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Investigating the viability of lithium-ion battery - fuel cell hybrid systems

- A case study for Greenland and Qatar

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Abstract

Renewable means of energy production have recently become cost competitive with fossil fuels. However, before they can be completely phased out, the issue of storing renewable energy must be addressed.

Two energy storage technologies that have gotten a lot of attention over the past years are lithium ion batteries and hydrogen energy storage. Each of these technologies have their advantages, lithium ion batteries are generally cheaper than the fuel cells and electrolysers typically needed in hydrogen energy storage, while also having a greater roundtrip efficiency. Hydrogen storage containers for compressed hydrogen can, however, be manufactured such that the costs per kwh are below that of current lithium ion batteries.

This makes hydrogen storage more attractive for long the long term, where greater energy capacity is needed, while lithium ion batteries become more attractive within a shorter time frame requiring less energy storage capacity and greater efficiency. A hybrid system relying on both hydrogen and lithium ion battery may thus be viable for situations in which both short- and long-term energy storage is required.

The viability of such a hybrid system is investigated in this thesis. More precisely this thesis focuses on a photovoltaic driven lithium ion battery – hydrogen fuel cell hybrid system for energy storage. This system, as well as a system relying purely on lithium ion batteries for storage and a system relying purely on hydrogen as energy storage are simulated using the simulation software HOMER PRO. Additionally, the systems are simulated considering two different locations, one being the town of Tasiilaq in Greenland and the other being a workers accommodation near Doha, the capital of Qatar. The former requires both long-term and short-term energy storage, whilst the latter requires short term storage.

Simulating the three system types in these two locations, allows for the analysis of the performance and applicability of the hybrid systems compared to the other systems under significantly different conditions. The simulations reveal that the hybrid system is more practical than any of the other systems when energy storage is required for both the long and short term at a location. Around 37 % less space is required for the photovoltaic panels of the hybrid system than for the photovoltaic panels of the other two systems.

Additionally, the hybrid system requires 25 % less storage space for the hydrogen compared to the pure hydrogen system. At the same time, the hybrid system is significantly less expensive than the other two systems, costing 34 % less than the pure hydrogen system and 72 % less than the pure battery system. However, large amounts of storage space, are still required, 70 m^3, considering compressed hydrogen at 700 bar.

The pure battery system cannot handle the long energy storage times as present in the Tasiilaq case. On the other hand, the pure battery system has a substantially smaller net present cost than the two other systems when the energy storage required is smaller and the battery can be recharged frequently. This is because the costs for fuel cells and electrolysers become more dominant.

This indicates that hybrid systems, as considered here, are more attractive than pure fuel cell systems for large scale storage, if space is important.

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The process of writing thesis seems, in retrospect, so logical and to some extent straight forward. However, in actuality it was not and without the feedback from Professor Matteo Chiesa and Dr. Victor Schäfer, my supervisors at the UiT - The Arctic University of Tromsø and TESVOLT GmbH respectively, would not have been possible.

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Abbreviations

V_m	Molar Volume
AFC	Alkaline Fuel Cell
ALKEL	Alkaline Electrolyser
C	Celcius
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
EUR	Euro
GDL	Gas Diffusion Layer
HCE	Hydrogen Combustion Engine
IRENA	International renewable Energy Agency
K	Kelvin
kg	Kilo Gram
KOH	Potassium Hydroxide
kW	Kilo Watt
kWe	Kilo Watt electric
kWh	Kilo Watt Hour
L	Litre

Li-ion Lithium ion

MEA Membrane Electrode Assembly

MJ Mega Joule

Mm Molar Mass

MPa megapascal

MW Mega Watt

OaM Operation and maintenance cost

Op.h Operating hours

Pa Pascal

PEM Proton Exchange Membrane

PEMEL Proton Exchange Membrane Electrolysis Cell(s)

PEMFC Proton Exchange Membrane Fuel Cell(s)

PHES Pumped Hydroelectric Energy Storage

PV Photovoltaics

rpm Rounds Per Minute

SEI Solid Oxide Interface

SoC State of Charge

USD United States Dollar

1

Introduction

1.1 Motivation

Facing global climate change it is necessary for electrical energy to come from renewable energy sources such as solar in order to reduce the effect of electricity generation on global warming. Over the past couple of years the installed capacity of solar power plants have increased significantly. In 2018 102 GW [1] of new solar power generating capacity was added globally, bringing the total amount of solar power capacity in the world up to around 509 GW [1], with 131.9 GW [2] located in Europe.

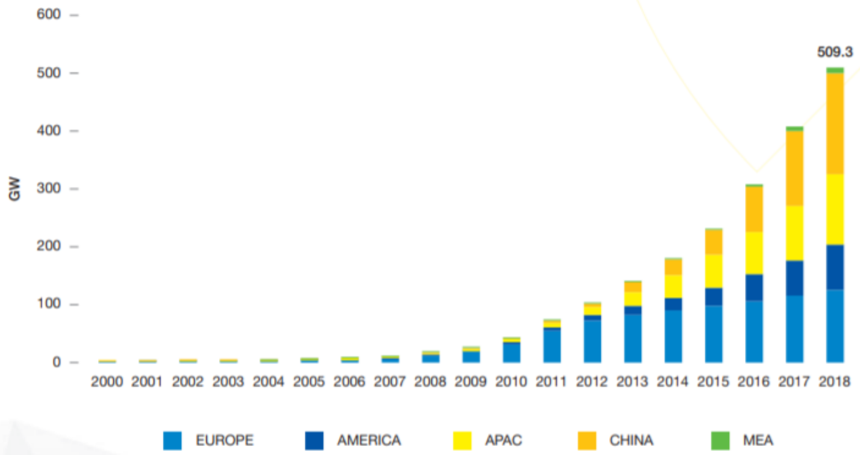


Figure 1.1: Global total solar power capacity installed in 2018 in Giga Watts [1]

At the same time, the per MWh cost of solar energy has fallen significantly. With around 0.05 USD/kWh or 50 USD/MWh, solar power has become cost competitive with other power sources such as coal, as illustrated in figure 1.2.

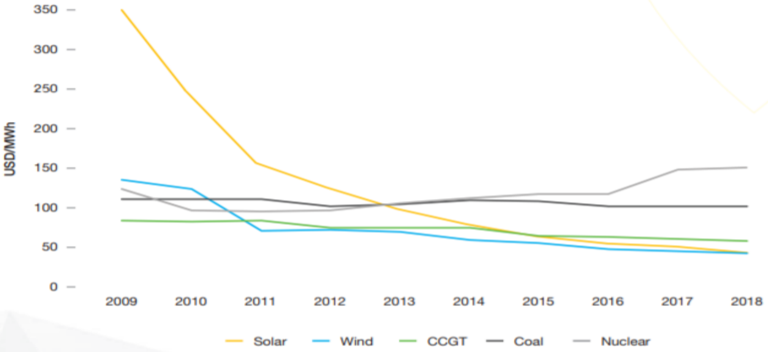


Figure 1.2: Solar electricity generation cost [1]

However, due to the intermittent nature of solar power, which relies on the availability of the sun, energy storage is a necessity in order to guarantee power availability even for times when the sun is not available. It has been reported that the photovoltaics in combination with energy storage can outperform carbon capture and storage in fossil-fuel power plants when considering the ratio between electrical energy return and electrical energy invested[3]. It therefore seems more reasonable to rely on systems with renewable energy generation and storage rather than on fossil fuel based power consumption with additional carbon capture and storage.

Two frequently considered energy storage technologies are lithium ion batteries and hydrogen energy storage. Lithium ion batteries have found wide adaption in the electric car industry and have also been employed in large scale energy storage projects. Hydrogen on the other hand has not yet seen the same success. This is probably due to the high costs and the low round-trip efficiency associated with hydrogen. Several countries and transnational entities, such as Japan, Germany, Norway and the European Union have however, put forward hydrogen strategies[4][5][6].

While most of toady's hydrogen production is fossil fuel based, it can be produced relying on renewable energy when using electrolysis[6]. As hydrogen is used extensively in sectors other than energy, such as the chemical sector where it among other things is used in the production of ammonia, a renewable based hydrogen production may be necessary making these areas sustainable[6]. In which case, further development in the hydrogen infrastructure may also be beneficial for hydrogen for energy storage.

Hydrogen offers a high energy density and can be stored over long periods of time. Additionally, while fuel cells and electrolysers are expensive, projections for hydrogen storage costs are lower per kWh compared to lithium ion batterie [7] [8]. However, as will be shown in 3.3 fuel cells and batteries are useful for different time scales of energy storage. Considering scenarios in which energy storage is required on multiple time scales there might be some benefit in employing both fuel cells and lithium ion batteries in a hybrid system.

In this thesis three types of systems will be modelled for two locations with one of the locations requiring both seasonal storage and short-term storage for renewable energy time shift. The systems simulated are a pure battery energy storage system, relying only on lithium ion battery storage, a pure hydrogen system and a battery – fuel cell hybrid system, employing both lithium ion batteries and hydrogen energy storage. Through the simulations the performance of the hybrid system can be compared to the other systems and for different energy storage time scales.

1.2 Outline

Chapter 1 gives the motivation for the thesis and presents the outline of it.

Chapter 2 gives a general description of multiple energy storage technologies, with special focus on the technologies used in the rest of this work. Additionally, a description of energy storage applications is given.

Chapter 3 presents, based on the capabilities of the energy storage technologies mentioned in Chapter 2 and based on the demands of the energy storage applications described in the same chapter, an evaluation trying to identify how suitable each of the storage technologies is for any of the applications.

Chapter 4 presents the pure fuel cell hydrogen system, the pure lithium ion battery system, and the battery-fuel cell system under consideration in this thesis, as well as the locations in which they are placed.

Chapter 5 shows the simulation results.

Chapter 6 discusses the results found in chapter 5 and concludes on the usefulness of the hybrid system.

Appendix A includes all calculations and data relevant for the thesis that was not included in the above mentioned chapters.

2

Overview of Energy Storage System Technologies

There exist a variety of different energy utilities, some of which are easier to store than others and a transformation from one form to another for storage is sometimes necessary. Electricity for example needs to be converted to chemical on mechanical energy to be stored. The energy storage technologies used for storing electrical energy are generally divided into categories based on the form of energy to which they convert electrical energy during storage. This is illustrated in figure 2.1

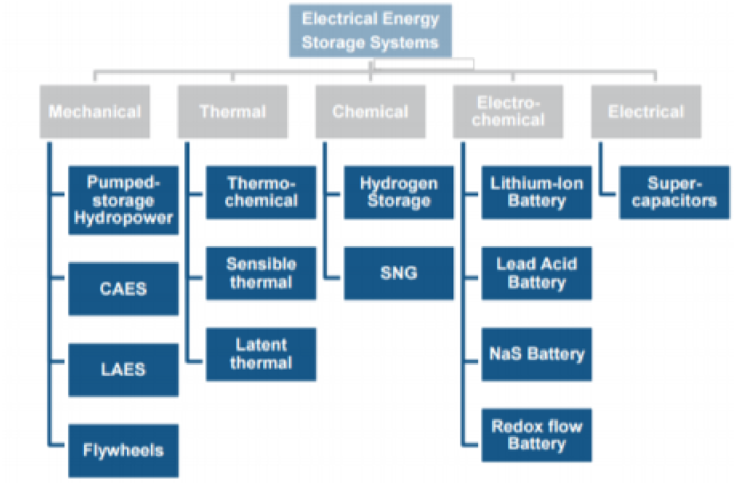


Figure 2.1: Overview over electrical energy storage systems [9]

In the following sections several mechanical, chemical and electrochemical energy storage technologies will be addressed, in order to give an overview over some of the most important energy storage technologies. Special attention will be given to hydrogen energy storage and lithium ion battery energy storage.

2.1 Mechanical Energy Storage

Mechanical energy storage has been around for a long time and with hydropower accounting for the greatest share of globally installed renewable energy capacity , mechanical energy storage is of great importance for the transition towards a more environmental friendly energy production. Below three mechanical energy storage technologies are presented, Pumped Hydroelectric Energy Storage (PHES), Compressed Air Energy Storage (CAES) and flywheels.

2.1.1 Kinetic Energy Storage: Flywheels

Flywheels are short term energy storage systems whose main components are a rotor, an electric machine, a central rod connecting the rotor to the electrical machine, bearings, bidirectional converters and an enclosure[9]. A schematic of a general construction is presented in Figure 2.2.

Flywheels are divided into two main categories based on their rotational speed.

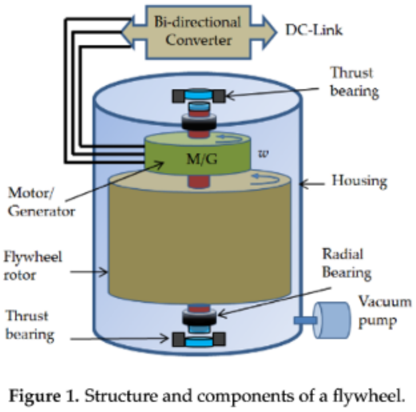


Figure 2.2: General schematic of a flywheel [9]

Low speed flywheels have rotational speed of up to 10 000 rpm [10]. High speed flywheels reach rotational speeds of up to 100 000 rpm [10]. As a result of these different rotational speeds, the rotors of the flywheel systems are subject to different forces. While low speed flywheel systems may utilise steel, high speed flywheels use composite materials[9].

During charge, the electric machine functions as an electric motor setting the speeding up the rotor and storing energy in form of kinetic momentum[11]. To reduce atmospheric drag, the air in the space between the actual flywheel construction and the enclosure is pumped out using a vacuum pump[12][9].

The reverse happens during discharge, here the electrical machine functions as a generator, extracting energy from the spinning rotors[11].

The energy stored in a flywheel depends on the square of its rotational speed ω^2 and its inertia I[9][12] and is given by equation 2.1:

$$E_{kin} = \frac{1}{2} I \omega^2 \tag{2.1}$$

The moment of inertia depends on the mass and the geometry of the rotor[11]. Thus the shape influences the amount of energy that can be stored within a given flywheel. Also, the maximum speed at which a flywheel can rotate is dependent on the tensile strength of the rotor material[11]. During rotation, the rotor is subject to stretching, within boundaries this will allow for extra amounts of energy to be stored. The energy stored this way can be around 5%

of the rotational kinetic energy[12].

Flywheels have several advantageous properties, such as high calendar and cycle life, fast response times and high round trip efficiencies of between 90% and 95%. Furthermore, they are not affected on the depth of discharge. Unfortunately, they have a high self-discharge rate.

Due to their properties they are suitable for applications that require high power for a short period of time. Thus flywheels may secure power quality for example by absorbing or providing power from/to the grid thereby keeping voltage and frequency within acceptable levels.

