Understanding Hydrogen Energy

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Pure Energy Centre

FOREGROUND

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Contents

List of Figures

List of Tables

1. Executive summary

Hydrogen energy was proposed nearly four decades ago as a permanent solution to the interrelated global problems of the depletion of fossil fuels and the environmental problems caused by their utilization. It was formally presented at the landmark *The Hydrogen Economy Miami Energy*[1].

It immediately caught the imagination and attention of socially contentious energy and environmental scientists and engineers. Research and development activities ensued around the world in order to develop the technologies needed for the introduction of the hydrogen energy system. It took a quarter of a century to research and develop most of the technologies required.

The hydrogen energy system started making inroads in the energy field early in the twenty-first century. Several types of fuel cells were developed for efficient conversion of hydrogen to electricity, as well as heat. In the United States, Germany, and Japan, solid oxide fuel cells are used to produce electricity and to heat homes and buildings. Hydrogen- fueled forklifts are now replacing battery-powered forklifts in warehouses, since they are much more economical. Several municipalities are experimenting with hydrogen-fueled buses as they are much quieter and cleaner. Major car manufacturers have developed clean and efficient hydrogen cars, which are already being tested in major cities around the world. Construction of hydrogen-fueling stations is also accelerating in several countries and in major cities, especially in Germany, Japan, and California. Car companies have introduced hydrogen-fueled cars for sale to the public since 2013[2]. Railway companies are experimenting with hydrogen-fueled locomotives. There are experimental trams running on hydrogen. Many navies are replacing their diesel-fueled submarines with hydrogen-fueled ones. Boeing and Airbus are studying the feasibility of hydrogen-fueled passenger planes. A hydrogen-powered supersonic private plane is also under development.

This brief course hydrogen energy covers all aspects of hydrogen energy technology, including hydrogen production, hydrogen storage, compression and delivery, hydrogen conversion and utilization and hydrogen safety.

The information contained within this report allows users to become aware of the importance of Hydrogen in the future economy, to learn for hydrogen can solve energy problems since future political and legislative trends move towards a renewable source no carbon-based society. This this scenario Hydrogen Energy in conjunction with renewables energy represent a key role in the green energy transition. .

[1] (THEME) Conference, March 18-20, 1974, Miami Beach, Florida.
[2] Hydrogen vehicle - Wikipedia

2. Introduction to Hydrogen Energy

Currently due to rising fuel prices and environmental concerns, such as local air pollution and climate change, renewable energy plants have gained high interest due to their ability to produce clean energy from natural resources such as sunlight, wind, tide and geothermal heat that are locally available and naturally replenished. According to IEA global renewable energy capacity is growing at rates of up to 45% annually and is providing 29 % of global final energy consumption[3]. Nevertheless, electricity generated from renewable plants can rarely provide immediate response to load demand, as these sources do not deliver a stable supply immediately compatible with consumption needs; therefore, these technologies require assistance in the form of energy storage to boost their penetration levels. For example, electricity generated from wind and solar is subjected to both predictable and unpredictable intermittencies and unexpected or expected weather variations can reduce electricity production rapidly from hour to hour and even minute to minute.

Stand-alone power supply systems are used by many communities around the globe that have no access to grid electricity. In order to integrate renewable energy into such systems and allow for the natural variability of wind and solar resources, some form of energy storage or additional 'on demand' generation is generally required.

Remote communities pay economic and environmental penalties for electricity, because they must import diesel as their primary fuel for electric power production. Heavy transportation costs are incurred and there is potential for environmental damage through empty drums, leakage, and spills. For this reason, remote villages offer a viable niche market where sustainable energy systems based on renewable resources and advanced energy storage technologies can compete favorably on purely economic grounds, whilst providing environmental benefits and energy security.

In grid-connected systems, the national grid has operated without energy storage by over-designing its energy generation capability and boosting production when demand exceeds expectations. The integration of renewable energy systems has been possible because the distribution grid has worked as an ideal store for the electrical energy. However, recent studies indicate that the present grid infrastructure could represent an obstacle to future renewable energy system development, because of the increasing introduction of renewable energy plants with fluctuating energy production. As example renewable grid integration issues have in particular been investigated for the German electricity grid. It has been identified that current load balancing and transport capacities are expected to fall short after 2025. The reality is the electricity system is old and a lot of the infrastructures were built before thinking about climate change. It's not designed to withstand the impacts of climate change. What can be seen as grid weaknesses by some, are seen by others as a unique opportunity for a new sector development that is energy storage. The introduction of storage power plants, when performing optimally and cost-effectively, can substantially mitigate the renewable integration issues.

[3] Renewables – Global Energy Review 2021 – Analysis - IEA

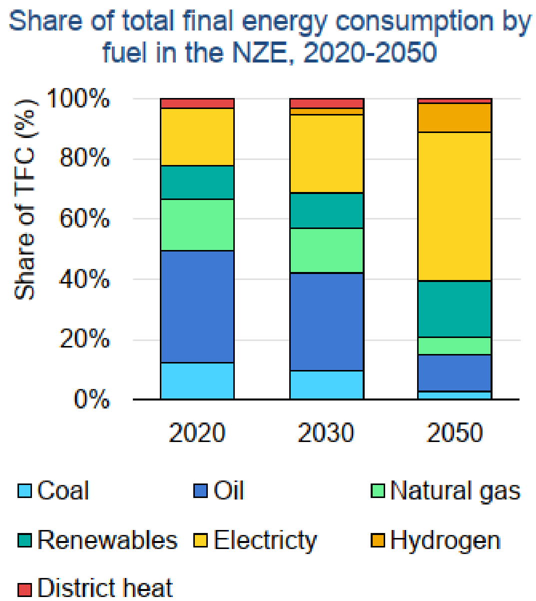

Figure 2.1 – Final energy consumption forecast (source: IEA)[4]

According to International Energy Agency (IEA) the future share of energy consumption will change greatly. Final electric energy consumption will increase greatly and also Hydrogen consumption will be much higher than Natural gas and will be comparable to Oil consumption,

The main question of this module is: What is the advantages of the usage of Hydrogen?

Before analyzing the development of a production system, a storage system and applications of hydrogen as fuel it is crucial to understand the advantages of Hydrogen compared to other energy storage systems.

There are essentially two types energy sources: renewables and non-renewables. Climate concern are pushing to reduce to usage of energy sources creating pollution, which are non-renewable and this fact will promote the usage of storage systems in particular fuel cells. In the following paragraphs it will be presented briefly the advantages of hydrogen as energy storage system.

3. Renewables and non-renewables energy

Electrical energy is so important in our life, in such a way that our lives totally depend on it. Electrical energy gives a faster life to everyone, i.e., fast manufacturing in industries, faster transport, and faster communication. It is more than a century that all population rely on non-renewables energy. Recently, due to climate change concern there is a phase out of many non-renewables' sources in many applications and this fact will push on renewables and hydrogen. Different methods have been developed for scavenging power from ambient energy sources. In harvesting energy for such applications, ambient energy is a reliable and low-cost energy source. There are different forms of energy, such as solar, wind,

[4] Hydrogen – Analysis - IEA

biomass and thermal, etc. The ambient vibrational energy is a reliable energy source for many applications in our life. In Figure 3.1, the following different renewable energy resources are shown: biomass, solar energy, and geothermal energy, hydro-power, and wind energies. These are the abundant forms of energy in our surroundings that are easily available and free of cost.

