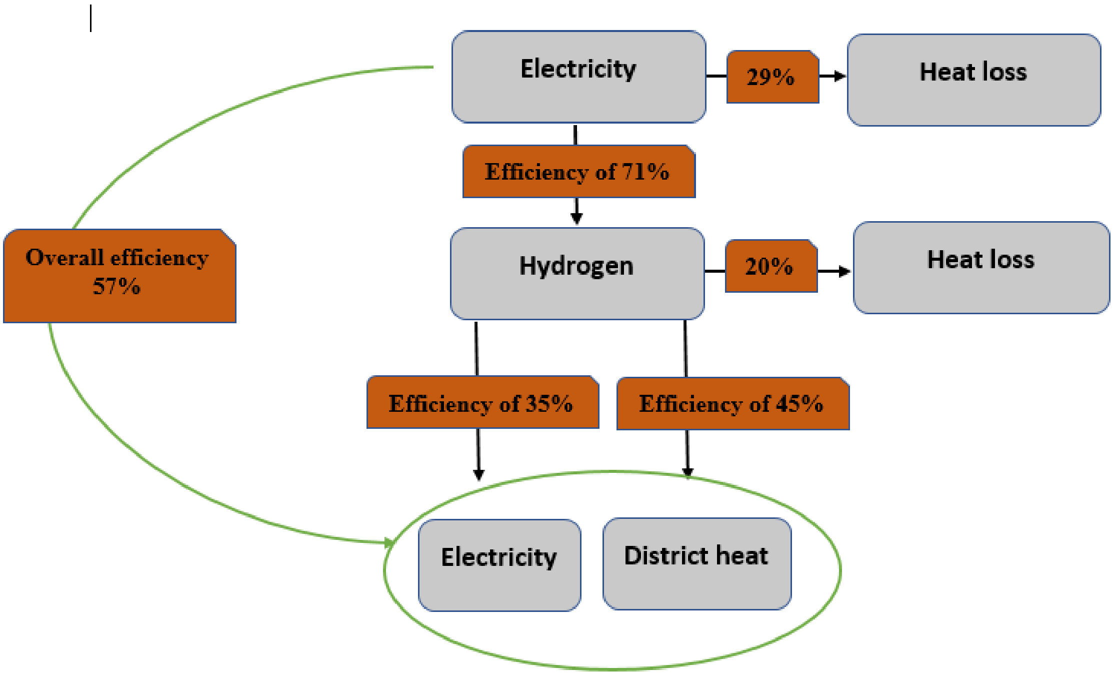


Figure 18. Overall efficiency.

The overall efficiency can be seen from Figure 18. The conversion to hydrogen from the produced electricity has 71% efficiency and heat loss of 29%. The conversion from stored hydrogen to electricity has 35% efficiency and during the conversion from stored hydrogen to electricity there is heat loss which will be used as a heat source in the district heat process. The conversion from stored hydrogen to district heat has an efficiency of 45% and there will be also a heat loss of 20% which will be non-usable. The overall efficiency of the power plant since the conversion from electricity to hydrogen and back to electricity is 57%. The calculations will be shown in the following paragraphs to explain how the efficiencies are obtained.

The manufacturer company of hydrogen electrolyser called Hydrogencis, has developed a new PEM electrolyser. The manufacturer informs that the device converting electrical energy within 3MW nominal power creates 1300kg hydrogen daily. The following calculation is done to find the device efficiency.

Input power: 3 MW

Energy consumed within 24h = 3 MW * 24h = **72 MWh**

Output hydrogen: 1300 kg

The higher heating value (HHV) of hydrogen was used for efficiency calculation. /3, 165/.

Hydrogen calorific value (HHV) = 141,88 MJ/kg

Energy output (W_{out}) = 1300 kg * 141,88 MJ/kg = **184443 MJ**

Energy input (W_{in}) = $72 \cdot 10^6$ 60 * 60 = **259200 MJ**

$$\eta = \frac{Wout}{Win} * 100 \tag{12}$$

η is the electrolysis efficiency, $Wout$ is the energy output of electrolysis, Win is the energy input of electrolysis.

$$= \frac{184443\,MJ}{259200\,MJ} * 100 \approx \underline{\mathbf{71\ \%}}$$

The calculated efficiency of the PEM electrolyser made by the manufacturer is 71 %. /11/.

The target technology of this project is to convert the stored hydrogen to electricity using a gas turbine in a combined heat power plant where the heat released in the conversion process can be used in a district heating system which will rise the overall efficiency.