2.1.2 Potential Energy Storage: Pumped Hydro Energy Storage

Hydroelectric energy storage has been around for a long time and is a relatively well established energy source. Generally hydroelectric energy storage transforms potential energy to kinetic energy by allowing water to fall or flow down from a reservoir at high elevation down to a lower reservoir. The kinetic energy of the flowing water is then transformed to electrical energy by means of generators connected to turbines[13].

By reverting the turbines energy storage is possible. The process is then simply the reverse of the above mentioned. Water is pumped from a lower reservoir to a higher reservoir. Two types of turbines can be reverted, the Kaplan turbine and the Francis turbine[14]. The latter is the most commonly used one. Francis turbines can be used for large volume streams, however, they cannot handle large pressures that occur when water falls from great heights[14]. Thus, most pumped hydroelectric energy systems do not use heads greater than 300 m[14].

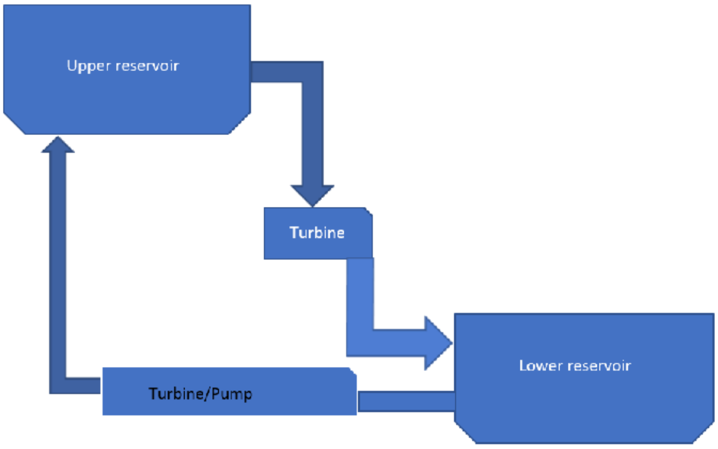


Figure 2.3: Schematic of pumped hydroelectric energy storage

The energy that can be stored in a hydroelectric energy storage system is given by equation 2.2, where ρ is the water density, g is the acceleration due to gravity and h is the height above the turbines [14].

$$E_{pot} = \rho g h \tag{2.2}$$

Equation 2.2 does not include losses, such as for example losses associated with turbines or the pumps. Efficiencies associated with pumped hydroelectric energy storage are around 75%[15].

Pumped Hydroelectric Energy Storage (PHES) is currently the energy storage technology that accounts for most energy stored. Globally the amount of pumped storage installed was about 153 GW in 2017[16].

Crucial for the development of PHES is the availability of suitable land. In addition local acceptance of such installations is a major factor to be considered in PHES projects. Although relatively few CO2 emissions are associated with the electricity generation via hydropower, the construction of such systems does require intervention into nature and thus may have severe environmental impact. Especially at sites where no natural reservoirs such as lakes are preexisting it is necessary to flood land. As a result the development of a site technical suitable may be stopped due to concerns of the local population or environmental organisations.

2.1.3 Compressed Air Energy Storage

Another way of storing energy is provided by Compressed Air Energy Storage (CAES). CAES systems use excess or cheap electricity from the grid to compress a gas, usually air, and store the compressed medium in a reservoir[17]. Often these reservoirs are old salt caverns or other airtight underground spaces[18]. Alternatively, balloons submerged in water in great depths may be used as reservoirs as well[19]. The process of storing energy by compressing air is a multi step process. At first air is compressed adiabatically, then it is cooled and stored in the cavern[20]. When time has come to generate electricity, the air is first reheated before it is allowed to expand again. Electricity generation is achieved by allowing the air to pass a turbine. Also, the reheating before the final expansion is necessary to prevent the build up condensing water and ice particles which may damage the equipment[20].In some applications the air extracted from the storage cavern is mixed with fuel and then combusted to generate more electricity[21]. Efficiencies of Compressed Air Energy Storage systems are below 50% for diabatic systems, however, adiabatic systems may reach up to 70%[22].

2.2 Chemical Energy Storage

2.2.1 Hydrogen Generation

Hydrogen has been one of the most prominent alternatives to batteries when considering pathways to a low emission future in the transportation sector. Also outside of transportation hydrogen has been much talked about as an energy carrier usable for storage when it comes to, for among other things, intermittent energy sources such as photovoltaics. Hydrogen has many attractive features, like a high specific energy of 120MJ [6], that make it ideal to replace known energy carriers such as natural gas.

The annual demand of hydrogen gas is estimated to be around 70 million tonnes[6]. Natural gas is the main source accounting for 76% of production[6]. 23% are produced from coal [6] . Only a fraction of the hydrogen has its origin in electrolysis, which when enabled by emission free energy sources provides an emission free way of producing hydrogen gas[23].

Generally hydrogen is divided into grey, blue and green hydrogen, depending on its origins [24]. Grey hydrogen has its origins in fossil fuels, blue hydrogen is fossil fuel based but includes carbon capture and storage and green hydrogen is produced using renewable sources. This thesis will focus on green hydrogen produced via electrolysis.

There are multiple water electrolysis technologies that either are already commercially available, still in the research phase or somewhere in between. Common to all technologies that are presented in the next sections is that they split water molecules into their constituent atoms, hydrogen and oxygen, resulting in the end products hydrogen gas and oxygen gas. The two main types often considered are Alkaline Electrolyser (ALKEL) and Proton Exchange Membrane Electrolysis Cell(s) (PEMEL) [25], these are described in greater detail below.

Alkaline Electrolysis

Alkaline Electrolyser (ALKEL) cells are the electrolyser cells currently used for large scale electrolysis of water[6][26]. The technology is relative mature and has lower CAPEX compared to other electrolysis technologies such as Proton Exchange Membrane Electrolysis Cell(s), estimated to be between 500 USD/kWe and 1400 USD/kWe[6]. Also, the estimated lifetime is between 60 000 and 90 000 hours of operation[6].

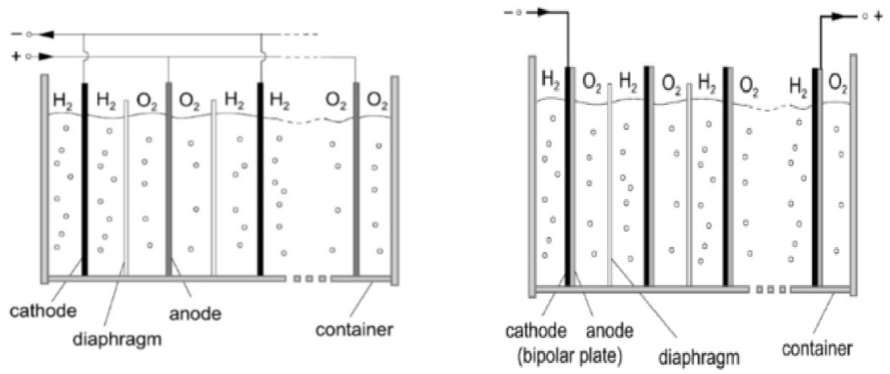
The electrolyte commonly used is an aqueous solution of Potassium Hydroxide and the chemical reactions are equation 2.3 and 2.4 [27].

$$Anode : 4\,OH^-(aq) \longrightarrow O_2(g) + H_2O\,(l) + 4\,e^- \tag{2.3}$$

$$Cathode : 4\,H_2O\,(l) + 4\,e^- \longrightarrow 2\,H_2(g) + 4\,OH^-(aq) \tag{2.4}$$

During operation, which usually happens at temperatures between 70 °C and 90 °C [28][27][26], the product gases need to be separated from the electrolyte resulting in electrolyte being pumped back into the cell after separation.

There are two ways ALKEL cells can be combined with one another, either in parallel or in series, known as unipolar/monopolar and bipolar respectively[28][26]. In the first case the anode and cathode electrodes are alternating whereas in the latter case both are combined to a bipolare plate[28]. Both cases require the electrodes in the electrolyser cells to be separated by porous diaphragms that allow for ion transfer through them, but prevent the electrodes from getting into contact with one-another[28][26]. Generally the bipolar variant is preferred and multiple cells are combined in larger stacks consisting of between 30 to 200 single cells[26]. Figure 2.4a and figure 2.4b show schematics of the unipolar and the bipolar electrolyser layout.



(a) Unipolar Electrolytic Cell[28]

(b) Bipolar Electrolytic Cell [28]

Figure 2.4: Schematics of Alkaline Electrolysis Cells

ALKELs are capable of producing hydrogen gas of high purity, 99.5%, and have an efficiencies of 60% to 80%[29][26]. However, both gas purity and the efficiency is dependent on the fraction of rated power it the electrolyser is operating at[26]. Both go down when the power goes down. Furthermore, the ALKEL have long startup times reaching from minutes to hours, making them less suitable in combination with varying energy sources such as PV[26].

Proton Exchange Membrane Electrolysis

Electrolysis via Proton Exchange Membrane Electrolysers is the second commercialised electrolysis technology currently available. The main components of a PEM electrolyser are bipolar plates, current collectors/ diffusion layers and the membrane electrode assembly[30]. The bipolar plates contain so called flow fields that allows as much water to diffuse through the diffusion layers as possible[31]. The membrane electrode assembly is a combination of catalytic layers (the electrodes) that surround a membrane that can allow protons to pass through[31]. Commonly the material Nafion is used for the membrane[32].

Water is split into oxygen gas, hydrogen ions and electrons at the anode side[30]. Electrons leave via an external electric circuit while the hydrogen ions, which are essentially protons, move through the MEA towards the cathode side[30]. At the cathode side they combine with electrons from the external circuit and form hydrogen gas, which then leaves the electrolyser[30]. These processes are described in equation 2.5 and 2.6[30] and figure 2.5, which is based on figure 5 in [30], gives a schematic illustration.

$$\mathit{Anode} : \mathrm{H_2O} \longrightarrow 2\,\mathrm{H^+} + \frac{1}{2}\,\mathrm{O_2} + 2\,\mathrm{e^-} \tag{2.5}$$

$$\mathit{Cathode} : 2\,\mathrm{H^+} + 2\,\mathrm{e^-} \longrightarrow \mathrm{H_2} \tag{2.6}$$

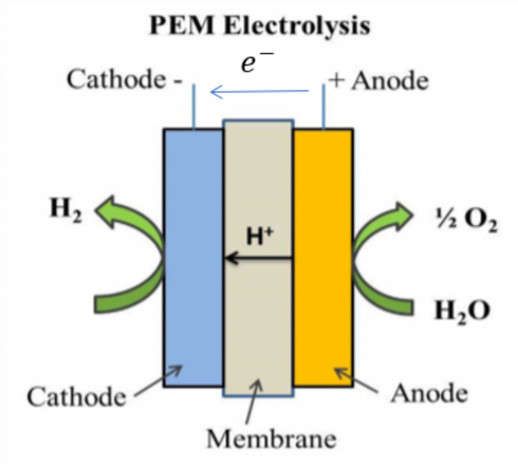


Figure 2.5: Schematics of a proton exchange membrane electrolyser [30]

PEM electrolysers require no liquid electrolyte such as alkaline electrolysers but are currently dependent on more costly electrode materials such as platinum[31]. Thus, a higher CAPEX is associated with their production[6]. The international energy agency estimates the costs to be between 1100 USD/kWe and 1800 USD/kWe,which is similar to the estimates presented by the International renewable Energy Agency of around 1200 EUR/kW (1361.71USD/kW), with replacement costs of around 420 EUR/kW (476.60 USD/kW) [25]. Thus almost twice as expensive as alkaline electrolysers[6]. The expected lifetime is also lower in comparison to alkaline electrolysers, at least on the lower end of the estimate, with 30 000 to 90 000 hours of operation[6].

In addition, the water used in the production of hydrogen is required to be of higher purity when using PEM electrolysers[31][32]. But PEM electrolysers are capable of operating at approximately the same temperature and the same system efficiencies as alkaline electrolysers, with operational temperatures being between 60 and 80°C and system efficiencies being between 60 and 70% [31]. Furthermore, Proton Exchange Membrane electrolysers can operate at higher pressures of 30 to 60 bars[6][31], so that no or fewer additional compressors are required for hydrogen storage.

Another advantage over alkaline electrolysis is the higher current density[32] and additionally they have shorter response times[6][32], even allowing them to provide grid services[24]. Due to the latter they are viewed as being especially suited for power to gas applications. There are currently several projects over the world where PEM electrolysers are either installed or planned to be installed, among them are 5 planned installations each 100 MW in size, in France[24].

2.2.2 Hydrogen Storage

Hydrogen may be stored through compression, liquefaction, in metal hydrides and in hydrogen-based fuel such as ammonia among others [6]. However, hydrogen storage in hydrides is not yet fully developed and ammonia, while requiring temperatures, for liquefaction, significantly higher than those required for liquid hydrogen, the amount of energy lost in the conversion is somewhat higher than for liquid hydrogen [6]. Furthermore, ammonia is toxic [6]. Therefore, the following sections will focus on compressed hydrogen storage and liquid hydrogen storage.

Liquid Hydrogen Storage

Hydrogen gas has naturally a low volumetric energy density. It is therefor necessary to find ways to store more of it in a given volume. One way this is achieved is by liquefying it. Hydrogen becomes a liquid at -253 degrees Celsius[33]. Ideally liquefying hydrogen would require about 11.62 MJ/kg, however, in reality energy requirements are usually between 36 MJ/kg and 54 MJ/kg[34]. Especially two processes are employed today for hydrogen liquefaction, the Claude cycle and the Reversed Helium Brayton Cycle[35].

The former utilises liquid nitrogen for precooling the hydrogen which is fed into the process at pressures between 15 to 25 bar[35][36]. The nitrogen cools the hydrogen down to -193 degrees[35][36]. Thereafter, through expansion turbines, the hydrogen is cooled further down to about -243 degrees Celsius before the gas is cooled down to -253 degrees in a Joule-Thompson valve[36]. Facilities using this approach are generally associated with higher initial investment costs (or capital expenditures)[35].

Alternatively, the Reversed Helium Brayton Cycle is applied. Again liquid nitrogen is used to precool the hydrogen after the hydrogen has been injected at pressures of 10 to 15 bar[35]. Then, helium is used to cool the hydrogen even further, before the hydrogen is cooled fully down through a Joule-Thompson valve[35].

The liquefaction of hydrogen can cost up to 40% of the energy stored in the hydrogen[33][37]. Furthermore, special tanks are required to store the liquid hydrogen. It is necessary to keep the temperatures in the containment vessels such that the hydrogen remains liquid. At ambient pressure the storage temperature is 21.2 K or -251.95 °C[34]. Alternatively at room temperature (300 K) pressures of 202 MPa are required[34]. The tanks that are used for liquid hydrogen storage consists of an inner and an outer containment vessel (double wall construction) with vacuum in between[38][37]. For additional insulation a multi-layer insulation is used, known as super insulation[37].