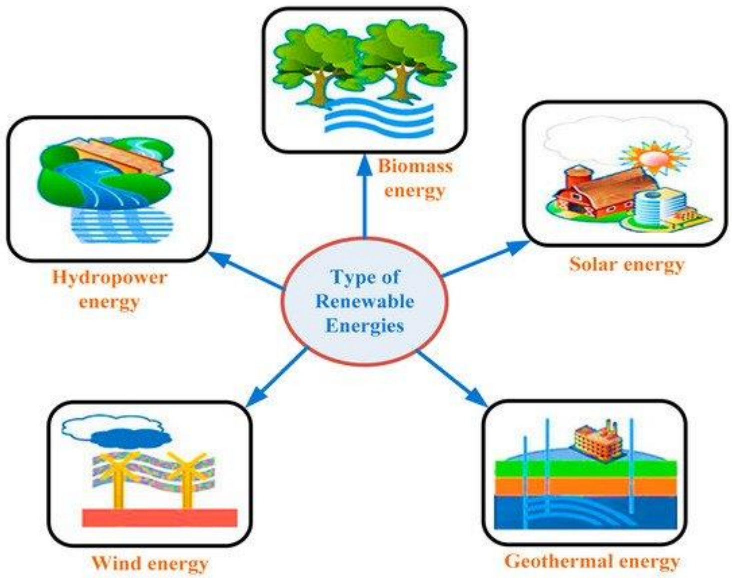

Figure 3.1 – Renewable energy resources.

First of all, examine the advantages and disadvantages of each source of energy.

Resource	**Advantages**	**Disadvantages**
Fossil fuels	provide a large amount of thermal energy per unit of mass	are nonrenewable
	are easy to get and transport	produce smog
	can be used to generate electricity and to make products such as plastic	release substances that can cause acid precipitation
		create a risk of oil spills /pollution
		cost influenced by political issue
Nuclear	is a very concentrated form of energy	produces radioactive waste
	does not produce air pollution	is nonrenewable
Solar	is an almost limitless source of energy	is expensive to use for large-scale energy production
	does not produce pollution	is practical only in sunny areas
Water	is renewable	requires dams, which disrupt a river's ecosystem
	does not produce pollution	is available only where there are rivers
Wind	is renewable	is practical only in windy areas
	is relatively inexpensive to generate	
	does not produce air pollution	

Geothermal	is an almost limitless source of energy	is practical only in areas near hot spots
	power plants require little land	produces wastewater, which can damage soil
Biomass	is renewable	requires large areas of farmland
	is inexpensive	produces smoke

Table 3-1 – Advantages and disadvantages of various energy sources

From the previous table it is clear that non renewables sources (blue), in particular fossil fuel are quite easy to be transported and converted into energy, as opposite a renewable energy (green) is directly converted into energy from the source and so they can be transported only as energy but they cannot be stored directly. They need some storage system.

4. Energy storage importance

Electricity storage offers alternative solutions to traditional methods of improving or enhancing network operation such as renewing or installing new cables, transformers or other equipment. Additionally, storage also has a significant impact on both ends of the network: on the generator side storage has the potential to improve the generator's efficiency and on the end-user side of the network, storage will improve power quality and reduce peak loads.

On the generation side, the peak load generation could be deferred or avoided if the utilization of existing mid-merit generation capacity is increased and integrated with an optimized energy storage system. The existing mid-merit capacity could be run at an increased load factor by storing the energy produced during off-peak periods. During peak periods, the energy can be discharged to meet peak demands. Taking advantage of the new contest of the free market of the electrical energy, in a distribution grid with energy storage systems, electrical energy can be generated and stored during a low load demand, at low cost rates, in order to be sold during a peak of the load demand, at a higher rate.

On the end-user side, the energy storage can be used to balance fluctuations in the supply and demand of electricity. Over short time periods (less than 1s) the requirement is essentially for the stability of the voltage frequency. Over longer time periods the requirements become those of energy management or provision of a contingency against an undesired event. Energy storage cannot replace generation completely, but it can complement other forms of generation whether on a large power system or in a stand-alone or non-grid connected application.

An energy storage device also has applications within the transmission and distribution network. Networks have been usually designed and built to be able to carry the expected peak loading, which may only happen for a very small part of its annual operating cycle. This results in considerable over-sizing of transmission and distribution equipment. Additional wires, transformers and other equipment are also needed to provide redundancy in the event of sudden loss of transmission capacity (such as a generator failure or an interruption to a transmission link). In this case the introduction of large energy storage can optimise and reduce the design and operational cost of the transmission and distribution network [5].

Electrical storage can achieve multiple benefits by combining applications resulting in increased returns on investment:

- Facilitates the active and reactive power flow control for distribution grid voltage regulation.
- Energy storage at power plants may provide start-up electricity required to start the electricity generation
- Energy storage may have special use in applications such as momentary carry over for short outages to high value industrial processes and/or plants, voltage support, power factor correction and other aspects of power quality.
- Energy storage facilitates the interconnection among different generation plants from renewable (solar, wind, fuel cells) and may make them more reliable and efficient.

For managing excess generated energy, there is a need for an efficient, reliable and low-cost storage system. This is one challenge, but delivering that energy to the consumers is another challenge. Storing and providing the excess energy to the consumers with less power loss, with a reduced cost, represent a number of challenges. Future technology in power engineering needs revolutionary changes. In order to reduce the cost and manage the energy demand, the world's interest has turned towards the alternate sources of energy, i.e., renewable energy. The main challenge of the renewable energy systems is their dependence on some factors, which are difficult to control; one of these factors is the climatic conditions.

The recent developments in electrical energy storage (EES) showed good results with the hybrid combination of various systems.

Energy storage devices should be located as close as possible to the end- user side of the electrical network. This is because the short distance minimizes the transmission losses and optimizes the energy storage capacity. In order to place a storage device close to the end consumer, the device would need to be matched for both power (kW or MW) and energy storage capacity (kWh or MWh) to the requirements of the consumer. The cost profile of storage devices varies according to the power and energy rating and a balance has to be achieved between the capital cost and operating benefits.

There is clearly a need for energy storage, specifically energy storage in a larger scale than in the past. Traditional energy storage methods, such as the electrochemical cell, are not necessarily applicable to larger scale systems, and their efficiency may be suboptimal. This report introduces some of the most common methods available or under development for storage systems and will be describe the benefit of using hydrogen as a storage mechanism.

Energy storage technology used in conjunction with stand-alone system or grid connected can be divided into two groups. The First group stores energy as electrical energy and the second group in some other form (e.g. electro-chemical storage, thermal storage, hydraulic storage, pressure storage, mechanical storage, electro-magnetic storage, electro-static storage etc.), which can be converted back into electrical energy when needed.