The efficiency of a gas turbine in a combined power plant is discussed in Chapter 4.5. From the fuel used in the gas turbine it is possible to collect energy efficiency of about 25-35% and heat energy from exhaust about 35 – 45%. By using district heat 80% as overall efficiency can be achieved. /9, 219/.

- The overall efficiency for the power plant can be calculated from equation 13 as follows:

$$\eta_{all} = \eta_{el\text{-}Hyd} \text{ x } (\eta_{Hyd\text{-}el} + \eta_{Hyd\text{-}dist}) \qquad (13)$$

η_{all} is the overall efficiency of the power plant, $\eta_{el\text{-}Hyd}$ is the efficiency of electricity to hydrogen, $\eta_{Hyd\text{-}el}$ is the efficiency of hydrogen to electricity. $\eta_{Hyd\text{-}dist}$ is the efficiency of hydrogen to district heat.

η_{all} = 71% (PEM electrolyser) x 80% (electricity efficiency 35% + district heat efficiency 45%)

η_{all} = 0,71 x 0,80 x 100 ≈ **57 %**

The efficiency rates seen in Figure 18 and as follows:

The efficiency from electricity to hydrogen is 71%, the efficiency from stored hydrogen to electricity is 35%, the efficiency from stored hydrogen to district heat is 45%, and the overall efficiency of the power plant is 57%.

6.1.2 The Electricity Purchase Price

The purpose is to study the electricity conversion to hydrogen and to store the produced hydrogen. The electricity produced from wind power plant is considered as electricity purchase which has the Elspot market price as euro/MWh. When the purchased electricity price is under the price limit to break-even then it is viable to convert the purchased electricity to hydrogen, when the electricity selling price rise over the price limit to break-even then is viable to convert the stored hydrogen back to electricity.

The concept of arbitrage takes advantage of price variations on the electricity spot market. With the help of technology, the system can be programmed to produce hydrogen when the spot price is low and convert the hydrogen back to electricity when the price is high. This is illustrated in Figure 19.

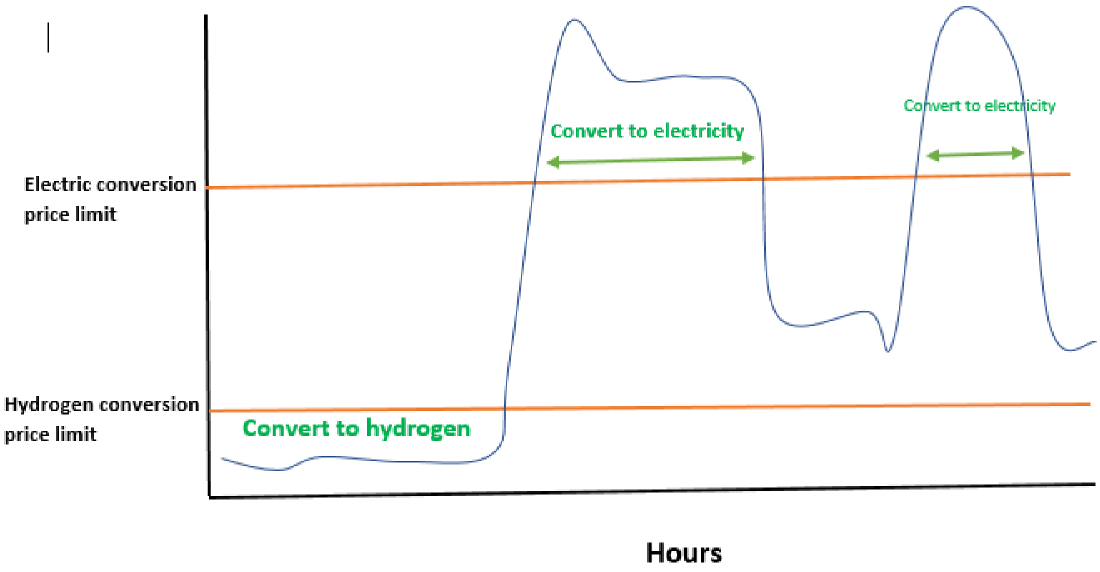


Figure 19. Converting from electricity to hydrogen and back to electricity.

6.1.3 Sales Price of District Heat

The sale price of district heat MWh was obtained from Vaasa sähkö Oy, and the price is 54 euro/MWh. /23/.