Storing liquid hydrogen is associated with several challenges due to the low temperatures required to keep the hydrogen in liquid state. The cool environment can make the stainless steel, which often is used of the inner storage vessel, brittle[37]. Also there are constantly losses of hydrogen over time due to boil-off, meaning some of the liquid hydrogen becomes gaseous[34]. Thus, either hydrogen is lost, if it can vanish out of the containment, or the pressure in the containment increases. However, boil-off losses have been reduced to a few percent per day[34].

Compressed Hydrogen Storage

Hydrogen may also be stored by simply compressing the gas without cooling it down. This approach is applied in hydrogen cars, where hydrogen is stored compressed to between 350 and 700 bar[39][37]. Since the hydrogen gas remains in its gaseous state the amount that can be stored in a given volume, is less than what would be achievable with liquid hydrogen. However, the compression is less costly compared to liquefaction. Only 10 % of the energy to be stored is lost in the compression process, compared to 30% to 40% used in the liquefaction process[37][33].

The space required to store a given amount of hydrogen can be found by considering the virial equation (equation 2.7) below.

$$P = RT\rho[A + B(T)\rho + C(T)\rho^2 + ...] \tag{2.7}$$

In equation 2.7, provided by [40], P is the pressure in pascal, R is the gas constant, ρ is the molar density and T is the temperature in Kelvin[40]. A, B(T) and C(T) are the first three so called virial coefficients[40][41]. As a gas is compressed, that is as a gas is subject to a given pressure, the interactions between the molecules become more important and the gas deviates from ideal gas behaviour[41]. The first virial coefficient A is always one and is the only one to be considered when dealing with an ideal gas or ideal gas like conditions[41]. The second and third term, B(T) and C(T), ought to be considered when the molecules become so close that interactions between two and/or three molecules become relevant[41]. At 300K the values for B(T) and C(T) are $14.38 * 10^{-6}\ {}^{m^3}/_{mol}$ and $343.8 * 10^{-12}\ {}^{m^6}/_{mol^2}$ respectively[40]. In order to store 5kg of hydrogen gas at 700 bar and 300K a storage vessel of approximately 125 L is required. The calculations for this are presented in the appendix (chapter A.1). Using equation 2.7 it is also possible to show that the energy required for compression of hydrogen is about 10 % of the energy stored in the hydrogen compressed, as mentioned previously. A corresponding calculation is shown in the appendix as well (chapter A.2).

Compressed hydrogen is stored in containers, of which different types exist[37]. The containers differ primarily in the materials from which they are constructed. Metal is used for Type 1 containers, metallic liner hoops wrapped in composite materials is used for Type 2 containers, metallic liners also wrapped in composite materials is used for type 3 containers and Type 4 containers are made from polymer liners again wrapped in composite materials[42]. The metals, polymers and composite materials that are used[37] each face different problems. Metals suffer from embrittlement when in contact with hydrogen[37]. Tanks from polymers are at risk of deformation during discharge of hydrogen gas[37]. Composite materials are prone to damage from pressure loads and through environmental impacts[37].

2.2.3 Electricity from Hydrogen

regaining the energy stored in hydrogen can be done either using hydrogen as fuel in existing or slightly modified combustion engines or using it in fuel cells. Below, hydrogen combustion engines and fuel cells are presented and following the chapter on electrolysers, Proton Exchange Membrane Fuel Cell(s) (PEMFC) and Alkaline Fuel Cell (AFC) are the fuel cell types covered.

Hydrogen Combustion Engines

Hydrogen combustion engines are an alternative especially attractive as they largely rely on known and well established technology. Hydrogen combustion engines are essentially standard combustion engines with minor tweaks to adapt them to some of hydrogen's special properties. The exhaust produced as a result of the combustion is CO_2 free, with water and NO_x being the primary exhaust gases[43][44][45]. NO_x gases are a result of reactions between oxygen and nitrogen in the air during the combustion process. The quantities of NO_x gases released are similar to that of conventional gasoline engines[44]. These being toxic they pose a threat to human health and are a significant drawback of this technology. However, solutions to this problem are under development. One example is a hydrogen combustion engine currently under development in Roßlau, Germany. This engine uses hydrogen and oxygen, rather than an air mixture, in the combustion process[46].

Combustion engines for hydrogen combustion have different ways to inject the fuel into the system. The hydrogen and the air or oxygen may be taken in as one single fuel mixture or both gases could be injected separately from one another through their own injectors mixing only right before the combustion chamber[43]. Alternatively, air or oxygen may be taken into its own injector or pipe while hydrogen is injected directly into the combustion engine[43]. In other words the mixing of the gases only happens in the combustion chamber itself.

Taking in a hydrogen-air mixture, as described in the first case, increases the risk for ignition prior to the combustion chamber[43] which often leads to knock[45].Hydrogen is especially vulnerable to ignition by hot spots[45].Therefore direct injection is advantageous as it largely eliminates the possibility for combustion outside the combustion chamber. Although pre-ignition can still occur in the combustion chamber[43].

Hydrogen combustion engines also face higher heat loss at the cylinder walls due to hydrogen's small quenching distance.

The costs of hydrogen combustion engines were estimated to be 300 USD/kW in 1998. The same report also states the efficiency of HCE at around 44%. [47]

Alkaline Fuel Cell

The general operating principal of fuel cells is the reverse of electrolysers. This is demonstrated by the chemical equations 2.8 and 2.9 describing the reactions in an Alkaline Fuel Cell (AFC), as provided by [48].

$$Anode : 2\,H_2 + 4\,OH^- \longrightarrow 4\,H_2O + 4\,e^- \tag{2.8}$$

$$Cathode : O_2 + 2\,H_2O + 4\,e^- \longrightarrow 4\,OH^- \tag{2.9}$$

AFCs utilise nickel as anode material and silver on a carbon cathode. Similar to their electrolyser counterparts they use KOH as an electrolyte[49]. A number of different AFC designs exist[49].Two prominent examples use a mobile liquid electrolyte and a matrix containing the electrolyte, respectively. In the former case the KOH electrolyte is pumped through the fuel cell[50]. In stack constructions the electrolyte is contact with all electrodes of the stack at all times[50]. Also the hydrogen which is applied at the anode is circulated as the water being produced there needs to be removed[50]. AFCs storing the electrolyte in a matrix do not require the circulation of electrolyte although the circulation of hydrogen gas is still necessary[50]. Also, while the alkaline fuel cell type with the flowing electrolyte can be operated with air, the matrix type requires operation with pure oxygen[51]. This is due to the formation of metal carbonates, such as K_2CO_3, which can occur through a reaction of KOH and CO_2 in the air[48][50]. Metal carbonates can steal hydroxyl anions from the electrolyte[48], alternatively they can obstruct the movement of the electrolyte[52].

There is also research going on to introduce a Membrane Electrode Assembly (MEA) design. Such a design would eliminate the problem with the formation metal carbonates. [53]

When connecting multiple alkaline fuel cells together to form a fuel cell stack bipolar plates are usually not an option, instead we get a unipolar set up[50]. This means that a positive electrode is connected to a negative electrode in another cell. This other cell needs not be an adjacent cell, as would be required by the bipolar design. Thus a variety of interconnections are possible [50].

AFCs usually operate in temperature ranges between 20°C and 90°C [49], with efficiencies of 60% to 70%[51].

Proton Exchange Membrane Fuel Cell

Proton Exchange Membrane Fuel Cell(s) (PEMFC) are the fuel cells currently considered for a number of applications including applications in cars. Among the qualities that make PEMFCs so attractive is their short response time, including short start-up times [51].

PEMFCs primary components are bipolar plates, current collectors and the Membrane Electrode Assembly (MEA). Although different designs exist, the bipolar plates often contain flow fields which are used to allow as much of the incoming gases, oxygen and hydrogen, to come in contact with the Gas Diffusion Layer (GDL), thereby increasing the amount of reactants that can come into contact with the catalysts. The MEA is a sandwich with a so called Proton Exchange Membrane (PEM) in the middle surrounded by catalyst layers on each side, who in turn have gas diffusion layers outside of them (seen from the inside out).

The PEM functions as the electrolyte and Nafion is at the moment one of the most used materials for the proton exchange membrane[51].The best catalyst available for proton exchange membrane fuel cells currently is platinum[54]. Platinum being quite expensive research is done on finding other, less costly, alternatives.

The working principle of a single PEMFC is that oxygen gas and hydrogen gas enter on the cathode and on the anode side respectively. The hydrogen diffuses through the GDL and splits into H^+ ions and e^-. Both negative and positive ions move to the cathode side, but the hydrogen ions move through the MEA, while the electrons move via an external circuit. At the cathode, the electrons, hydrogen ions and oxygen molecules react and combine so that water is formed. the water is then transported out of the fuel cell. Equation 2.10 and 2.11, as provided by [55], show the reactions at the electrodes and figure 2.6.

$$Anode : \mathrm{H_2} \longrightarrow 2\,\mathrm{H^+} + 2\,\mathrm{e^-} \tag{2.10}$$

$$Cathode : \frac{1}{2}\mathrm{O_2} + \mathrm{H_2} + 2\,\mathrm{e^-} \longrightarrow \mathrm{H_2O} \tag{2.11}$$

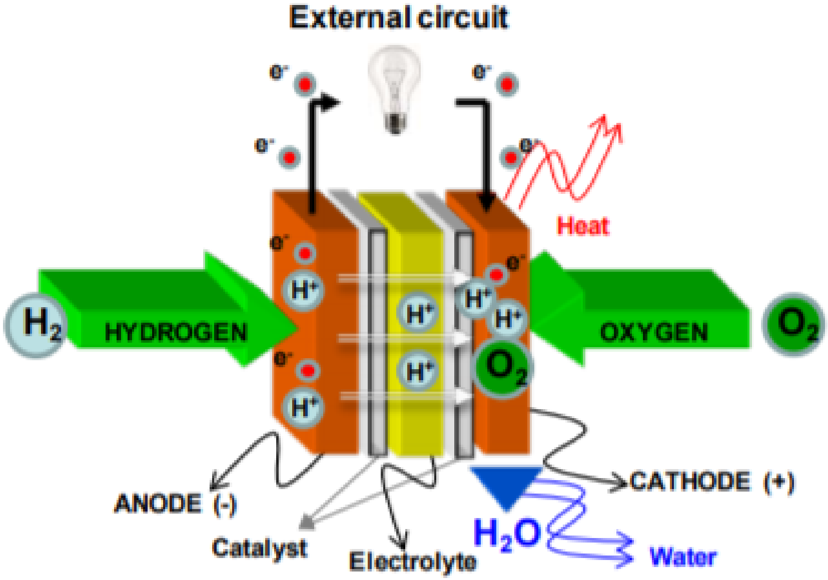


Figure 2.6: PEMFC schematics [56]

As has also been the case for alkaline fuel cells, multiple PEMFCs are connected together to stacks[54][55]. The predominant way this is done is by series connecting the different cells in a bipolar design[55]. Thus increasing the voltage. Multiple stacks may then be parallel connected to increase the current.

Two variants of PEMFCs do exist, these being high - and low temperature PEMFCs. High temperature refers to operating temperatures of 110 °C to 180 °C[51]. Low temperature fuel cells operate between 60 °C and 80 °C[51]. Efficiencies of the two types are largely the same, 50% to 60 % and 40% to 60% respectively[51]. One of the advantages of higher operating temperatures is the increase in tolerability for carbon monoxide, which usually poisons the platinum catalyst layer and thereby reduces the efficiency of the fuel cell[51].

It is the intolerance for carbon monoxide poisoning that is the reason for why PEMFCs generally require hydrogen of very high purity[57][54], which increases the cost of operation for this kind of fuel cell technology.

It is estimated that the current price for fuel cells is between 3000 and 4500 USD per kW[58], while the life expectency is between 5 and 15 years[59].

Finally, the next figure gives an overview over the losses and costs associated with the entire chain of operation from hydrogen production via electrolysis, storage and re-electrification via the use of fuel cells.

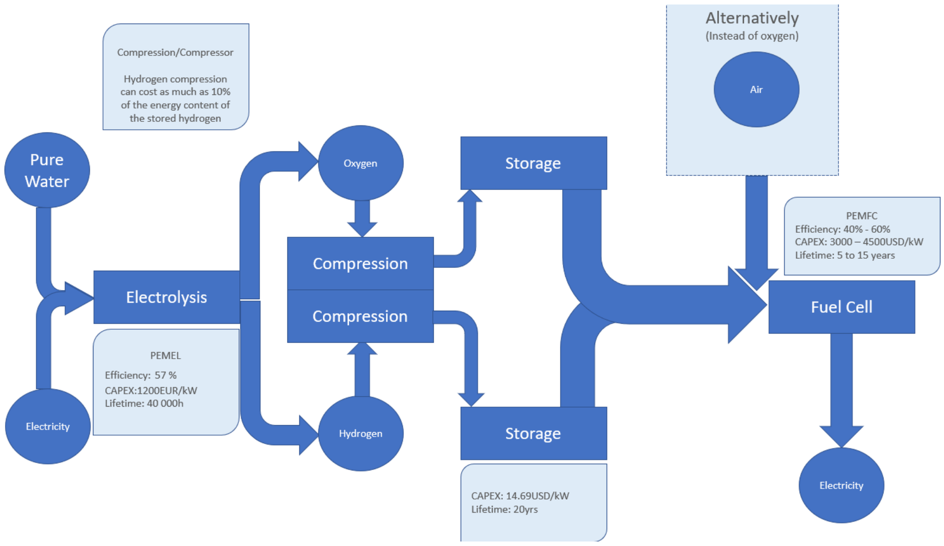


Figure 2.7: Overview over electricity to hydrogen to electricity cycle for Hydrogen Fuel Cell systems considering compressed hydrogen storage

2.3 Electrochemical Energy Storage

2.3.1 Lithium Ion Batteries

Lithium ion batteries are the most prevalent form of electrochemical energy storage at the moment and they have experienced a significant drop in per kWh costs over the past years, as represented in figure 2.8. Bloomberg reported cost of 176 USD/kWh for 2018 [60].
The term lithium ion battery is an umbrella term for a wide variety of different chemistries[61]. Generally they are known for high specific energy and high specific power and usually have round trip efficiencies of around 95%[61]. Lithium ion batteries are categorised according to the material from which the cathode is produced[61][62]. The overall structure of these different lithium ion batteries is however, similar. Each cell has two electrodes, each of which is connected to their own current collector[61][62][63]. The current collectors are connected to one another through an external circuit which may include the load[61][63]. Located between the electrodes are both the electrolyte and the separator[61][62][63].