EES is divided into following types, according to their characteristics, as shown figure below.

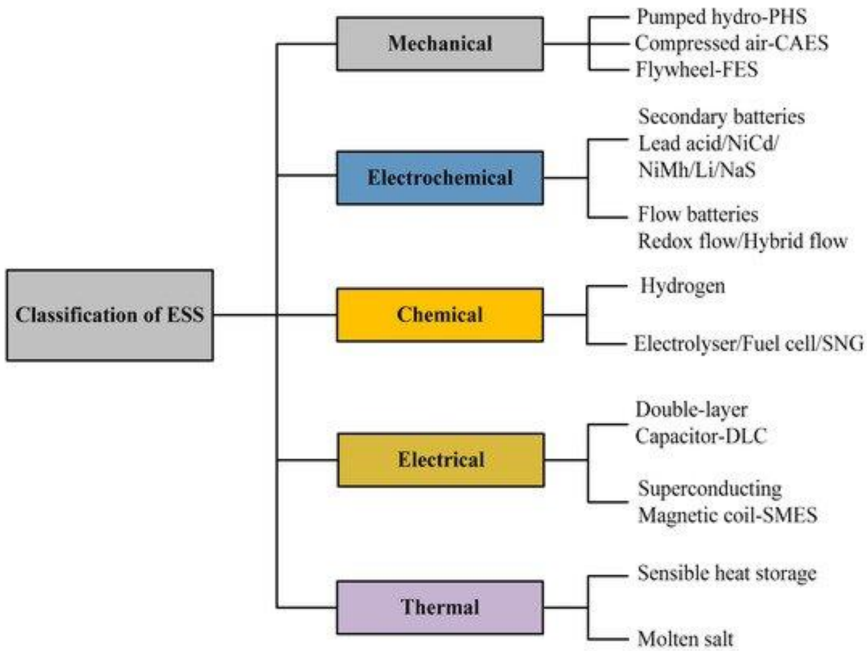

Figure 4.1 - Classification of energy storage systems.

Each ESS has a proper energy density. It is relevant to compare for each ESS the energy density. From the graph below Fuel cell batteries have the highest energy density compared to all other storage system and also with the new advancement in FC the highest power.

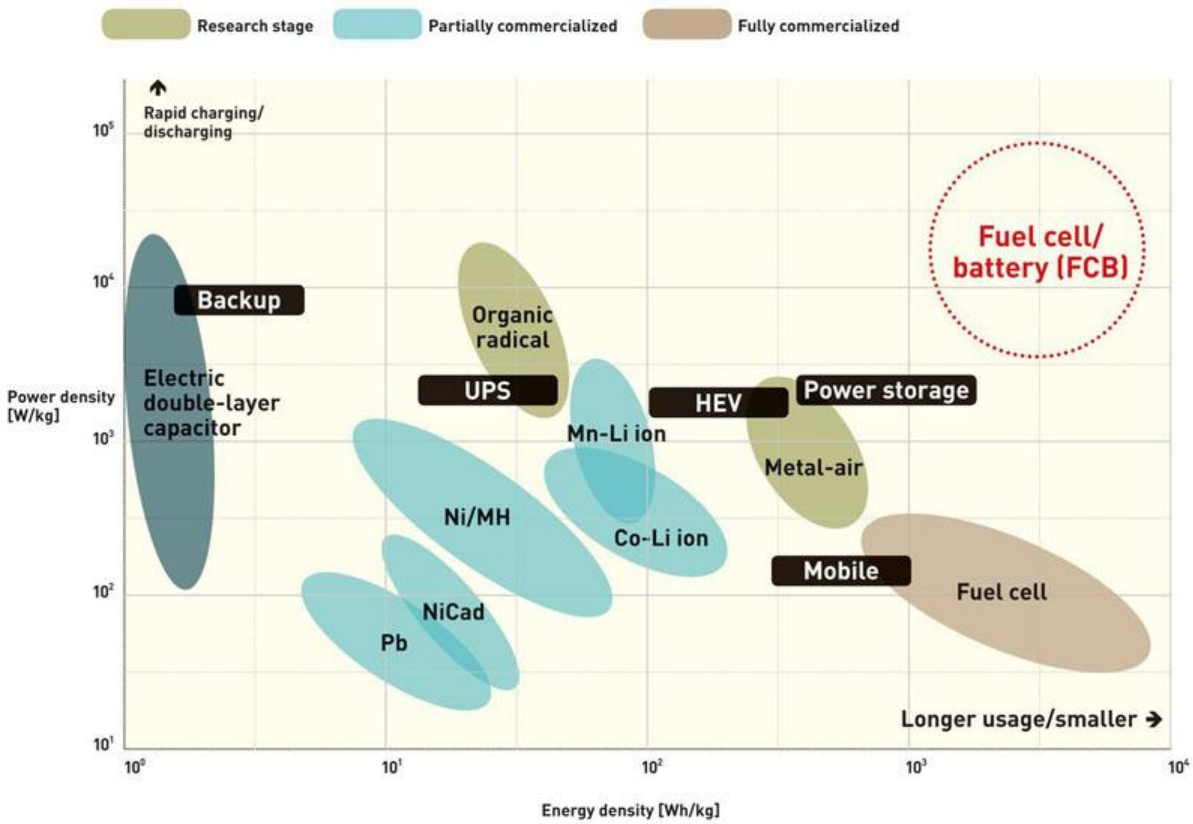

Figure 4.2 - The comparison of energy density and power density for different energy storage

It is possible to evaluate the energy content of fuel and battery per kg. Hydrogen will be the winner in the classification.