6.2 Break-even Analysis without Costs

Break-even viability will be analysis for the electricity purchase price, district heat selling price and electricity selling price. The analysis has been done by collected data from Nord Pool Elspot electricity market, hourly prices for year 2017 in Finland. /20/. The market electricity hours and prices of year 2017 have been entered to an Excel file to form a chart that results how many hours per the year 2017 a specific energy price was sold in the electric market. Another Excel file was created to calculate the break-even viability without any other than electrical energy cost, the calculations take account the conversion efficiencies, district heat prices for Vaasa City and compared to other two different district heat prices that could be offered by other company than Vaasan sähkö Oy. Used Elspot market prices for year 2017 to obtain the electricity purchase and electricity sale prices as shows in figure 20.

In order to calculate and determine the break-even viability without costs, the efficiencies of electricity to hydrogen, hydrogen to electricity and hydrogen to district heat are used. The district heat selling price is used. The Elspot market hourly prices for 2017 is used.

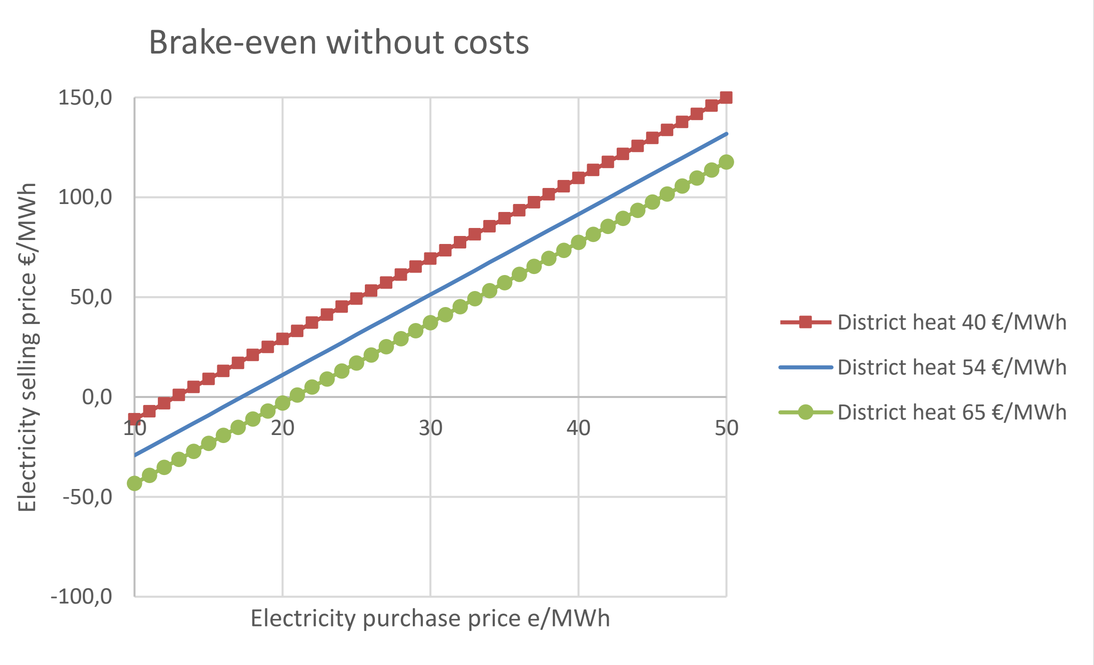


Figure 20. Brake even without costs.

Figure 20 shows the results of the used data; an example is extracted from the calculation and chart to explain the break-even viability without costs in specific electricity purchase price.

The example as follows, the efficiency conversions used for the calculation are from electricity to hydrogen with efficiency of 71 % and the conversion of the hydrogen to electricity with 80% efficiency consist of district heat efficiency

45% and electricity efficiency 35%. The purchase price of electricity is 30 euro / MWh and the district heat selling price in Vaasa City by Vaasan sähkö Oy is 54 euro/MWh. The results in the chart shows that to be viable and break-even without costs the electricity selling price must be above 50 euro/MWh without taking in consideration any other costs than electrical energy purchase cost. If consider the costs, the selling price will be higher to break-even.

6.3 Plant Operational Time Viability

Figure 21 is the Nord Pool Elspot market yearly hours for year 2017 and the electricity revenue during year 2017. The figure has been done with Excel to obtain how many hours the power plant operates for a specific price during year 2017.

Calculated in figure 21 that, Nord Pool market average electricity revenue for year 2017 if the price is 33 euro/MWh or higher so, then the hours is 8760 hours – 3196 hours = 5564 hours CHP operational hours. If the price is below 33 euro/MWh so, then the operational hours per year is 3196 hours. If the price is 33 euro/MWh and higher then compare the operation hours of the plant 5564 to the whole year hours 8760, the combined heat power plant (CHP) operational time would be 63% of the total operational hours during the whole year concerning the conversion from stored hydrogen to electricity which is the electricity sales.