In the majority of the commercially available cells the anode is made from graphite, a carbon layer based material[61][63][64]. The active material used for the cathodes depends on the application for which the cell ought to be used. A common material has been lithium cobalt oxide ($LiCoO_2$) or LCO, which is also what was used in the first commercially available lithium ion batteries[65]. Other active materials used include; lithium manganese oxide ($LiMnO_2$) or

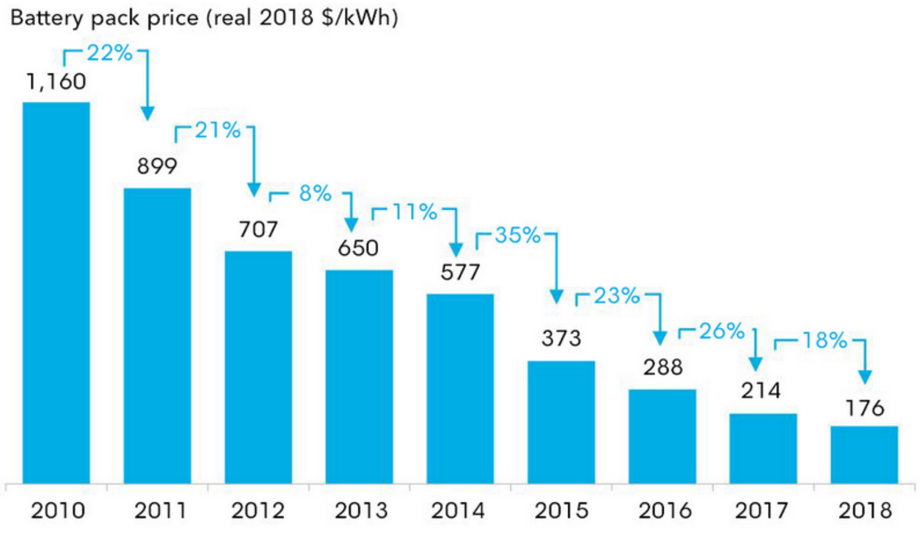


Figure 2.8: Cost development of lithium ion batteries [60]

LMO , lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA)[61][62][64]. The components of a lithium ion battery are illustrated in figure 2.9.
NMC batteries are considered suitable for large-scale energy storage applications and are characterised by a good rate capability and high capacity[62]. Typical values for operating voltage are around 3.6 V and energy densities of approximately 100 to 170 Wh/kg are common[66].

Both electrodes are constructed from powder, meaning that the active material, such as graphite and lithium nickel manganese cobalt oxide, start as a powder rather than a solid block[63][67]. The powders are then mixed with binders that are used to hold the electrode structure together, and conducting particles that help the conduction to the current collectors[67]. On the anode side the current collector is usually copper while aluminium is used at the cathode[61]. Both are only a few micrometres thick.[63][67]

Between the electrodes the electrolyte and the separator are located. The electrolyte is a mixture of a lithium salt and an organic solution, that allows for the transport of lithium ions[61][62][63]. Because, however, the conductivity of the electrolyte is rather poor, the distance between the electrodes is usually kept small[61]. The separator is a diaphragm that allows for lithium ions but not electrons to pass through and is an important safety feature, as it prevents the electrodes from coming into contact with each other, which would result in a short circuit[61][63].

During the discharging process positive lithium ions deintercalate (move out

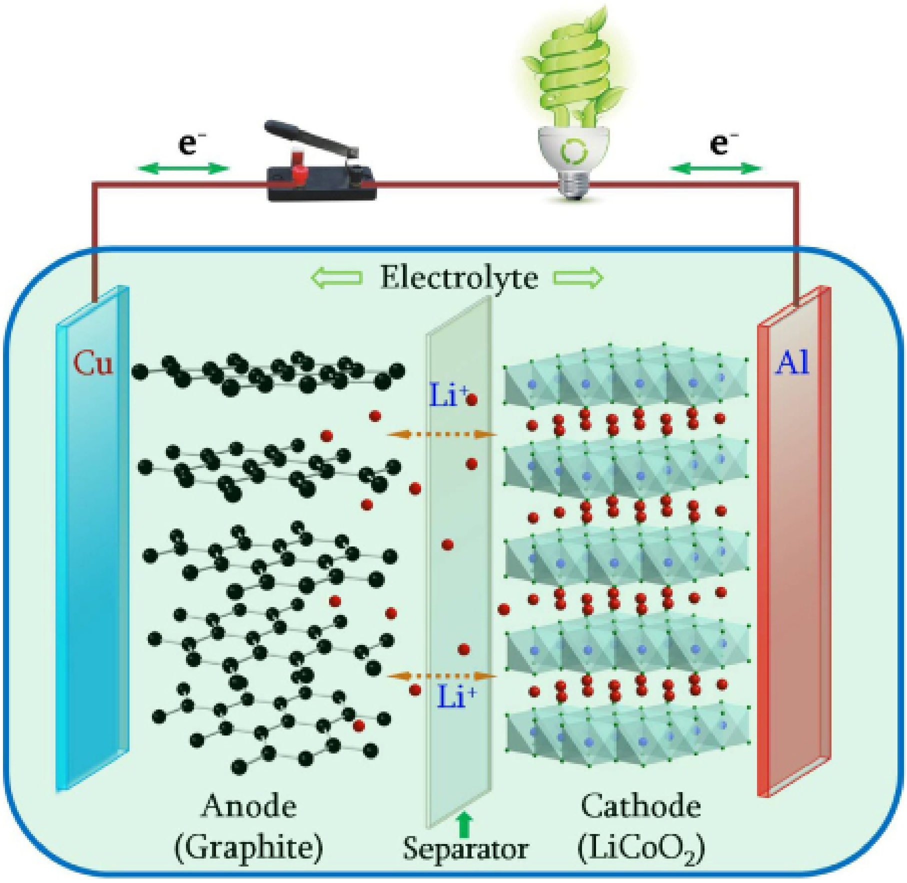


Figure 2.9: Lithium ion battery cell schematics

of) from the anode and migrate through the electrolyte to the cathode where they intercatale (move into) [61][63][65]. It is important to note that not all of the lithium ions but only around 50% may leave the cathode, otherwise the cathode structure may collapse[67][68]. At the same time as the lithium ions move through the electrolyte from the anode to the cathode, electrons leave the anode and move via the external circuit towards the cathode[65]. The opposite is true for the charging process[65], although all lithium ions that previously had been stored in the anode can leave the anode again, as the anode structure is stable without the lithium ions[67].

Battery cells are manufactured in three main form factors, cylindrical, pouch and prismatic,[61][62][63][68][65] where each cell consists of multiple current collector, anode, separator and cathode layers[68]. Multiple cells are then connected in parallel and/or series to a battery module, depending on the requirements.

For safe operation and an optimal life time lithium ion batteries ought to be operated at adequate temperatures and charged and discharged within acceptable limits[69]. To guarantee this battery modules are equipped with battery management systems, for safety reasons[61]. These management systems monitor quantities such as the cell temperature, cell voltage, the current and allows for the regulation/management of temperature[61][69].

An important parameter to consider for the operation is the battery State of Charge (SoC). The SoC refers to the stored energy in percent of total capacity of the battery. Alternatively the amount of charge can also be expressed via the depth of discharge which is equal to 100% -SoC and indicates how many percent of the stored energy has been discharged.

Usually lithium ion batteries are operated in an interval of between 20% and 90% SoC [70]. Discharging the battery below 20% and overcharging the battery above 90% increases the abrasion of the battery, resulting in shorter battery life[70].

Other factors that influence the ageing of a battery cell include mechanical stresses on the active materials in the electrodes as a result of the intercalation processes[61]. Furthermore, layers that form on the outside of the anode that bind some of the lithium ions, which will become unavailable for the normal battery operation, and also increase the amount of material lithium ions need to move through[63][63]. This increases the electrical resistance of the cell.

The above mentioned layers form around an initial layer, the Solid Oxide Interface (SEI), that forms during the first charging of a lithium ion battery cell[63]. While it uses up a certain amount of lithium ions, it also increases the safety of the cell[63].

2.4 Applications of Energy Storage Technologies

Energy supply requires a near perfect match between energy supply and energy demand. Sometimes changes in demand are known in advance, for example when people return home after work and turn on the lights. People generally return home at around the same time of day. However, in many other cases this is not possible. Consumers may suddenly switch on power hungry electronic devices, thus causing the need for additional supply on the utility side.

Variations in demand and supply, if not handled correctly, may cause severe problems for the grid and even lead to blackouts. Energy storage technology can help handle these issues, and in the following various areas of application for energy storage technologies are presented.

2.4.1 Power Quality

The power quality provided by a transmission system depends on how close the system can keep the current and voltage to their ideal wave form. A deviation from the ideal wave forms corresponds to a lowering of the power quality. Challenges related to a degradation of the power quality are under- and over-voltage, swells and swags, harmonics as well as interruptions and outages[71][72].

Under-voltages and over-voltages are periods where the voltage drops below or rises above acceptable levels for more than a few seconds respectively[71][72]. Swells and swags are essentially the same, however the duration of swag events is shorter, meaning less than a few seconds[71]. Causes for such events include among others; starting of large loads, in the case of sags, loss of generation (under-voltage) and start or stop of heavy loads and poorly dimensionalised power sources (swells)[72].

Harmonics represent a distortion of the voltage or current wave, which ideally is sinusoidal[71]. Such distortions are caused by for example all nonlinear loads[71]. Harmonics can cause problems in computers, reduce the lifetime of transformers and also result in fires[71].

Poor power quality is harmful to production as it affects machinery as well as computers. The life time of transformers and other technical devices can be reduced and even more severe effects such as fires can be results of the events mentioned above. Therefore, energy storage technologies are employed to mitigate these consequences by keeping the power quality at acceptable levels.

2.4.2 Ancillary services

"Ancillary services" is an umbrella term for a number of different applications concerning frequency regulation, voltage regulation, and generally keeping the grid as a system operational[73]. Although it has been noted that no universal international definition is given for what ancillary services are[73].

Spinning reserves

Spinning reserves are a form of ancillary services and are applications that only are utilised should a power plant on the grid fail and shut down. In such cases the spinning reserves are activated and operate until other, slower systems are operational to bridge the gap until the power plant is back online or alternative generator units are available[74].

A consequence of a power plant failure is a frequency drop in the grid which poses a risk to the grid as frequency drops may damage generators and require a shut down to protect them[75].

Energy storage technologies that operate as spinning reserves are required to respond immediately as the failure occurs and should be fully operational within 10 minutes[74]. Furthermore, it is crucial that the energy storage technologies functioning as spinning reserves should be synchronised with the grid[74].

After the activation of spinning reserves additional regulatory reserves, non-spinning reserves, are activated[74]. In California non-spinning reserves need also be operational within 10 minutes but are not required to respond immediately, which permits them not to be synchronised with the grid initially[74]. While spinning reserves only need to operate for minutes, the operational time for non-spinning reserves might last for half an hour[74][73].

Eventually even slower responding reserves are activated[74].

Black Start

In case of a larger failure, when a power system has collapsed, a black start is necessary[76]. Here energy needs to be provided by a unit without that unit or its supportive systems requiring energy from the grid[76].

2.4.3 Load Following

Ancillary services that are applied outside of emergency situations include load following. Here the difference between demand and supply is observed[77] on time frames in the order of minutes to hours[78].

Frequency-&Voltage Control

Both frequency and voltage control are services that are applied to keep frequency and voltage, respectively, within acceptable bounds. A drop in frequency that is not compensated, may cause system failures and machine malfunctioning thus affecting operation in industries[73]. The time frame for operation reaches from seconds to minutes[76].

2.4.4 Energy Arbitrage

The demand for electricity is not constant and there are periods of low and high demand. Correspondingly the electricity costs may vary also. One application of energy storage is therefore to buy and store energy when prices are low and then sell that energy when demand and electricity prices are high[76]. This approach is called energy arbitrage and requires energy storage in the range of days[76]. Naturally, the round-trip efficiency of the storage system,that is the ratio between the energy into the energy storage system and the energy out of it, is important. Higher round-trip efficiency translates to more energy to be sold[76].

2.4.5 Renewable Energy Capacity Firming

Capacity firming is used to mitigate the variability of renewable energy sources such as solar energy. The variability of such energy sources results in a variation in power that is sent to the grid. As a result, the power delivered may leave allowed/ desired ranges. Using energy storage in between the grid and the renewable energy source the energy storage can act as a buffer and regulate the power output to the grid.[79]

Capacity firming requires energy storage technologies operating on time scales of 30 minutes to hours, though no explicit time frames are known and highly dependent on the specific application. The energy capacity is also dependent on the specific use case. Energy storage technologies for capacity firming should have a constant power output.[80]

2.4.6 Renewable Energy Time Shift

Renewable energy sources such as solar are dependent on the weather, and it happens that the times during which they provide the most power, the power consumption by the load is the lowest [81]. It is therefore necessary to shift the production to the times of high demand. This can be achieved through energy storage.

2.4.7 Seasonal Storage

Energy storage technologies that have ability to store energy for very long periods of time, that is in the order of months, may be used as seasonal energy storage. Utilising seasonal energy storage energy that is produced during the summer can be utilised during the winter. [82]

2.4.8 Peak Shaving

The energy consumption is not always constant, and variations occur. During short periods of a day the energy consumption might be especially high, meaning that a lot of energy is required within a short time frame. This requires high power output on the utility side, which generally is compensated by starting expensive to run generators that often have high CO2 emissions. Consequentially the electricity price can increase substantially for the consumer[83][84].

To circumnavigate the increased electricity prices energy storage systems may be installed. These systems, upon an increased energy demand, add energy and cover for the arising peaks, fully or partially. Thereby the utility only experiences the regular demand and no additional, expensive, generators need to be powered up.

Additional benefits that come from installing peak shaving systems are improved power quality, reduced CO2 emissions and improved reliability.

Peak shaving requires operations that have a duration of between 1 and 10 h according to [85].

3

Metrication

In the previous chapter various energy storage technologies and applications have been presented. In the following chapter these will be tied together as energy storage technologies will be evaluated for different applications.

3.1 Characteristics and Demands

Not all energy storage technologies can be used for all applications described in the previous chapter. Each application has certain requirements that an energy storage technology needs to fulfil to be suitable. These requirements are shown in table 3.1. Parameters of importance are for example the response time and the storage duration, as the storage system needs to be able to respond within a certain time to be useful and has to be able to store energy over the required amount of time for an application. An energy storage system that can only store energy for hours cannot be used as seasonal storage, where energy storage for months is needed. Some of the capabilities of the energy storage technologies mentioned in chapter 2 are listed in table 3.2.