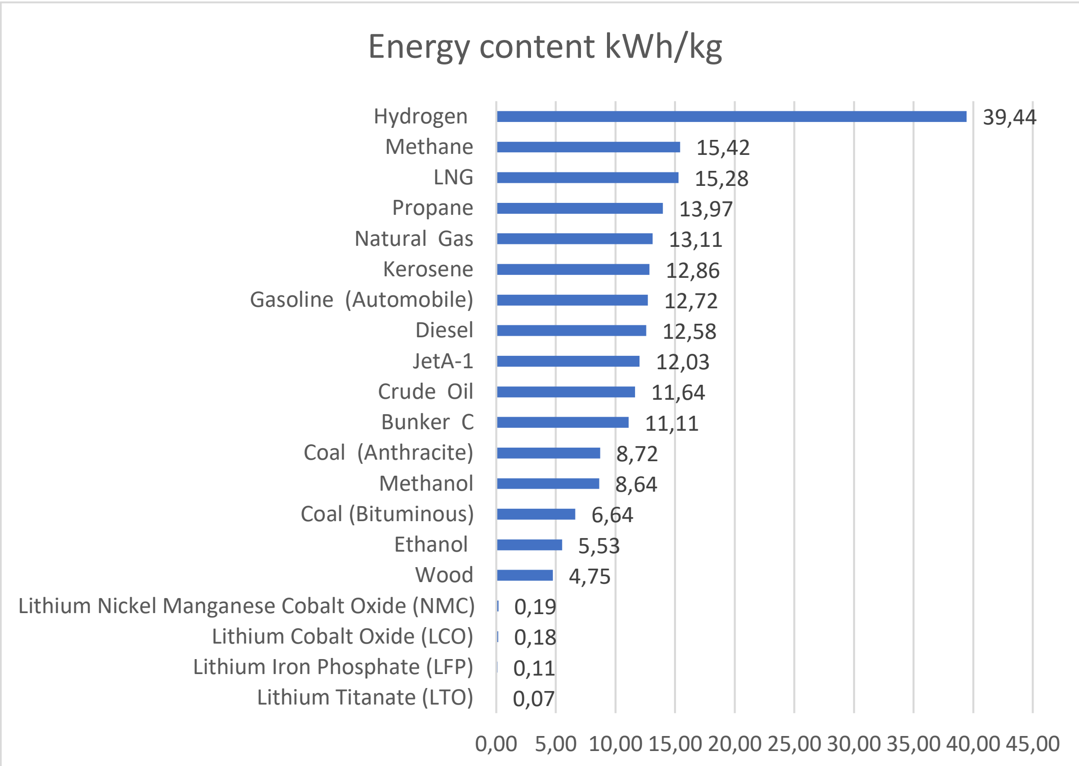

Figure 4.3 - Chemical Energy Content of some Fuels (in kWh/kg)

It is clearly evident that Fuel cell batteries are much lighter than lithium batteries and storing energy with lithium battery requires a much higher weight. The cost of lithium battery is at the present about 100 euro/kg depending on technology. The investment required will grow linearly on the size of kWh. On the contrary the investment on fuel cell is related with the max power of the system. There is also a limit on maximum charging times which is up to 2000 times depending on the battery.

4.1. Electrochemical Batteries

Electrochemical batteries produce electricity by causing a chemical reaction in the presence of an electrolyte, in such a way that releases ions, which then travel through electrolyte, creating a direct current flow at relatively low voltage. Usually, batteries are stacked to produce modules with higher voltages much like fuel cells. Batteries store energy by having electric flow crammed through them in the opposite direction, forcing ions in the other direction, and reversing the chemical transformation. An increasing number of chemistries are used for this process. More familiar ones include the following: Lead Acid Batteries, Nickel-metal hydride, Lithium, Sodium-Sulfur (NaS), Alkaline and Nickel Cadmium.

Battery Type	Energy Density (Wh/kg)	Cycle life	Advantages	Disadvantages
Lead acid	30-50	200-300	Low cost	Low energy density,low cucle life, long charging time
NiCd	45-80	1000	Lower cost than Li- ion	Low energy density and lower cycle life than Li-ion
NiMH	60-120	300-500	Lower memory effect than NiCd, more environmental friendly	Lower cycle life
NaS	110	>1000	Low cost	High working temperature (350°C)
Lithium-Ion LTO	50-80	3,000-7,000	Long life, fast charge	Low energy density, more expensive
Lithium-Ion LCO	150-200	500-1000	High specific energy	Expensive,volatile
Lithium-Ion NMC	150-220	1,000-2,000	High capacity and high power.	Safer than LCO but still relatively unstable and expensive
Lithium-Ion LFP	90-120	2,000 and higher	Medium-high energy density	Stable, long lasting and low energy density

Table 4-1 – Comparison of various batteries

An important consideration on Lithium-ion batteries is the dependence of the performance of the battery with the temperature. In particular the life of the battery is highly reduced at temperature higher than 40°C (up to 80% lower life) and the capacity is reduced below -10°C (half capacity). Due to the temperature relation, it is advisable to use this battery from 10°C to 30°C. During charging temperature will increase and hot weather condition will limit the maximum power for charging to limit the temperature below 50°C.

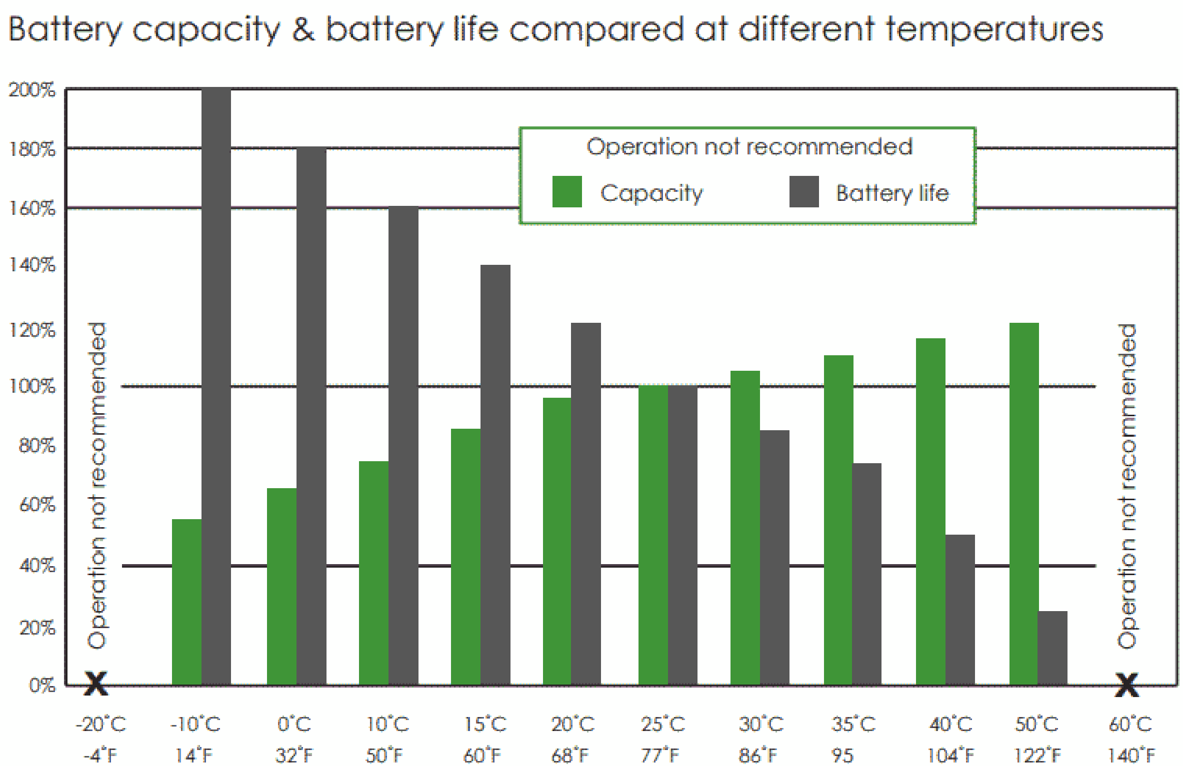

Figure 4.4 - Li-Ion battery capacity and life Vs. temperature

4.2. Super Capacitor Energy Storage

Supercapacitors also called ultracapacitors and electric double layer capacitors (EDLC) are capacitors with capacitance values greater than any other capacitor type available today (up to 400 Farads. Supercapacitors are not as volumetrically efficient and are more expensive than batteries but they do have other advantages over batteries making the preferred choice in applications requiring a large amount of energy storage to be stored and delivered in bursts repeatedly. They have the ability to be charged and discharged continuously without degrading like batteries do. This is why batteries and supercapacitors are used in conjunction with each other. The supercapacitors will supply power to the system when there are surges or energy bursts while the batteries can supply the bulk energy since they can store and deliver larger amount energy over a longer slower period of time.