The electricity average price in Finland year 2017 which is 33 euro/MWh is used as the electricity sales price when converting from stored hydrogen to electricity. The reason for choosing the average price as the electricity sale price, the average price is a good evaluation point to get the sale price in compare to the whole year sales. The average price also reflects relative supply and demand of the electricity market over time at different prices.

“The CHP plant should be sized to operate at maximum continuous rating for a minimum of 6000 hours theoretically per year and in reality, 4000 hours to maximise return on investment and maximise the carbon dioxide emission benefits”. /30, 12/ The operation time is just applying to the conversion from hydrogen to electricity in combined heat power plant and does not concern the conversion from electricity to hydrogen with the electrolysis method. But in the case of energy storage, the minimum operating hours should be considered separately. /30, 12/

The production from stored hydrogen to electricity when the electricity sale price is more than the average price, and the operation time for the CHP plant to produce electricity is 5564 hours/year of the theoretically maximum recommended operation hours which is 6000 hours and 93% and 140% of the reality recommended operation hours of 4000.

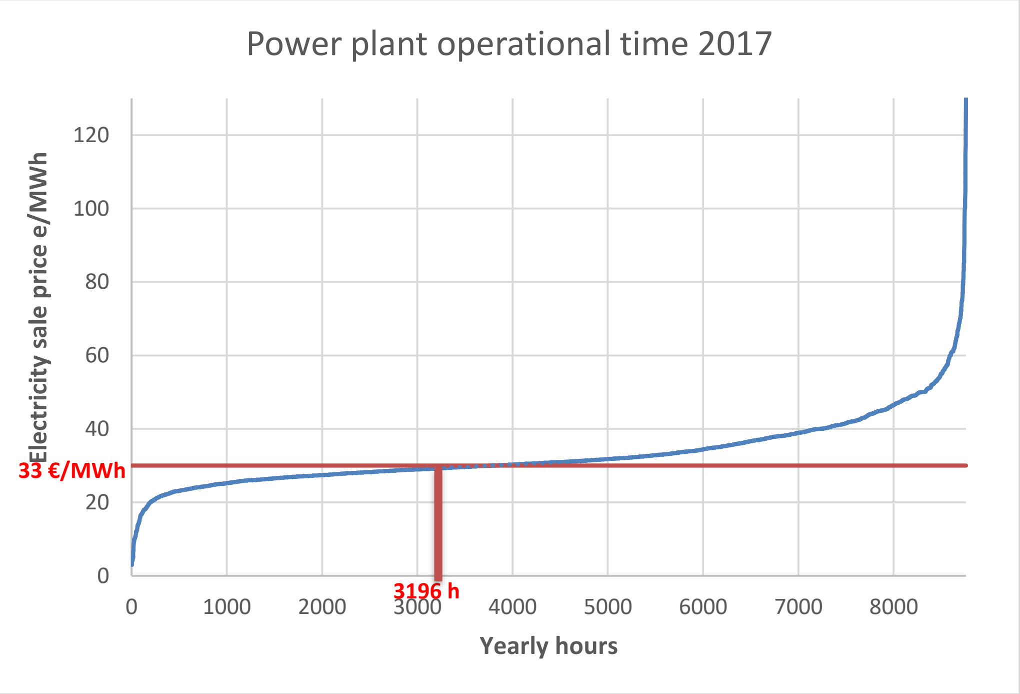


Figure 21. Power plant operational hours for sales 2017 for Finland.

Figure 20 shows that if the electricity sales price is 33 euro/MWh and district heat selling price for Vaasa is 54 euro/MWh the result of electricity purchase price is 26 euro/MWh or less, to break-even without costs and to maximise the return on investment.