Energy Storage Applications	Power Requirements	Storage Time	Response Time	Discharge Time	Other	Suited Technology
Energy Arbitrage	$\leq 500MW$	h-Days	-	$\leq 10h$	Requires High Efficiency	Li-ion, PHES CAES
Peak Shaving	2 MW/<1 MW	1-10 h/ca.1h	<1 Min	Min - h	-	Li-ion, Fuel Cell PHES, CAES
Load Following	1-100MW	Min - h	<1 s	15 Min - 1h	-	Li-ion, Fuel Cell Flywheels
Black Start	5-50MW	-	$\leq 2h$	15 Min - 1 h	Requires ESS to be Independent of Grid	Li-ion, Fuel Cell PHES, CAES
Spinning Reserve	10-100 MW	$\leq 30Min$	s - Min	15 Min-1 h	-	Li-ion, Fuel Cell
Frequency Regulation	$\leq 100MW$	-	Instantaneous-Min	$\leq 1h$	-	Fuel Cell HCE
Voltage Support	1-10MVAR	-	<100ms	1 s - 1 Min	-	Li-ion, Fuel Cell Flywheels
Power Quality	1-4MW/ 100kW-10MW	s	<200 ms	10 s - 15 Min	-	Li-ion, Fuel Cell HCE, Flywheels
Power Reliability	<10MW	-	Min	$\leq 4h$	-	Li-ion, Fuel Cell CAES, PHES Flywheels
Renewable Capacity Firming	<500 MW	-	<30 Min	$\leq 4h$	-	Li-ion, Fuel Cell PHES, CAES
Renewable Energy Time Shift	<500 MW	-	<30 Min	$\leq 5h$	-	Li-ion, Fuel Cell PHES, CAES
Seasonal Storage	>1MW/ 50-300MW	Weeks	Min	-	-	Fuel Cell, HCE? PHES, CAES

Table 3.1: Energy Storage Application Requirements [47] [78] [85] [86] [87] [88] [89]

Energy Storage Technology	Roundtrip Efficiency	Power Rating	Discharge Time	Self-Discharge Per Day	Storage Duration	Response Time	Full Cycle Life	CAPEX ($/kW)
Li-ion	95%/>90%	0-100kW 100MW	Min - h/s-h	0.1 - 0.3%	Min - Days	< 1 s	1000 - 10000	1200-4000
Fuel Cells	<59%/<50%	200kW 0-50MW	s - h	Almost Zero	h - Months	≤ 1*s*	1000+	500/10000+ 3000 - 4500(fuel cells only)
HCE	<44%	1-2MW	-	-	-	s	-	300
PHES	87% /ca.75%	4000MW 100-5000MW	1 - 24h	Very Small	ca.12h h - Months	Min	-	600 600-2000
CAES	<50%-70%	50-220MW 5-300MW	1 - 24h+	Small	h - Days h - Months	s - Min	-	425-517 400-800
Flywheels	90-93% /90-95%	750kW-1650kW 0-250kW	ms - 15Min	100%	-	<1 s	20000+	300-350 250 - 350

Table 3.2: Characteristics of Energy Storage Technologies [47] [58][59]

To get an overview over which energy storage technology can be used for certain applications a grading scheme has been developed to rank the systems according to their applicability. The grading scheme considers requirements such as the initial cost associated with an energy storage technology (CAPEX), the need for specific geographic locations such as caverns or basins, and general applicability. The general applicability considers whether an energy storage technology meets the requirements of a given application.

To each of the requirements mentioned a maximum set of points are given. Geographic requirements are classified into three main categories, INSIGNIFICANT, NORMAL, and HIGH, associated with 9, 5 and 2 points, respectively. Insignificant means that the energy storage technology does not require any special geographic conditions other than perhaps a flat surface to be implemented. NORMAL indicates that some geographic requirements need to be met, such as access to the sea, as can be the case for CAES. High geographic requirements express the need for specific geographic locations for the energy storage technology to be used. Additionally, this score is multiplied by 0.7.

Any storage technology can get a maximum score of 6 points in the CAPEX category, with the least expensive technologies getting the maximum score and the next cheapest getting 5 points and so on. Points are not awarded if the technology does not fulfil the general applicability, meaning that it is not applicable for the specific application considered. In addition, the score in this category is multiplied by a factor of 0.3.

The above-mentioned scores are then multiplied with each other and then multiplied by either a 1, if the technology fulfils the general applicability category, or by 0, if the energy storage technology does not fulfil this category. Thus, the maximum score to be gained overall is 11.34, while the lowest score is 0 points. The higher the score the better. Considering the maximum amount of points awarded in each category and the additional weights by which they are multiplied, the category weighted the most is the geographic demands category. This is because not all locations for which energy storage is required necessarily have the right geography, thus making certain energy storage technologies less universally applicable. Ideally, an energy storage technology is applicable in as many locations and scenarios as possible.

The scores of the technologies presented in chapter 2 are listed in table 3.3, and as the grading scheme is based on points, the numbers presented are dimensionless. Furthermore, the points given to the energy storage technologies in each category and for each application can be seen in table a in the appendix.

Energy Storage Applications						
	Li-Ion	Fuel Cell	HCE	PHES	CAES	Flywheels
Energy Arbitrage	9.45	0.00	0.00	2.52	6.3	0.00
Peak Shaving	9.45	7.56	0.00	2.52	6.3	11.34
Load Following	9.45	7.56	0.00	0.00	0.00	11.34
Black Start	9.45	7.56	0.00	2.52	6.3	0.00
Spinning Reserve	9.45	7.56	0.00	0.00	0.00	11.34
Frequency Regulation	9.45	7.56	11.34	0.00	0.00	11.34
Voltage Support	9.45	7.56	0.00	0.00	0.00	11.34
Power Quality	9.45	7.56	11.34	0.00	0.00	11.34
Power Reliability	9.45	7.56	0.00	2.52	6.3	11.34
Renewable Capacity Firming	9.45	7.56	0.00	2.52	6.3	0.00
Renewable Energy Time Shift	9.45	7.56	0.00	2.52	6.3	0.00
Seasonal Storage	0.00	7.56	9.45	2.52	6.3	0.00

Table 3.3: Rating Energy Storage Technologies for Energy Storage Applications

As illustrated by the scores in table 3.3, the lithium ion batteries and fuel cells are applicable for most applications and they outscore the other technologies mainly because they are less limited by geography and thus more universally applicable and attractive.

Table 3.3 also shows that lithium ion batteries generally outperform fuel cells except when it comes to long term/seasonal storage. A hybrid system based on both fuel cell and lithium ion battery can be assumed to work best in a situation where fuel cells and hydrogen storage take care of the long term energy storage, while lithium ion batteries are used for energy storage on shorter time scales.

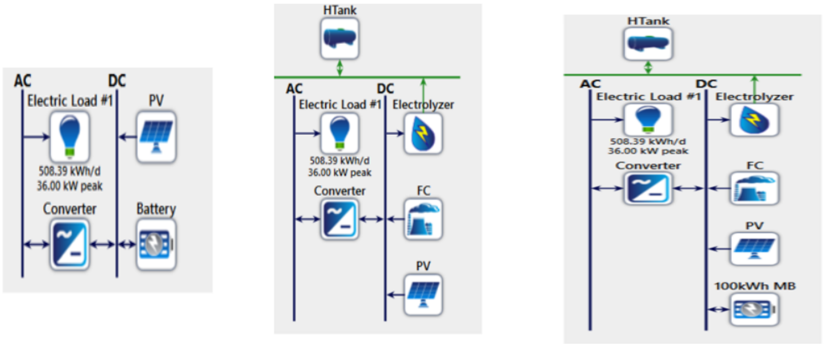
With regards to seasonal storage a Hydrogen Combustion Engine would be preferable over fuel cells, however, due to the lack of data on fuel use, fuel cells are considered from here on forward.

In the following chapters two scenarios are considered. One of these requires long term energy storage, in the form of seasonal storage and short-term energy storage, for renewable energy time shift. The other requires energy storage for the short term.

4

System description

In the following chapter two locations are considered, Greenland and Qatar, for which three systems are set up, one pure fuel cell – hydrogen-based system, one pure battery system and a battery-fuel cell hybrid system. These systems, illustrated in figure 4.1 below, and the components chosen will be described.



(a) Pure battery system Tasiilaq

(b) Pure hydrogen system Tasiilaq

(c) Hybrid system Tasiilaq

Figure 4.1: System schematics for the three systems at Tasiilaq

4.1 Greenland

The first system is located at 65.6145096 latitude, -37.6367607 longitude in Tasiilaq, Greenland. In actuality the town is powered by two 68kW diesel generators, however, in the simulations carried out these generators will be omitted as they are not included in the hybrid system under consideration. The town is not connected to any external grid and therefore all electricity must be generated on site. In the systems presented the electricity will be generated using photovoltaics.

As can be seen from the graph below, which shows the global solar radiation for each month on site, there is great variability in the amount of solar energy available for electricity generation. During December there is no solar energy available at all.

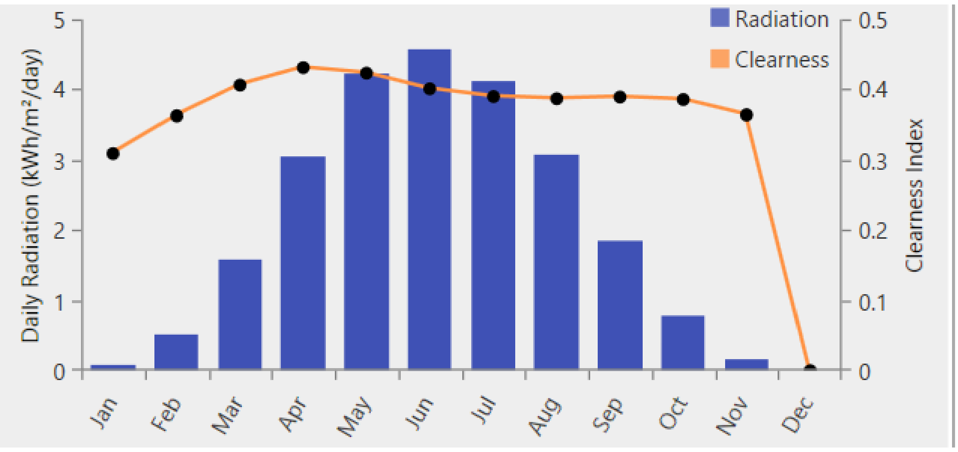


Figure 4.2: Global Horisontal Irradiation for Tasiilaq, Greenland

An important consideration here is the tilt of the solar panels. Not considering axis tracking, the best tilt angle for a solar panel, overall, equals the latitude of the panel [90] . To optimise the PV system for a given season, that is positioning it so that it can generate more electricity than what would be possible with the tilt angle equal to the latitude angle during that season, one has either to add or subtract some degrees from the latitude angle [90]. To optimise for the winter season, one may add 15 degrees to the latitude angle and for the summer season 15 degrees may be subtracted [91]. Furthermore, it is important that on the northern hemisphere the PV system is oriented such that it faces due south towards the equator [90].

Due to the lack of solar energy during the winter, greater production during the summer season is important at the Greenland site. Therefore, the solar panels will be facing due south with a tilt angle of 51 degrees. In the coming figure, the solar radiation on the solar panels is indicated as well as the usable energy part of it based on the efficiency of 19% of the solar module type chosen and presented later in this chapter.

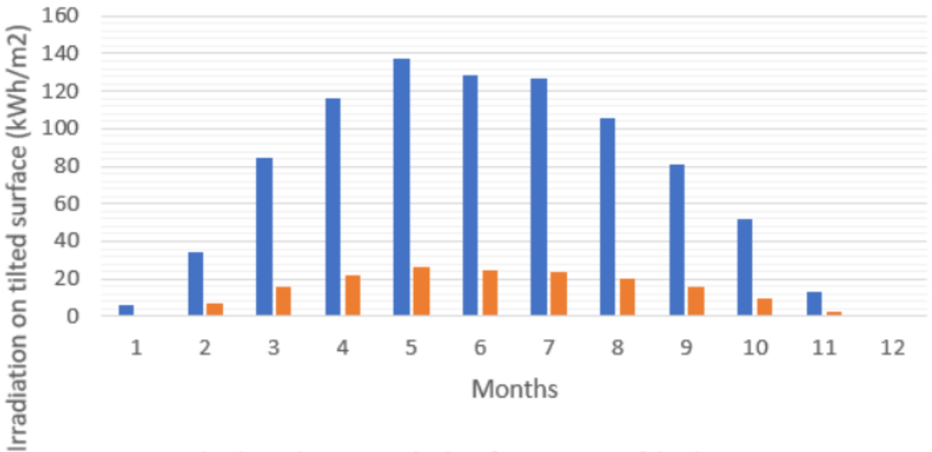


Figure 4.3: Total and useful solar irradiation on the PV modules at Tasiilaq

The demand on site is given in the form of hourly measurements for one representative day each month. A table showing this data is presented in appendix A. In the next graph the total monthly consumption is shown. Comparing the consumption each month with the solar radiation in the area, it can be seen that large amounts of energy need to be stored during the summer for the winter months. This will be achieved through battery and/ or hydrogen storage in the systems considered.

Schematics for the storage systems were given in figure 4.1.

4.2 Qatar

Doha, Qatar differs greatly from the Greenland in the availability of solar radiation throughout the year. As evident from the next graph, solar radiation on site, while somewhat diminished during the winter, is still available in significant quantities at all times.