4.3. Compressed Air Energy Storage

Compressed air energy storage (CAES) involves compressing air using inexpensive energy so that the compressed air may be used to generate electricity when the energy is worth more. To convert the stored energy into electric energy, the compressed air is released into a combustion turbine generator system. Typically, as the air is released, it is heated and then sent through the system’s turbine. As the turbine spins, it turns the generator to produce electricity. For larger CAES plants, compressed air is stored in underground geologic formations, such as salt formations, aquifers, and depleted natural gas fields. For smaller CAES plants, compressed air is stored in tanks or large on-site pipes such as those designed for high-pressure natural gas transmission.

4.4. Flywheel Energy Storage

Flywheel electric energy storage systems (flywheel storage or flywheels) include a cylinder with a shaft that can spin rapidly within a robust enclosure. A magnet levitates the cylinder, thus limiting friction-related losses and wear. The shaft is connected to a motor/generator. Electric energy is converted by the motor/generator to kinetic energy. That kinetic energy is stored by increasing the flywheel's rotational speed. The stored (kinetic) energy is converted back to electric energy via the motor/generator, slowing the flywheel's rotational speed.

4.5. Pumped Hydroelectric

Energy storage systems deploying hydraulic power are based on the concept of potential energy utilization. During off-peak period the electric power is used to pump the water to the reservoir on high hill or mountain. While during peak period, the water is released through a pipe downhill to a hydroelectric generator. Such storage is generally used for utility to meet the peak demand. The efficiency for one cycle is between 70- 85%. One of the major problems related to such storage is that it adversely affects the ecology due to building of reservoir.

4.6. Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) systems store energy in a super conducing magnetic coil immersed in a very cold liquid such as liquid helium, contained in a highly insulated thermal bottle. Super conducting magnetic coils have zero electrical resistance, so once electric current being circulated will not diminish over time. Power is stored in SMES by circulating DC electric current in the coil magnetically. It is withdrawn through reversal of the process. A typical SMES unit stores about 250 kWh of energy in a space of about a large refrigerator's size, weighting approximately 700 Pounds. The advantages of SMES are efficient, robust, very reliable and noiseless operation. It operates at microsecond speed with very good voltage regulation precision the only drawback are the expenditure involved for the cooling requirement, which is 20 times that of lead-acid batteries.

4.7. Solar Thermal Energy Storage

Solar thermal electric steam (STES) power plants store energy as molten salt or super-heated oil. Solar power is used to heat the salt or oil, put into large tanks, at temperatures between 600ºF - 1,100ºF. The heat from the salt or oil can be used when needed to turn the water into steam to run a steam turbine coupled with electric generator. A STES system is completely dispatchable. Most STES units store energy for about 20 hours at their rated output. They are efficient, robust, and relatively inexpensive.

4.8. Hydrogen Energy Storage

Hydrogen is not a primary energy source such as coal or gas but is an energy carrier and can store and deliver energy in a widely usable form. The unique characteristic of hydrogen is that it is the only carbon-free or zero-emission chemical energy carrier when produced from renewable sources. It is one of the most promising alternative fuels for future transport applications, stationary and portable electrical power generation. Hydrogen Energy Storage System (HESS) is one of the most promising energy storage techniques available. As an energy storage system, HESS acts as a bridge between all three major sectors of an energy system: the electricity, heat, cooling and transport sectors. It is the only energy storage system that allows this level of interaction between these sectors and hence it is becoming a very attractive option for integrating large quantities of intermittent renewable energy such as wind and solar.

There are three stages in HESS:

1. Create hydrogen
2. Store hydrogen
3. Use hydrogen (for required application)

There are three primary techniques to create hydrogen: extraction from fossil fuels, reacting steam with methane and electrolysis. Producing hydrogen from fossil fuels is four times more expensive than using the fuel itself, and reacting steam with methane produces pollutants, therefore electrolysis has become the most promising technique for hydrogen production in the future, especially when combined with renewable, thereby not associated with CO2 emissions. An electrolyser uses electrolysis to breakdown water into hydrogen and oxygen. The oxygen is dissipated into the atmosphere and the hydrogen is stored so it can be used for future generation. Due to the high cost of electricity, the most attractive option for hydrogen production is integrating electrolyser units with renewable resources such as wind or solar.

Figure 4.5 shows a typical diagram of Solar/Wind hydrogen system.

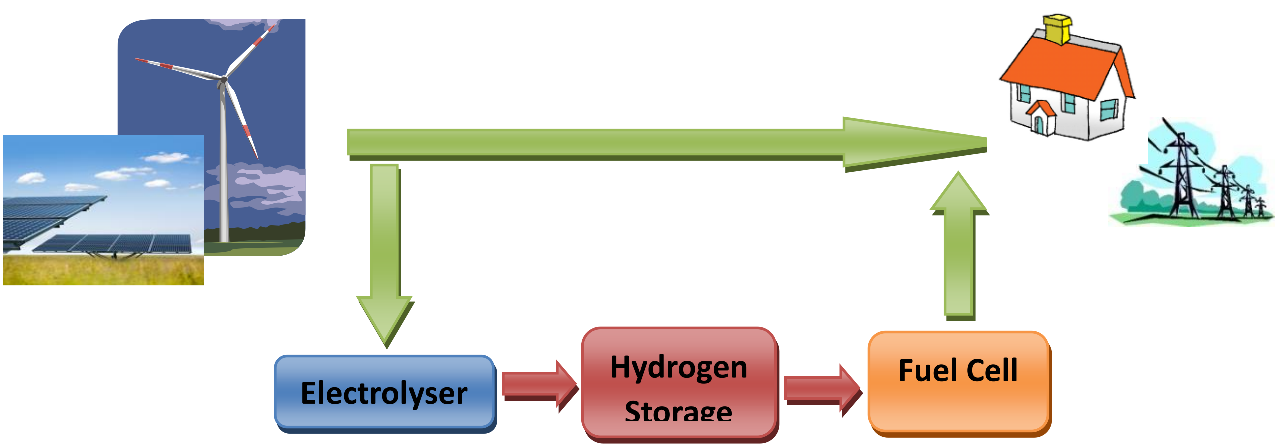

Figure 4.5 – Solar/Wind hydrogen energy system

There are different options currently available to store hydrogen: compression, liquefaction and metal hydrides. The hydrogen can be compressed into cylinders or pressure vessels and underground reservoirs. However, at present the most common form of hydrogen storage for the transport industry are high pressure cylinders, with approximately 700 bar pressure. Hydrogen can be liquefied by pressurising and cooling. Although the energy density is improved, this storage method requires a very high amount of energy to keep hydrogen at a low temperature below 20.27K. The energy required for this process is high and this reduces the energy efficiency of this method to about 25%. Metal hydrides absorb molecular hydrogen such as nanostructured carbons and clathrate hydrate. By absorbing the hydrogen in these materials, it can be easily transported and stored and once required, the hydrogen can be removed from the parent material. Metal hydride use thermal energy for the storing and release of hydrogen. The thermal heat could be obtained from the waste heat of other processes with HESS, such as the electrolyser or fuel cell, to improve overall efficiency.