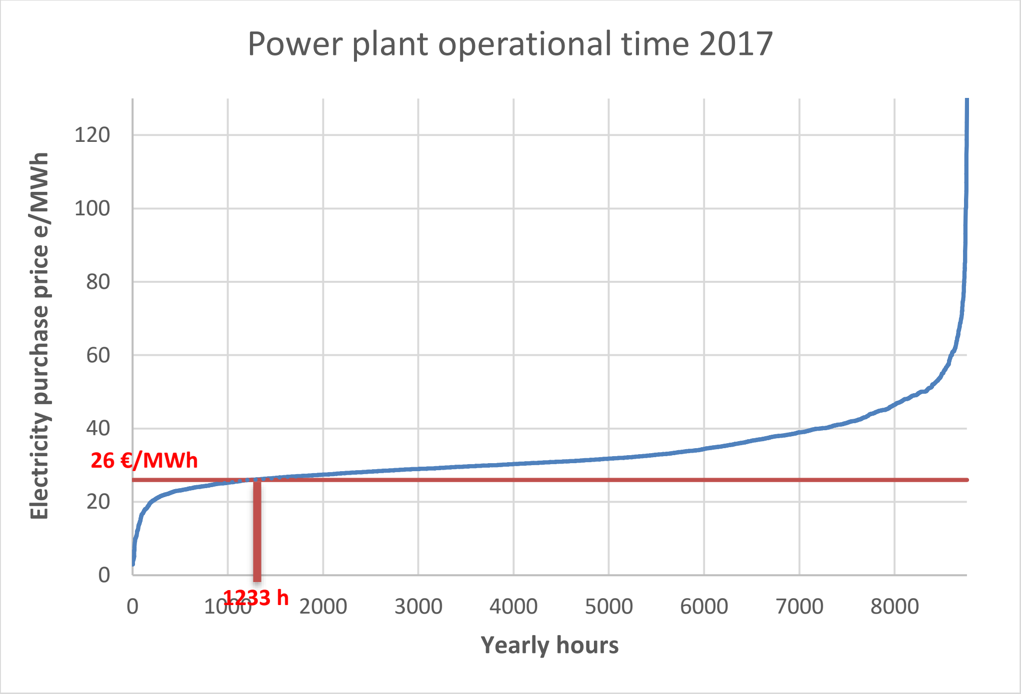


Figure 22 Power plant operational hours for purchase year 2017 for Finland.

It can be seen from Figure 22 that Nord Pool market hourly purchase price, If the purchase price is 26 euro/MWh or less so, then the hours is 8760 hours – 1233 hours = 7527 electrolyser operational hours concerning the conversion from electricity to hydrogen. If the purchase price is 26 euro/MWh or higher so, then the operational hours would be 1233 hours during year 2017, Compare to the yearly hours 8760, the plant operational time would be 85% of the total operational hours during the whole year concerning the electricity purchase.

The operation time for the electrolyser plant when converting from electricity to hydrogen is 7527 hours/year with 85%.

The plant operational time when selling electricity (converting from stored hydrogen to electricity) is 93% of the maximum recommended operation hours and 140% of the reality recommended operation hours. That means a high plant operation time in compare to the recommended hours. /30,12/, results of a good power plant operation hours to break-even without cost when selling electricity, and enough to maximise return on investment.

7 CONCLUSIONS

To conclude the research, the viability analysis of the thesis shows that converting electricity to hydrogen is a viable solution to the storage problem of renewable generated energy by means the electricity generation must balance electricity demand any moment. The electrolyser plant operation time is 7527 hours with 85% and that is consider as good operation hours. That would point out that there will be possible future opportunity for such conversion projects Add to that Hydrogen is used in many successful applications in Europe. The factors for success of the projects in Europe is the high price of electricity and the possibility of the produced hydrogen to be injected directly to the gas grid or to be used in mobile application to refuel vehicles. Hydrogen can also be used as input material for chemical processes.

The electricity average price in Finland year 2017 which is 33 euro/MWh is used as the electricity sales price when converting from stored hydrogen to electricity. The reason to choose the average price as the electricity sale price is that, the average price is a good evaluation point to get the sale price in compare to the whole year sales. The average price also reflects relative supply and demand of the electricity market over time at different prices. The electricity average price is extracted from Nord Pool Elspot market hourly price.

The conversion from stored hydrogen to electricity resulted of 93% of the maximum theoretically recommended operation hours and 140% of the reality recommended operation hours. That means a high CHP operation time in compare to the recommended hours.

Theoretically a minimum of 6000 hours annually operating time is required, and reality a minimum of 4000 hours annually operating time is required but in the case of energy storage, the minimum operating hours should be considered separately.

If the electricity revenue is above than the average price, the cost of the conversion from stored hydrogen to electricity would cover the break-even analysis. That would lead to good investment in the conversion from stored hydrogen to electricity because of the high operational time for the combined heat power plant.

The conversion from hydrogen to electricity would be more profitable when the efficiency of the technology is higher, and the cost of technology is reduced, and the electricity average price in Finland is higher.

The profitability of storage is important than the difference between the low and high price and the time duration as the average price. Such issues are influenced, for example, by the availability of electricity in relation to consumption and the share of renewable production.

The hydrogen mobile applications has vital role in Europe and especially in Germany, and becoming in the future as important role in the energy dependency in Europe. It could be good to continue analyze the electricity hydrogen storage conversion in mobile applications in Finland, as a study case and investment and cost calculations. Other opportunity to apply study case for the conversion of stored hydrogen to electricity in Finland with investment and cost calculations.

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