Again, the load profile is based on hourly measurements for representative days of each month shown in the appendix. Here the total consumption is shown for each of the representative days. The main task of the energy storage

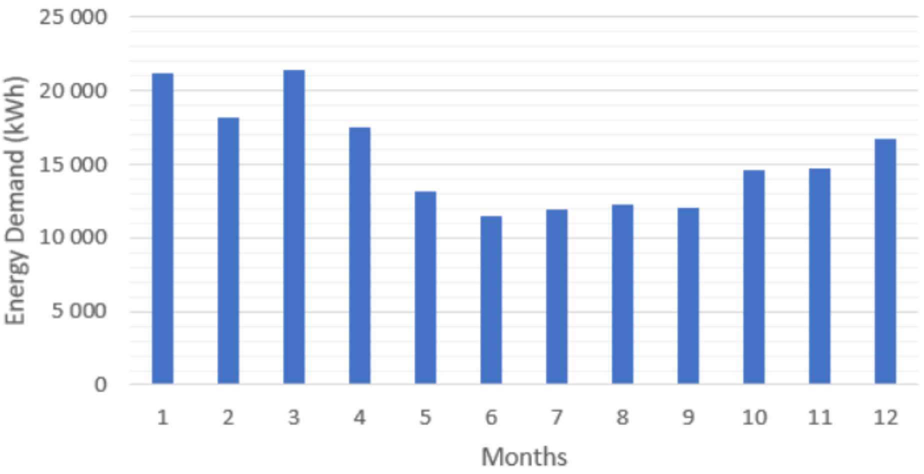


Figure 4.4: Average monthly energy demand Tasiilaq, Greenland

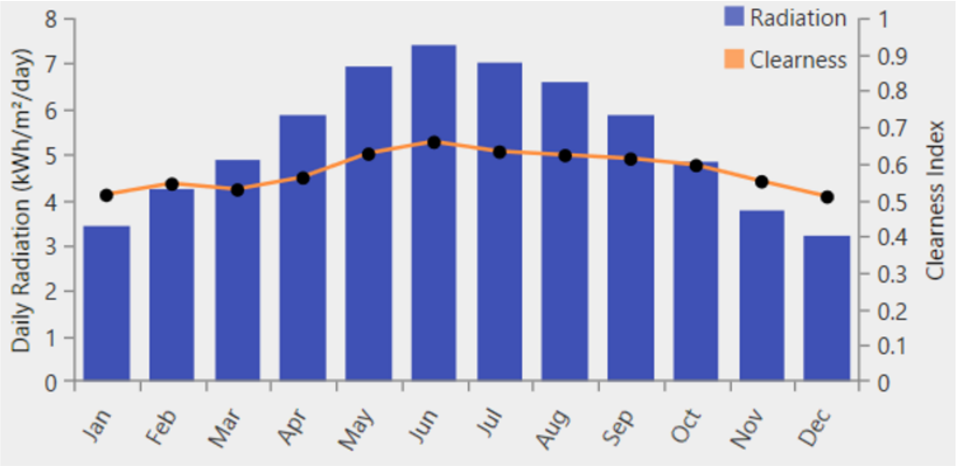


Figure 4.5: Global Horisontal Irradiation on surface at Qatar, Doha

will here be storing enough energy during the day, for consumption during the night. Seasonal storage will not be necessary.

The system schematics for the pure battery, the pure hydrogen-fuel cell and the battery – fuel cell hybrid system are generally identical to the system schematics shown for the systems with regards to the Greenland site, but show different peak power demands.

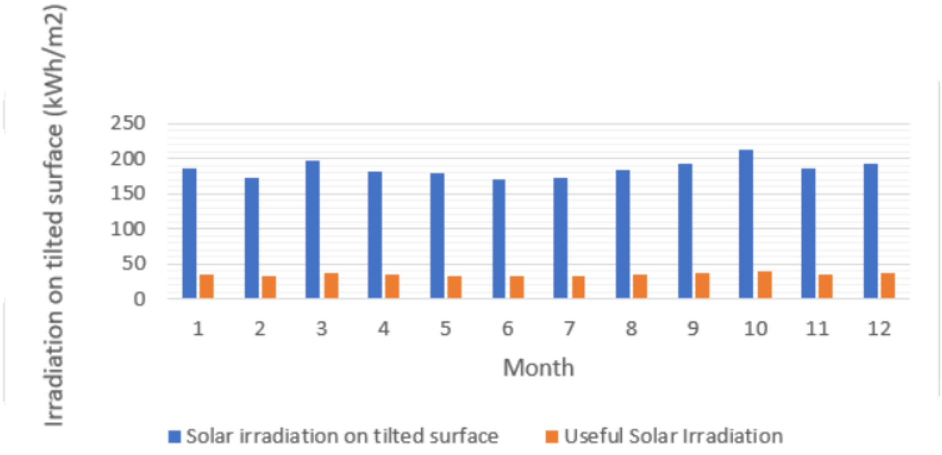


Figure 4.6: Total and useful solar irradiation on PV panel tilted 40°

4.3 Components used

As mentioned previously the main source of energy will be solar power. LG's LG325N1C-A5 model was chosen as the solar panel type for both locations, mainly because the high efficiency associated with it being monocrystalline. Higher efficiency being assumed to be beneficial for the Tasiilaq case, allowing more solar energy to be used and stored. The datasheet for the panel type is given in the appendix, but data that has been entered into HOMER PRO is presented in the table below. It should be noted that no actual module prices could be determined and the per kW prices are based upon prices given by [92].

Category	Greenland	Doha	Unit
CAPEX	374.47	374.47	USD/kW
Replacement Cost	374.47	374.47	USD/kW
OaM	0	0	USD/kW
Tilt	51	40	degrees
Orientation	Due South	Due South	
Tracking	No	No	
Lifetime	25	25	Years
Efficiency at STC	19	19	%
NOCT	45	45	°C
$Pmax_{temp}$	-0.37	-0.37	$-\%/°C$

Table 4.1: LG325N1C-A5 characteristics for HOMER PRO

The electrolyser chosen for the systems are PEMEL rather than ALKEL, due to

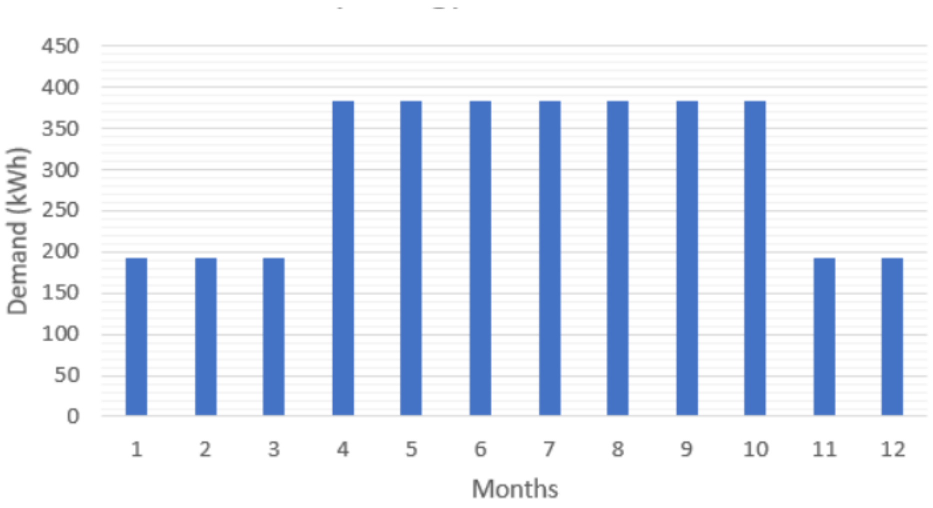
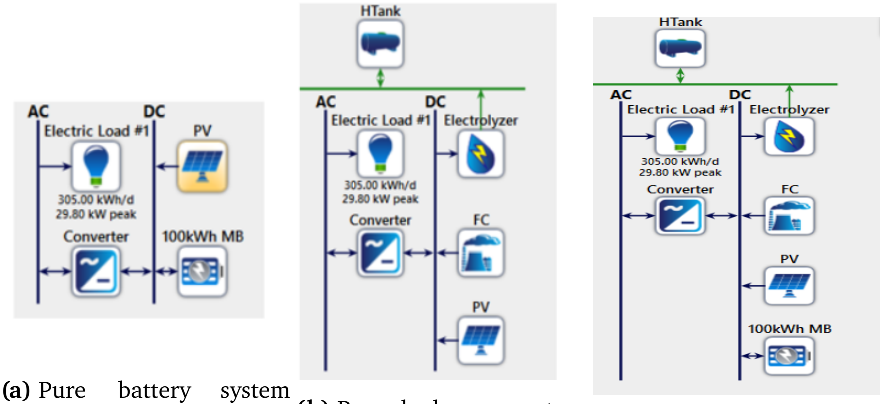


Figure 4.7: Average monthly energy demand workers accommodation near Doha



(a) Pure battery system Doha

(b) Pure hydrogen system Doha

(c) Hybrid system Doha

Figure 4.8: System schematics for the three systems at Doha

them being better suited for power to gas applications. PEMFC are selected as fuel cells. The cost and efficiency data, as well as information regarding the lifetime of the components are given in table 4.2 for the electrolysers and table 4.3 for fuel cells. Table 4.4 and 4.5 show equivalent data for the bidirectional converter and the lithium ion batteries used. The data in the tables is compiled from the data as presented in chapter 2 and 3 for the fuel cells, electrolysers, and batteries. Information shown for the bidirectional converter are taken from the simulation software directly as a generic model was used here.The lifetime of the hydrogen storage tank is also taken from the simulation software. Additional sources are referenced in the table captions.

Category	Greenland	Doha	Unit
CAPEX	1,361.71	1,361.71	USD/kW
Replacement Cost	476.60	476.60	USD/kW
OaM	27.23	27.23	USD/kW
Lifetime	15	15	Years
Efficiency	57	57	%
Minimum load ratio	0	0	%

Table 4.2: PEM electrolyser characteristics [25]

Category	Greenland	Doha	Unit
CAPEX	3000	3000	USD/kW
Replacement Cost	3000	3000	USD/kW
OaM	0	0	USD/Op.h
Lifetime	50 000	50 000	Op.h
Efficiency	50	50	%
Minimum load ratio	0	0	%
CHP Heat recovery ratio	0	0	%
Minimum runtime	0	0	Min
Power	43.2	35.76	kW

Table 4.3: PEM fuel cell characteristics

Category	Greenland	Doha	Unit
CAPEX	300	300	USD/kW
Replacement Cost	300	300	USD/kW
OaM	0	0	USD/kW
Inverter Efficiency	95	95	%
Inverter Lifetime	15	15	Years
Rectifier Efficiency	95	95	%
Rectifier Relative Capacity	100	100	%
Power	43.2	35.76	kW

Table 4.4: Bidirectional converter characteristics

Category	Greenland	Doha	Unit
CAPEX	176000.00	17600.00	USD/Unit
Replacement Cost	176000.00	17600.00	USD/Unit
OaM	0.00	0.00	USD/Year
Capacity	1000	100	kWh/Unit
Lifetime	15	15	Years
Efficiency	90	90	%

Table 4.5: Li-ion battery characteristics

Category	Greenland Hybrid	Greenland Pure Hydrogen	Qatar	Unit
CAPEX	489.62	489.62	489.62	USD/kg
Replacement Cost	489.62	489.62	489.62	USD/kg
OaM	0.00	0.00	0.00	USD/kg/Year
H2 tank capacity	3000	4000	50	kg
H2 tank start of year	1500	2000	25	kg
Lifetime	25	25	25	Years

Table 4.6: Hydrogen storage tank characteristics

The shown sizes for the fuel cell and the bi-directional converter were determined by taking the peak demand as shown in figure 4.1 and figure 4.8 and multiplying these values by 1.2, thereby oversizing the components by 20 %. This was done to account for hypothetical increases in peak demand over time. Both the size of the electrolyser and the size of the hydrogen storage tank were found through preliminary simulations.

It should be noted that while the effects of temperature on PV panels are included in the simulation, the effects of ageing on batteries and fuel cells are omitted. This is done to better compare the systems afterwards, as it is possible to simulate the ageing of batteries in the software, however, fuel cell ageing is not possible. Additionally, the need for hydrogen compression is not simulated because there is no compressor component available.

4.4 Dispatch Strategy

The dispatch strategy employed in all cases is the load following dispatch strategy which, when needed activates/uses generators, such as the fuel cell or batteries, but allows them only to operate with exactly the power needed to satisfy the demand. Additionally, this dispatch strategy uses the generators such as to keep the total costs as low as possible.

5

Simulation and Comparison

To look at the feasibility, both in terms of economy and in terms of practicability, of the systems described in the previous chapter, simulations were carried out. The results of these simulations as well as a description of the software chosen are the content of this chapter.

5.1 Choice of Software

For finding the solar radiation at the locations and on the tilted panels the software PVSOL was used. PVSOL uses the MeteoNorm as a source for its weather data and uses various models to calculate the global irradiation on the tilted PV panels, on a flat surface and so on. Furthermore, it is possible to generate yearly, monthly and hourly data for the time interval under consideration. The hourly global horizontal irradiation on a flat plane generated using PVSOL was imported to HOMER PRO, the software used to carry out the actual simulation of the systems.

HOMER PRO was chosen as it already has models for most of the components relevant for the systems under consideration. This eliminated the need to generate a model for every component and then implement it in MATLAB/SIMULINK or similar programs. Furthermore, HOMER PRO is capable of calculating the economics associated with the systems, such as the total net present cost and the levelized cost of energy. In particular, the software is capable of optimising the systems for the lowest net present cost, showing the most economically viable system configuration.

5.2 Economics

For all simulated systems HOMER finds the total net present cost[93]. The total net present cost is a way of looking at all expenditures and incomes of a system over its lifetime and calculating how much these costs and incomes are worth at the present moment[93]. This is important as the value of money varies over time. One dollar today may be worth more than a dollar in 20 years from now due to for instance inflation. For the same reason earnings of 2000 USD in 10 years from now correspond to earnings of less that 2000 USD today.

In its net present cost calculations HOMER first calculates the discount factor [94] given in equation 5.1.

$$f_d = \frac{1}{(1+i)^N} \tag{5.1}$$

Above, N is the number of years. The discount factor expresses the change in value of some expenditure and/or expenditure in the future[94]. Here the real discount rate is used, which excludes inflation[95]. Given the nominal discount rate, the real discount rate can be found by excluding inflation using equation 5.2 where i is the real discount rate, i' is the nominal discount rate and f is the inflation .

$$i = \frac{i' - f}{1 + f} \tag{5.2}$$

After applying the discount factors to all expenditures and incomes over the lifetime of the system, these cash-flows are summed up and the net present value is found.

Based on the net present cost HOMER finds the total annualised cost, which is the constant cash-flow that needs to occur each year over the course of the lifetime of the project/system in order to arrive at the net present cost for the system[96].

$$A_T = CRF(i, R_{proj}) * NPC_T \tag{5.3}$$

In equation 5.3 A_T is the total annualised cost,NPC_T is the total net present cost, i is the real discount rate and R_{proj} is the project lifetime. CRF is the cost recovery factor given as:

$$CRF(i, N) = \frac{i(i+1)^N}{(1+i)^N - 1} \tag{5.4}$$

Using the annualised cost HOMER is then able to calculate the levelized cost of electricity[97], which is a financial tool to compare different energy storage technologies and generators with one another. The levelized cost of electricity is the average cost of electrical energy produced by a system and is found by the software using the equation below[97]. Since no boiler are involved and no thermal load is served these terms will be omitted.

$$LCOE = \frac{A_T - c_{boiler} * H_{served}}{E_{served}} \tag{5.5}$$

E_{served} is the electrical load served.

5.3 Simulation Results

In the following two sections the results of the simulation for the systems at Tasiilaq and Doha are presented.

5.3.1 Greenland

Pure battery system

The optimised pure battery system consists of a 31 MWh battery bank and 1527 kW of PV power. About 1161GWh of electric energy are provided by the solar panels over the course of a year, serving the load and storing about 102 MWh a year in batteries. Also providing a large amount of excess electricity.

Considering the PV modules employed the total number of modules required in this case is close to 4700 modules. This corresponds to a total area of $8051m^2$.