The two most common means of using hydrogen are Internal Combustion Engine (ICE) and Fuel Cell (FC). It is expected that the ICE will act as a transition technology while fuel cells are improving, because the modifications required to convert an ICE to operate on hydrogen are not very significant. However, the FCs, are expected to be the generator of choice for future hydrogen powered energy applications due to their efficient, reliable characteristics and emission free electrical generation. Fuel cells, like all electrochemical cells, convert stored chemical energy directly into electrical energy. Often the source of the energy is a gaseous fuel, which is reacted with oxygen in the atmosphere to produce energy. This is the equivalent of burning the fuel. However, in a fuel cell the energy is directly converted to electricity resulting in an increase in its efficiency. Unlike fossil fuels, fuel cells do not produce any pollutants. Fuel cells are also more efficient mainly because the energy is directly converted to electricity resulting in less energy losses. The most favoured and common fuel used in these cells is hydrogen. The combustion of hydrogen in oxygen produces only water, which is not a pollutant, and in addition hydrogen has a very high energy density when compared with other fuels.

Due to the number of energy conversions required there is a reduction in the overall system efficiency, with the following processes, the corresponding efficiencies are:

1. Hydrogen created by electrolysis – 85% efficient,
2. Hydrogen that is stored – 65% to 70% efficient,
3. Hydrogen consumed in a fuel cell car, power plant, or CHP unit – efficiency of 40% to 90%.

This results in an overall efficiency ranging from 22% to 60%. Although Hydrogen storage method presents a low efficiency if compared with similar energy storage techniques the main advantage of using hydrogen as a storage mechanism is found in the numerous applications that can be used simultaneously. Hydrogen can be used as a fuel for portable power supply, fuel for vehicle transportation, it can be used for heating and cooling system, for hydrogenation and it can be used to produce ammonia and fertilizers, etc. None of the other energy storage systems can do this.

Hydrogen provides the connecting point between renewable electricity production and transportation, stationary and portable energy needs. When the electricity from solar photovoltaics, wind, geothermal, ocean and hydro technologies is used to produce and store hydrogen, the renewable source becomes more valuable and can meet a variety of needs. In transportation applications, hydrogen provides a means to convert renewable resources to fuel for vehicles. Renewably produced hydrogen for transportation fuel is one of the most popular hydrogen economy goals, as it can be domestically produced and is free of emissions. Figure 4.6 provides a picture of the PURE project in Unst, Shetland Island, a demonstration project that shows how wind power and hydrogen technology can be combined to provide the energy needs for a remote rural industrial estate. Hydrogen is produced when there is excess wind energy and used for several applications developed at the Pure Energy Centre, including hydrogen cars, hydrogen fuel cell and CHP as well as cooking and heating equipment.

Figure 4.6 – The PURE project in Unst: pictures of wind turbine, hydrogen production system, the H2car and H2 barbecue.

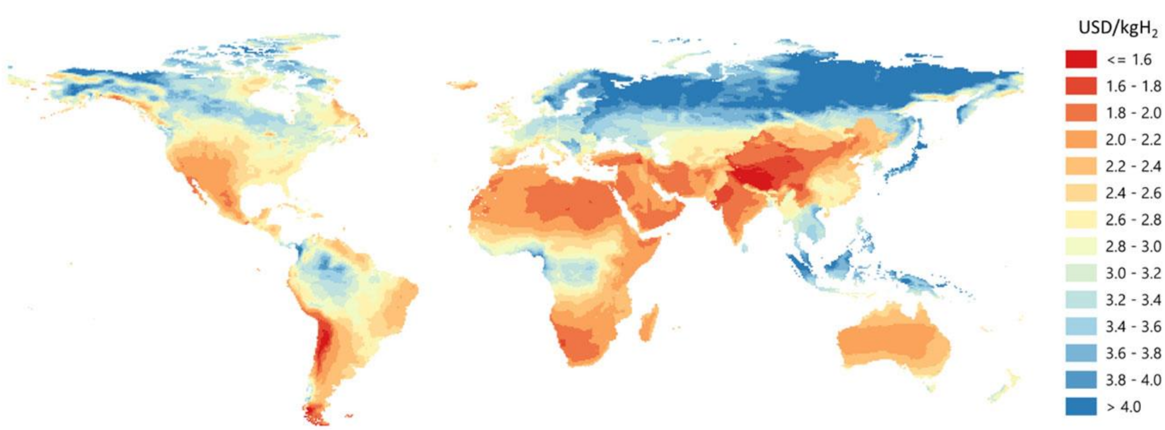

Figure 4.7 – Cost of the hydrogen by 2030 created with long term photovoltaic and wind energy (source IEA)

From the Figure 4.7, Hydrogen cost per kg by 2030 can be well below $4/kg in many areas of the world, so energy produced can be stored as hydrogen. A price of green Hydrogen below $4/kg will make fuel cell systems much more convenient than lithium battery and conventional internal combustion engines.

5. Hydrogen technology benefits and applications

The interest in the development of a wider hydrogen economy is supported by several benefits that this technology can provide. The driving forces can be grouped within the following areas:

5.1. Energy Security

The transportation sector relies almost exclusively on refined petroleum products. For many Nations, the reliance on imported fuels drives the need for an alternative fuel that can be domestically produced. Hydrogen (along with biofuels) is a versatile energy carrier that is environmentally clean and could be produced in large quantities entirely from domestic sources.

5.2. Environmental

Whilst addressing the energy security issue, we must also address our environmental viability and reduce our CO_2 emissions. Widespread use of fuel cell vehicles and electrical generators, because they are zero-emission and have no emission deterioration, could have a measurable effect on reducing nitrogen oxides, volatile organic compounds, and particulate matter produced by light-duty vehicles.

5.3. Economic competitiveness

Abundant, reliable, and affordable energy is an essential component in a healthy economy. The energy prices spike, that has occurred several times recently due to supply interruptions and/or high demand, creates economic instability. Hydrogen offers unique opportunities to drastically increase the efficiency with which we generate and use energy. As it can be produced from a wide variety of domestically-available resources, we can reduce the impact of energy prices. Moreover, Hydrogen power parks could provide an economic development path for the integrated production of energy services such as electricity, transportation fuels, heating and cooling. This may lead to the creation of high-tech jobs to build and maintain these systems. Hydrogen also offers a wide variety of opportunities for the development of new centers of economic growth in both rural and urban areas that are currently too far off-line to attract investment in our centralized energy system.