While the battery system is able to provide enough energy throughout the year and thereby avoid unmet load, its state of charge at the end of the year is lower compared to its state of charge at the beginning of the simulation. It is therefor to be assumed that the battery is unable to provide enough energy for the coming year, which will start with a period of little available solar resource. This is illustrated in figure 5.1.

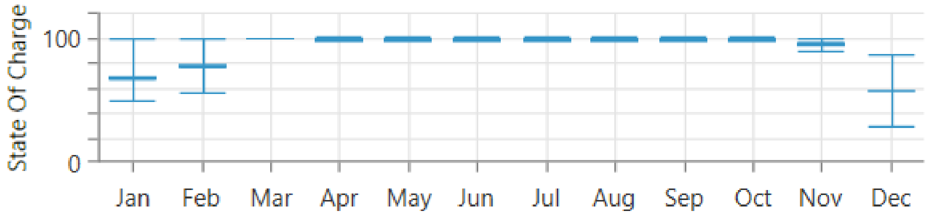


Figure 5.1: End of year battery SOC

Pure Hydrogen System

Using only hydrogen, the optimised system requires 1527 kW of solar power, generating 1160777 kWh per year, with less excess electricity than the pure battery system.

Unlike the battery system the fuel cell is capable of carrying over enough stored energy for the coming year, as evident from the next graph showing the hydrogen stored. Starting out with 2000 kg of hydrogen, the amount of stored hydrogen at the end of the year is again 2000 kg.

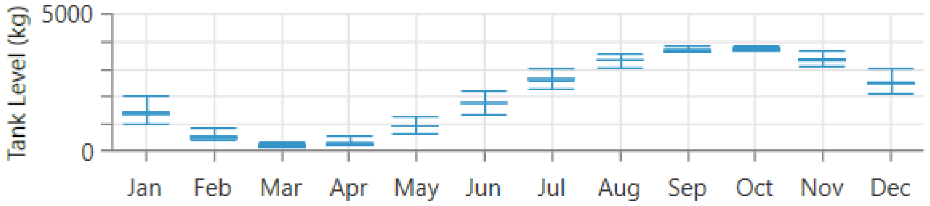


Figure 5.2: Pure Hydrogen System, tank level development

Battery - Fuel Cell hybrid system

Combining both energy storage technologies, the amount of needed solar power was drastically reduced compared to the other systems. 962kW being 37% less than the PV power needed in the pure battery and hydrogen systems. Consequentially the area needed for solar panels is also reduced, with 2960 modules occupying a total area of $5070.48m^2$.

Not only the solar power needed for operation, but also the hydrogen storage capacity is greatly reduced in the hybrid system. Instead of 4000 kg of storage, 3000 kg are sufficient. As has been shown in the calculations in the appendix a 125 L containment is required to store 5kg of hydrogen. Thereby a reduction from 4000 kg to 3000 kg corresponds to a decrease in volume by 25

%, from 100000 L to 75000 L.

Yet the hybrid system, similarly to the pure hydrogen system does avoid the problem faced by the pure battery system in the simulation, ending up with too little energy in store at the end of the year.

More importantly, the hybrid system is significantly cheaper than any of the other systems. With a net present cost about 34 % lower than the pure hydrogen system and close to 72 % lower than the pure battery system. Table 5.1 summarises the results from above.

Category	Pure Batter	Pure Hydrogen	Hybrid	Unit
NPC	8080576.00	3449710.36	2281064.84	USD
LCOE	3.37	1.44	0.9501	USD/kWh
CAPEX	5999546.69	2903968.69	2187035.50	USD
OaM	197403.18	70403.26	35201.63	USD
Fuel Cell	0	43.2	43.2	kW
PV	1527	1527	962	kW
Converter	43.2	43.2	136	kW
Electrolyser	0	200	100	kW
Hydrogen tank	0	4000	3000	kg
Battery	31	0.00	6.00	MWh
Battery SoC start of year	100	-	100	%
Battery SoC end of year	26.69	-	21.6	%
H2 tank level start of year	-	2000	1500	kg
H2 tank level end of year	-	2209	1502	kg

Table 5.1: Optimised Sytem Parameters Tasiilaq, Greenland

5.3.2 Qatar

Category	Pure Batter	Pure Hydrogen	Hybrid	Unit
NPC	227476.15	729191.26	446867.75	USD
LCOE	0.1581	0.5067	0.3106	USD/kWh
CAPEX	187410.32	530294.20	326384.49	USD
OaM	0	70403.26	26701.79	USD
Fuel Cell	0	35.8	35.8	kW
PV	205	332	131	kW
Converter	35.8	32.9	35.8	kW
Electrolyser	0.00	200	50	kW
Hydrogen tank	0.00	50	50	kg
Battery	600	0.00	4	kWh
Battery SoC start of year	100	-	100	%
Battery SoC end of year	82.25	-	66.18	%
H2 tank level start of year	-	25	25	kg
H2 tank level end of year	-	41.5	50	kg

Table 5.2: Optimised Sytem Parameters Doha, Qatar

The results for Qatar show that the situation is the opposite to what has been found for Tasiilaq, Greenland. The amount of hydrogen storage needed is relatively small because of the readily available solar energy during all months of the year. Therefore, costs for the fuel cell and the electrolyser represent a greater fraction of the system cost.

Looking at an excerpt from the load profile for Doha, figure 5.3, for the hybrid system, we can see that the fuel cell is only used for short periods of time of the day. During wintertime, when the solar power is greater due to the angle of choice for the PV system, the fuel cell is not used at all. In other words, the hybrid system implements expensive components that are rarely used. Unlike the Greenland case, there are no substantial space savings either, and so the hybrid system, being twice as costly is not a valuable system design for this scenario.

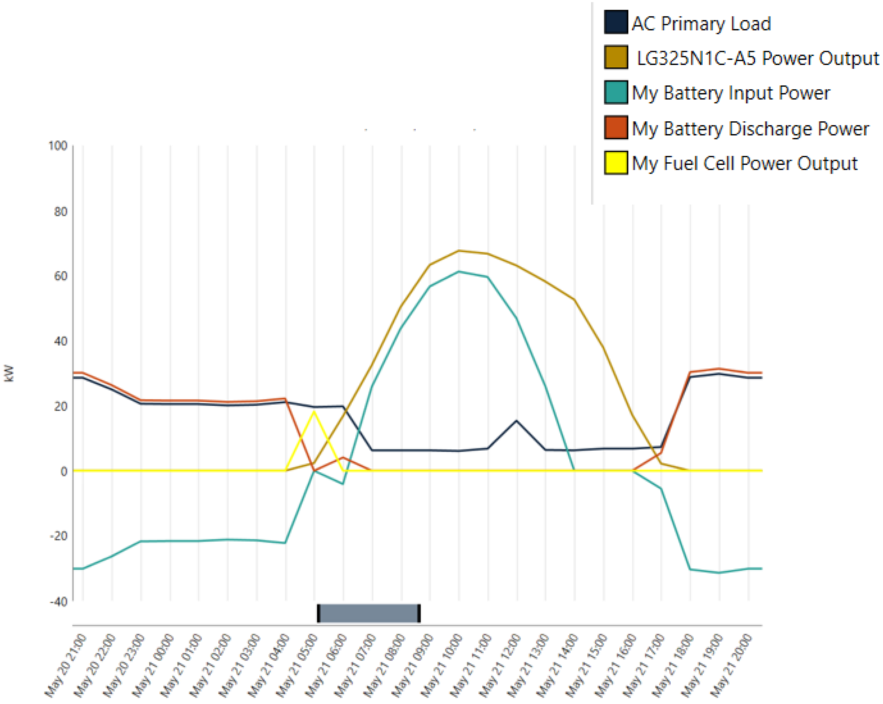


Figure 5.3: Winter day load Qatar

6

Discussion and Conclusion

As mentioned previously, important factors such as component ageing were not included in this study. Including these parameters would most likely lead to greater system sizes and thus greater expenses. The reason for this would be the additional capacity to be added in order to guarantee the needed capacity at the end of the component's life.

Furthermore, the results in this study are highly dependent on the actual cost of the individual components. Fuel cells and electrolysers are not yet mass produced, nor applied to the same extent as lithium ion batteries, the cost of these components in this work is therefore largely based on estimates. Especially for the cost of hydrogen storage makes this clear, as the estimated cost is dependent on annually manufactured quantities of 500 000 units.

That being said, the general trend is clear. The greater the seasonal variations in renewable energy, the greater the value of hydrogen storage becomes. Significantly outperforming battery storage. However, the greatest results are achieved when combining fuel cells and batteries in a hybrid system. As has been shown, a significant drop in cost could be observed while at the same time reducing the space needed for storage and for the PV system. The cost reduction is a result of the smaller electrolyser size required for the hybrid system, as well as due to the reduced time the electrolyser needs to operate. As such both the OaM costs and the CAPEX are reduced with respect to the pure hydrogen system.

Still, in spite of great reduction in space, the area needed to run the town of Tasiilaq on pure renewable energy is quite large.

With greater availability of renewable energy, the system size is reduced, but as mentioned, the less attractive hydrogen storage becomes. Here, the pure battery system outperformed both the pure hydrogen fuel cell system and the hybrid system economically.

The reason behind the greater cost for fuel cell systems with respect to lithium ion battery systems on smaller scale seems to be that the costs associated with the more expensive components of a fuel cell system, namely the fuel cell and the electrolyser, become more dominant. For large systems, it is necessary to scale up the entire battery, in the battery system, while it is only necessary to increase the storage capacity of hydrogen in the fuel cell driven systems. The fuel cell and the electrolyser do not need to be scaled up unless the peak power demand of the system increases.

Therefore, in order to become more viable for projects requiring smaller quantities of hydrogen, a significant reduction in cost is required for fuel cells and electrolysers.

In the beginning of this thesis it was mentioned that hydrogen is used extensively in areas other than energy storage, areas which eventually need to become more environmentally friendly, consequentially a significant development in electrolyser technology is to be expected, with associated cost reduction. A general improvement in the hydrogen infrastructure as a result of said development is likely, given the quantities of hydrogen required.

Hydrogen may therefore develop into a medium for energy storage, not on a direct route, but rather as a byproduct of the need to make other industries more environmentally friendly. As for now, hydrogen as an energy storage medium is not an attractive option for small scale energy storage and large scale applications are even without the requirement of special geographic features such as caverns, limited by the available space.

6.1 Further Work

The key hurdle for hydrogen energy storage as described in this thesis remains the space needed. However, methods other than compressed hydrogen exist and future research may focus on one of these methods to see whether the space required for hydrogen storage can be reduced to an extent were it is no longer a deal breaker.

Further additions can made through the consideration of degradation of the fuel cell and the battery and including compressors. Thereby gaining a better representation of a real world system.

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A

Appendix

A.1 Storage requirements for hydrogen

Below the calculations for the volume required to store 5kg of hydrogen gas.

Starting point for these calculations is the virial equation presented below.Only the first three virial coefficients will be considered.

$$P = RT\rho[A + B(T)\rho + C(T)\rho^2 + ...] \tag{2.7}$$

In the virial equation P is the pressure in Pa, R is the gas constant and T is the temperature in Kelvin. A, B(T) and C(T) are the so called virial coefficients, where A is always 1. Furthermore, ρ is the molar density. Put in another way $\rho = \frac{1}{V_m}$ where V_m is the Molar Volume.

Symbols	Values	Units
P	$700 * 10^5$	Pa
T	300	K
R	8.314	
$B(T)$	$14.38 * 10^{-6}$	m^3/mol
$C(T)$	$343.8 * 10^{-12}$	m^6/mol^2
Mm	$2.016 * 10^{-3}$	kg

Table A.1: Values for virial and density calculations

Equation 2.7 can be rearranged to equation A.1

$$-\frac{P}{RT} + \rho + B(T)\rho^2 + C(T)\rho^3 = 0 \tag{A.1}$$

Plugging in the values from table A.1 and solving for ρ the following value for the molar density can be found.

$$\rho = 19779.15205 \, mol/m^3$$

Using the Molar Mass (Mm) of hydrogen, the density of the compressed gas is found.

$$\frac{Mm}{V_m} = 39.87 \, kg/m^3 = 0.03987 \, kg/L \tag{A.2}$$

Given then that we consider 5kg of hydrogen gas, the volume required to store it under the pressure of 700 bar and at 300K is:

$$\frac{5kg}{0.03987 {}^{kg}/_{L}} = \underline{\underline{125.39L}} \tag{A.3}$$

A.2 Work needed for compression of hydrogen

Here it will be shown what work is necessary to store 5kg of hydrogen. Furthermore the energy lost due to the compression will be calculated.

Equation 2.7 will be rewritten to the form shown below by multiplying with the molar volume on both sides.

$$PV_m = RT[A + \frac{B(T)}{V_m} + \frac{C(T)}{V_m} + ...] \tag{A.4}$$

Now the number of moles of which 5kg H_2 consists can be found by dividing the mass with the molar mass. The number of moles is therefore $n = 2480.15873$.

The number of moles can be used to manipulate equation A.4 to become:

$$PV = nRT[A + \frac{B(T)}{V_m} + \frac{C(T)}{V_m} + ...] \tag{A.5}$$

by multiplying with the number of moles on both sides. V is the volume.

Considering that the compression is isothermal, meaning that it happens without temperature change, the work needed for compression is given by equation A.6 [98]:

$$\Delta W = -\int_{V1}^{V2} PdV \tag{A.6}$$

Substituting for P and plugging in the values from table A.1 and n into A.6 the work is calculated as shown in equation A.7 and A.8 .

$$\Delta W = -nRT[A + \frac{B(T)}{V_m} + \frac{C(T)}{V_m} + ...] \int_{V1}^{V2} \frac{1}{V} dV \tag{A.7}$$

$$\Delta W = -nRT[A + \frac{B(T)}{V_m} + \frac{C(T)}{V_m} + ...] * \ln \frac{V2}{V1} = 38.3047MJ \tag{A.8}$$

This corresponds to $\frac{38.3047MJ}{\frac{120MJ}{kg} * 5kg} * 100 = 6.38\%$ of the total energy content of the 5kg of hydrogen gas.

A.3 Preliminary evaluation of energy storage technologies

Energy Storage Applications	Energy Storage Technologies						Categories
	Li-Ion	Fuel Cell	HCE	PHES	CAES	Flywheels	
Energy Arbitrage	YES	NO	NO	YES	YES	NO	Technically Feasable
	5	0	0	6	6	0	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Peak Shaving	YES	YES	NO	YES	YES	YES	Technically Feasable
	5	4	0	6	6	6	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Load Following	YES	YES	NO	NO	NO	YES	Technically Feasable
	5	4	0	0	0	6	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Black Start	YES	YES	NO	YES	YES	NO	Technically Feasable
	5	4	0	6	6	0	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Spinning Reserve	YES	YES	NO	NO	NO	YES	Technically Feasable
	5	4	0	0	0	6	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Frequency Regulation	YES	YES	YES	NO	NO	YES	Technically Feasable
	5	4	6	0	0	6	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Voltage Support	YES	YES	NO	NO	NO	YES	Technically Feasable
	5	4	0	0	0	6	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGHLY	NORMAL	INSIGNIFICANT	Geologically Dependent
Power Quality	YES	YES	YES	NO	NO	YES	Technically Feasable
	5	4	6	0	0	6	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Power Reliability	YES	YES	NO	YES	YES	YES	Technically Feasable
	5	4	0	6	6	6	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Renewable Capacity Firming	YES	YES	NO	YES	YES	NO	Technically Feasable
	5	4	0	6	6	0	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Renewable Energy Time Shift	YES	YES	NO	YES	YES	NO	Technically Feasable
	5	4	0	6	6	0	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent
Seasonal Storage	NO	YES	YES	YES	YES	NO	Technically Feasable
	0	4	5	6	6	0	Economically Feasable
	INSIGNIFICANT	INSIGNIFICANT	INSIGNIFICANT	HIGH	NORMAL	INSIGNIFICANT	Geologically Dependent

Table A.2: Preliminary Evaluation of Energy Storage Technologies

A.4 Consumption on representative days during each month of the year

Time of Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	24	23	24	21	15	13	14	14	16	16	17	19
1	23	22	23	19	14	13	13	13	17	16	16	18
2	25	24	25	22	16	14	14	15	16	17	18	20
3	29	28	29	25	18	16	16	17	13	20	21	23
4	24	23	24	21	15	13	14	14	17	16	17	19
5	28	26	28	24	17	16	16	16	17	19	20	22
6	24	23	24	21	15	13	14	14	12	16	17	19
7	24	23	24	21	15	13	14	14	14	16	17	19
8	30	29	31	26	19	17	17	18	20	21	22	24
9	25	24	25	22	16	14	14	15	19	17	18	20
10	28	26	28	24	17	16	16	16	22	19	20	22
11	24	23	24	21	15	13	14	14	18	16	17	19
12	32	30	32	27	20	18	18	18	17	22	23	25
13	33	31	33	28	20	18	19	19	16	23	24	26
14	29	28	29	25	18	16	16	17	17	20	21	23
15	32	30	32	27	20	18	18	18	16	22	23	25
16	35	34	36	30	22	20	20	21	15	24	25	28
17	32	30	32	27	20	18	18	18	16	22	23	25
18	32	30	32	27	20	18	18	18	19	22	23	25
19	34	32	34	29	21	19	19	20	17	23	25	27
20	30	29	31	26	19	17	17	18	19	21	22	24
21	30	29	31	26	19	17	17	18	18	21	22	24
22	28	26	28	24	17	16	16	16	16	19	20	22
23	29	28	29	25	18	16	16	17	16	20	21	23

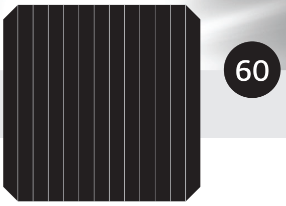
Table A.3: Consumption on representative days during each month of the year, Tasiilaq

Time of Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0	5.3	5.3	5.3	20.5	20.5	20.5	20.5	20.5	20.5	20.5	5.3	5.3
1	5.3	5.3	5.3	20.5	20.5	20.5	20.5	20.5	20.5	20.5	5.3	5.3
2	4.9	4.9	4.9	20.1	20.1	20.1	20.1	20.1	20.1	20.1	4.9	4.9
3	5.1	5.1	5.1	20.3	20.3	20.3	20.3	20.3	20.3	20.3	5.1	5.1
4	5.8	5.8	5.8	21.1	21.1	21.1	21.1	21.1	21.1	21.1	5.8	5.8
5	15.0	15.0	15.0	19.6	19.6	19.6	19.6	19.6	19.6	19.6	15.0	15.0
6	15.2	15.2	15.2	19.8	19.8	19.8	19.8	19.8	19.8	19.8	15.2	15.2
7	3.2	3.2	3.2	6.3	6.3	6.3	6.3	6.3	6.3	6.3	3.2	3.2
8	3.2	3.2	3.2	6.3	6.3	6.3	6.3	6.3	6.3	6.3	3.2	3.2
9	3.2	3.2	3.2	6.3	6.3	6.3	6.3	6.3	6.3	6.3	3.2	3.2
10	3.0	3.0	3.0	6.1	6.1	6.1	6.1	6.1	6.1	6.1	3.0	3.0
11	3.7	3.7	3.7	6.8	6.8	6.8	6.8	6.8	6.8	6.8	3.7	3.7
12	10.1	10.1	10.1	15.4	15.4	15.4	15.4	15.4	15.4	15.4	10.1	10.1
13	3.3	3.3	3.3	6.4	6.4	6.4	6.4	6.4	6.4	6.4	3.3	3.3
14	3.2	3.2	3.2	6.3	6.3	6.3	6.3	6.3	6.3	6.3	3.2	3.2
15	3.7	3.7	3.7	6.8	6.8	6.8	6.8	6.8	6.8	6.8	3.7	3.7
16	3.7	3.7	3.7	6.8	6.8	6.8	6.8	6.8	6.8	6.8	3.7	3.7
17	4.2	4.2	4.2	7.3	7.3	7.3	7.3	7.3	7.3	7.3	4.2	4.2
18	18.3	18.3	18.3	28.8	28.8	28.8	28.8	28.8	28.8	28.8	18.3	18.3
19	19.2	19.2	19.2	29.8	29.8	29.8	29.8	29.8	29.8	29.8	19.2	19.2
20	18.1	18.1	18.1	28.6	28.6	28.6	28.6	28.6	28.6	28.6	18.1	18.1
21	18.1	18.1	18.1	28.6	28.6	28.6	28.6	28.6	28.6	28.6	18.1	18.1
22	12.4	12.4	12.4	25.0	25.0	25.0	25.0	25.0	25.0	25.0	12.4	12.4
23	5.7	5.7	5.7	20.6	20.6	20.6	20.6	20.6	20.6	20.6	5.7	5.7

Table A.4: Caption

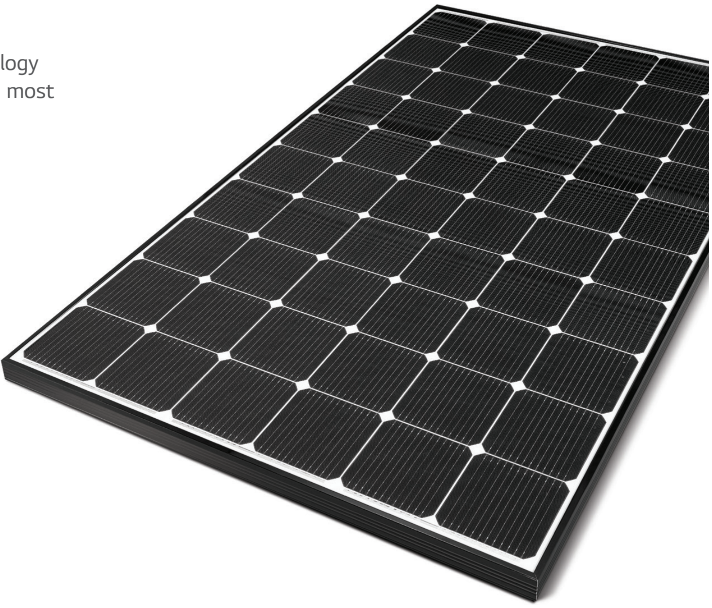
LG NeON® 2

LG335N1C-A5 | LG330N1C-A5 | LG325N1C-A5



335W | 330W | 325W

The LG NeON® 2 is LG's best selling solar module. It received the acclaimed 2015 Intersolar AWARD for featuring LG's Cello Technology that increases its power output and reliability making it one of the most powerful and versatile modules on the market.



Feature

Enhanced Performance Warranty

LG NeON® 2 has an enhanced performance warranty. After 25 years, LG NeON® 2 is guaranteed at least 84.8% of initial performance.

High Power Output

Compared with previous models, the LG NeON® 2 has been designed to significantly enhance its output efficiency making it efficient even in limited space.

Aesthetic Roof

LG NeON® 2 has been designed with aesthetics in mind; thinner wires that appear all black at a distance. The product can increase the value of a property with its modern design.

Outstanding Durability

With its newly reinforced frame design, LG has extended the warranty of the NeON® 2 for an additional 2 years. Additionally, LG NeON® 2 can endure a front load up to 6000 Pa, and a rear load up to 5400 Pa.

Better Performance on a Sunny Day

LG NeON® 2 now performs better on a sunny days thanks to its improved temperature coefficient.

Near Zero LID (Light Induced Degradation)

The n-type cells used in LG NeON® 2 have almost no boron, which may cause the initial performance degradation, leading to less LID.

About LG Electronics

LG Electronics is a global big player, committed to expanding its operations with the solar market. The company first embarked on a solar energy source research program in 1985, supported by LG Group's vast experience in the semi-conductor, LCD, chemistry and materials industries. In 2010, LG Solar successfully released its first MonoX® series to the market, which is now available in 32 countries. The NeON® (previous. MonoX® NeON), NeON®2, NeON®2 BiFacial won the "Intersolar AWARD" in 2013, 2015 and 2016, which demonstrates LG Solar's lead, innovation and commitment to the industry.

LG NeON® 2

LG335N1C-A5 | LG330N1C-A5 | LG325N1C-A5

Mechanical Properties

Cells	6 x 10
Cell Vendor	LG
Cell Type	Monocrystalline / N-type
Cell Dimensions	161.7 x 161.7 mm / 6 inches
# of Busbar	12 (Multi Wire Busbar)
Dimensions (L x W x H)	1,686 x 1,016 x 40 mm
	66.38 x 40 x 1.57 in
Front Load	6,000Pa / 125 psf
Rear Load	5,400Pa / 113 psf
Weight	18 kg / 39.68 lb
Connector Type	MC4 (MC)
Junction Box	IP68 with 3 Bypass Diodes
Cables	1,000 mm x 2 ea / 39.37 in x 2 ea
Glass	High Transmission Tempered Glass
Frame	Anodized Aluminium

Certifications and Warranty

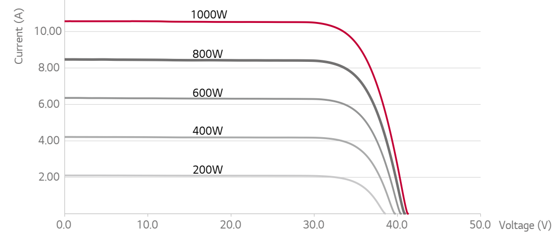
Certifications	IEC 61215, IEC 61730-1/-2
	UL 1703
	IEC 61701 (Salt mist corrosion test)
	IEC 62716 (Ammonia corrosion test)
	ISO 9001
Module Fire Performance	Type 1 (UL 1703)
Fire Rating	Class C (ULC/ORD C 1703, IEC 61730)
Product Warranty	12 Years
Output Warranty of Pmax	Linear Warranty*

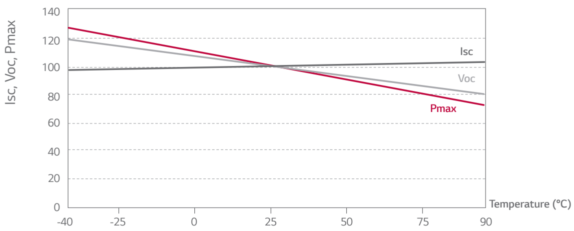
* 1) 1st year: 98%, 2) After 1st year: 0.55% annual degradation 3) 84.8% for 25 years

Temperature Characteristics

NOCT	[°C]	45 ± 3
Pmax	[%/°C]	-0.37
Voc	[%/°C]	-0.27
Isc	[%/°C]	0.03

Characteristic Curves





Electrical Properties (STC*)

Model		LG335N1C-A5	LG330N1C-A5	LG325N1C-A5
Maximum Power (Pmax)	[W]	335	330	325
MPP Voltage (Vmpp)	[V]	34.1	33.7	33.3
MPP Current (Impp)	[A]	9.83	9.80	9.77
Open Circuit Voltage (Voc)	[V]	41.0	40.9	40.8
Short Circuit Current (Isc)	[A]	10.49	10.45	10.41
Module Efficiency	[%]	19.6	19.3	19.0
Operating Temperature	[°C]	-40 ~ +90		
Maximum System Voltage	[V]	1000 (UL / IEC)		
Maximum Series Fuse Rating	[A]	20		
Power Tolerance	[%]	0 ~ +3		

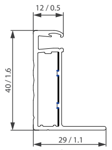
* STC (Standard Test Condition): Irradiance 1000 W/m², cell temperature 25 °C, AM 1.5
The nameplate power output is measured and determined by LG Electronics at its sole and absolute discretion.
The Typical change in module efficiency at 200 W/m² in relation to 1000 W/m² is -2.0%.

Electrical Properties (NOCT*)

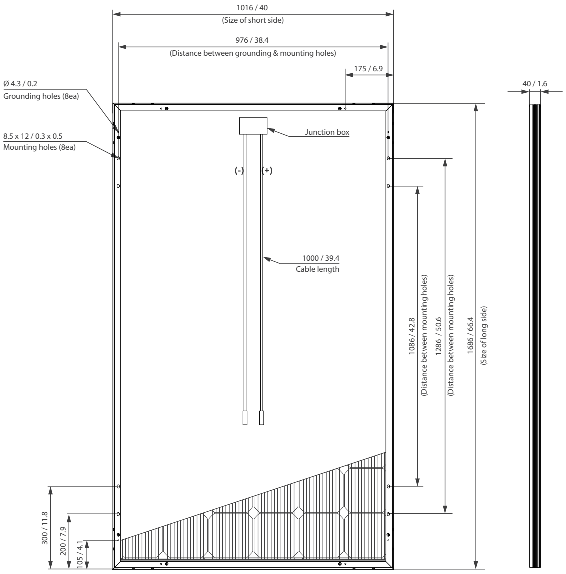
Model		LG335N1C-A5	LG330N1C-A5	LG325N1C-A5
Maximum Power (Pmax)	[W]	247	243	240
MPP Voltage (Vmpp)	[V]	31.5	31.2	30.8
MPP Current (Impp)	[A]	7.83	7.81	7.78
Open Circuit Voltage (Voc)	[V]	38.2	38.1	38.0
Short Circuit Current (Isc)	[A]	8.44	8.41	8.38

* NOCT (Nominal Operating Cell Temperature): Irradiance 800 W/m^2, ambient temperature 20 °C, wind speed 1 m/s

Dimensions (mm / inch)



Frame Cross-section



* The distance between the center of the mounting/grounding

LG Life's Good

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Product specifications are subject to change without notice.
DS-N5-60-C-G-F-EN-70521