By 2050, according to IEA Hydrogen will come mainly from electricity as green Hydrogen. Hydrogen consumption will be 5 more times the 2020 consumption.

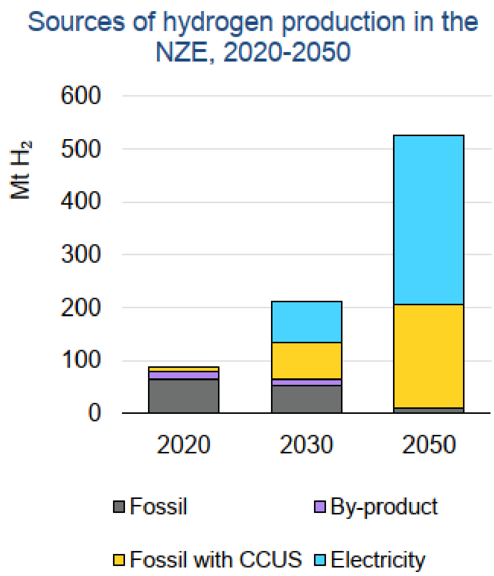

Figure 5.1 – Cost of the hydrogen by 2030 created with long term photovoltaic and wind energy (source IEA)

5.4. Hydrogen applications

Hydrogen properties make it a very useful substance for a wide range of applications. Hydrogen has been used safely in industry for many decades in the manufacturing processes of many common household products, for example: glass, margarine, soap, and even toothpaste. In the emerging hydrogen energy market hydrogen is used as clean fuel for fuel cell vehicles and appliances, or internal combustion engines that have been modified to operate on hydrogen.

The most common uses for industry application are:

- **Ammonia production:** the production of ammonia uses nitrogen from the air, which is reacted with the hydrogen to produce ammonia in the Haber process. Ammonia itself is then primarily used in fertiliser manufacture, but also in industrial refrigeration and the manufacture of a variety of industrial chemicals

- **Oil refineries:** hydrogen is used for upgrading the more viscous oil fractions to produce products such as gasoline and diesel and for removing contaminants such as Sulphur.

- **Metallurgy Industry:** Hydrogen is mixed with inert gases to obtain a reducing atmosphere, which is required for many applications in the metallurgical industry, such as heat-treating steel and welding. It is often used in annealing stainless steel alloys, magnetic steel alloys, sintering and copper brazing.

- **Chemicals**: Hydrogen is used as a raw material in the chemical synthesis of hydrogen peroxide, polymers, and solvents.

- **Purification**: hydrogen is used to purify gases (e.g. argon) that contain trace amounts of oxygen, using catalytic combination of the oxygen and hydrogen followed by removal of the resulting water.

- **Pharmaceuticals**: The pharmaceutical industry uses hydrogen to manufacture vitamins and other pharmaceutical products.

- **Glass and Ceramics:** In float glass manufacturing, hydrogen is required to prevent oxidation of the large tin bath.

- **Food and Beverages:** It is used to hydrogenate unsaturated fatty acids in animal and vegetable oils, producing solid fats for margarine and other food products.

- **Electronics**: Hydrogen is used as a carrier gas for such active trace elements as arsine and phosphine, in the manufacture of semi-conducting layers in integrated circuits.

- **Miscellaneous**: Generators in large power plants are often cooled with hydrogen, since the gas processes high thermal conductivity and offers low friction resistance.

The most common applications as fuel are:

- **Stationary application**. Hydrogen is used as fuel to power fuel cell for the generation of electricity for residential and commercial needs or stand-by generators. The by-product, heat, can be recovered and used primarily for a heating and cooling system. The overall efficiency of the system can reach comparatively higher values (typical 90%) if compared to a system producing electricity alone.

- **Telecommunications:** among the stationary applications, hydrogen is used within a fuel cell for next-generation telecom UPS or continuous power. With an ever-increasing telecom network hydrogen fuel cells are becoming a real alternative to standard battery back-up systems, especially in areas where the electrical grid is unreliable.

- **Portable application:** In addition to large-scale power production, miniature hydrogen fuel cells could replace batteries that power consumer electronic products such as cellular telephones, portable computers, and video cameras.

- **Transportation:** All the world leading car manufacturers have designed at least one prototype vehicle using hydrogen as alternative fuel for motive power. The motion power for such vehicles is obtained with conversion of the chemical energy of hydrogen to mechanical energy either by burning hydrogen in an internal combustion engine, or by reacting hydrogen with oxygen in a fuel cell. The typical applications are cars, buses, forklifts, tractors, and scooters.

5.5. On Field Hydrogen energy system Applications

The integration of renewable technologies with energy storage systems based upon converting electricity to hydrogen gas and back represents the answer to the problem of intermittency within stand-alone renewable-energy systems. It also provides an alternative energy power system, free of carbon emissions and relies on domestic sources. Numerous hydrogen energy systems have been installed all around the World and have proved the benefit of this technology in real life applications. This paper will therefore describe two projects that use H2 technology to store the excess energy produced by renewables: H2Office and H2SEED and will present the real-life learnings from these projects including real life field data. These examples show not only the practical use of hydrogen but also demonstrate how hydrogen fuel can be safely produced and stored in a renewable, environmentally friendly manner.

5.5.1.The H2OFFICE project

The Hydrogen Office project was set up to support the accelerated development of the renewable, hydrogen, fuel cell and energy storage industries in Scotland. Based in Fife, on the east coast of Scotland, the project is an hour's drive north of Edinburgh. The project represents the next generation of energy technologies and is seeking to develop a cluster of renewable, energy storage and fuel cell activities which will see the area lead the transition from the old carbon-based fuels of the past, to the new low or zero carbon based fuels of the future. The Hydrogen Office energy system includes a 750kW wind turbine, 30kw electrolyser, 10kW hydrogen fuel fell and a geothermal source heat pump. Fig. 4.2 shows a layout of the power system and a picture of the hydrogen storage system.

The 750KW wind turbine manufactured by Global Wind Power is based on proven technology which has been operating in Europe for over ten years. The turbine has on average generated in excess of 4,000KWh of electricity per day, equivalent to the annual consumption of a typical four-bedroom home. During windy periods the wind turbine will also export electricity to the national grid. The electricity generated from the turbine directly provides for the electrical needs of the Hydrogen Office and surplus electricity is also used to generate hydrogen through the process of electrolysis.

The electrolyser provided by Pure Energy Centre® is based on latest advanced technology available on the market that makes it particularly suitable for intermittent electricity sources such as renewable energies. The production capacity is $5Nm^3/h$ and the hydrogen generated is stored for periods where there is insufficient energy from the wind to meet the demands of the Hydrogen Office Demonstration Centre. During calm periods the hydrogen fuel cell provides the electricity for the Demonstration Centre in a process whose only by-products are heat and water.

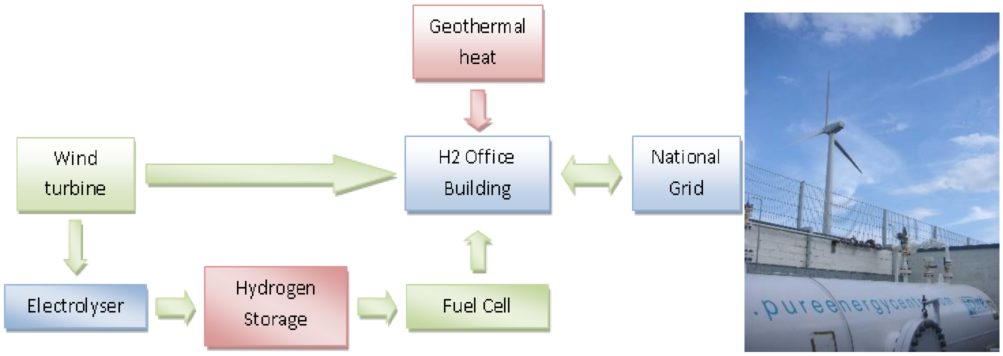

Figure 5.2 – The Hydrogen Office energy system layout

A Geothermal Source Heat Pump utilizes heat below the surface of the earth, using four boreholes 100m deep. The system concentrates heat extracted from the ground and supplies this to the building in a highly efficient manner.

A real time Control and Monitoring system ensures the highest operational safety and acquires instant data available for the evaluation of the system performance and educational purpose [15]. It offers an HMI with direct visualization of the most important operational and safety parameters of the Electrolysis process, the renewable energy production and fuel cell operational status. Table 1 present a summary of the system performance of the first 2000 hours.

Wind Turbine	Grid Energy exported 400MWh
Electrolyser	Hydrogen produced 1200Nm3
Fuel cell	Electrical production 466kWh
CO2 offset	2,002 kg

Table 5-1 – H2OFFICE Site Statistics

The realization of this innovative hydrogen energy system has proved the ability to store intermittent renewable energy while available, for use when it is not available. This is one of the greatest challenges impacting on the transition to a low carbon future and requires a stepped change in the policy support offered to the development and uptake of these technologies. Communities in particular stand to benefit most from these technologies and as such are being encouraged to champion and push for policy changes that support the accelerated development of these technologies.

5.5.2.The H2SEED project

The H2SEED is a pioneering demonstration project for hydrogen technology in Outer Hebrides, Scotland. It was the first project delivered in the Outer Hebrides covering the whole value chain of hydrogen technologies: hydrogen production, hydrogen storage, hydrogen filling station and hydrogen use in both stationery and transport applications. The Comhairle H2SEED Facility produces renewable hydrogen by water electrolysis using excess power available from the bio-gas combined heat and power unit at the Comhairle Integrated Waste Management Facility, the bio-gas is produced by anaerobic digestion of the organic matter contained in municipal waste. The hydrogen is compressed and stored in readiness for dispensing. Fig. 4 shows a layout of the H2SEED hydrogen system.

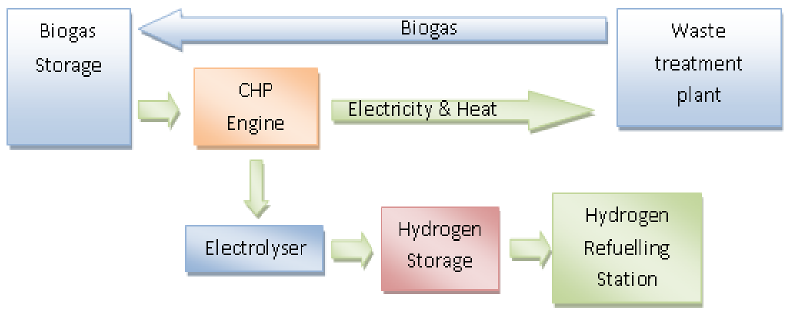

Figure 5.3 – The H2SEED hydrogen system layout

At present, the annual biogas production from the Comhairle Waste Management Plant accounts for more than 1 million Nm^3/year, with a methane content around 60%. This biogas is used to feed an engine producing electricity and heat. With the present biogas production, the engine could operate for 8 hours per day from Monday to Friday at a partial load close to 80% providing the 100% of the Waste Plant electric requirements and 40% excess. The heat produced by the engine is also used for heating requirements of the plant, accounting for around 30% of total heating needs. The excess of electric energy generated accounts to around 700 kWh per day.

The electrolyser is provided by Pure Energy Centre® and is based on the robust and established alkaline process, designed for optimal operation with a renewable electrical energy supply and a production capacity of 5Nm3/h. The electrolyser absorbs part of the Biogas engine energy surplus by producing hydrogen.

The H2 produced is stored in a compressed tank, with a storage capacity around 35 kg of hydrogen, allowing the storage of one week of hydrogen production. Two applications have been selected for the use of the H2: a fleet of H2 vehicles and stand-alone applications using k-type pressurized cylinders. The vehicles proposed to be used are two converted Ford transit vans, working with H2ICE engines. During the trial period Stornoway Royal Mail office used the converted Ford Transit on regular delivery routes between June and August 2010. The H2seed Facility performed 24 successful refueling operations supplying a total of 71 kg of hydrogen as the vehicle clocked up 723 miles operation using hydrogen.

A real time Control system ensures the operational of the system in accordance with the highest safety and optimization of the energy flow process. The acquired data are available for the evaluation of the system performance and educational purpose. Table 4-2 presents a summary of the system performance of the first 3000 hours.

Biogas CHP	Average daily energy produced 1.3MWh
Electrolyser	Hydrogen produced 1690 Nm3
Refuelling	Hydrogen refuelled 84.7kg
Green distance	723 miles with hydrogen fuel

Table 5-2 – H2SEED Site Statistics

The development of this project has provided several benefits and has proved the optimal concept operation of the system and the integration of a renewable intermittent source with hydrogen technologies for the production of fuel for automotive application. This project has produced many benefits including:

- An improvement of the performance and operating conditions of the biogas engine currently installed in the Comhairle Waste Treatment Plant.
- The production of a new, renewable, local and clean fuel (hydrogen) to be used in vehicles, therefore substituting oil, which is not renewable, not autochthonous and pollutant.
- The creation of a basic hydrogen infrastructure in the Outer Hebrides Island that could grow in the near future with other renewable energy sources, such as wind energy.
- Public awareness, especially the high visibility of the hydrogen public vehicle fleet.
- Human resources training and knowledge transfer on new technologies & development of new knowledge in the Island
- Creation of an attractive (innovative, environmentally friendly, dynamic) image of the Island that could be beneficial in terms of tourism, attraction of industry / investments, etc.

Figure 5.4 – Panoramic view of the H2SEED project.

5.6. Benchmark of various cars

At present time it appears that future means of transport will mostly use Lithium ion batteries. Considering energy density of a lithium battery and cycle life, total capacity life is around 400 kWh/kg, considering an average consumption of 0,25 kWh/km it equal to say that 1 kg of battery can move a car for about 1600 km in average conditions. For this reason, lithium-ion batteries have to weight even more than 400 kg. In many cases replacing batteries will be a relevant cost. For example, the battery weight of a tesla model 3 75 kwh is 479 kg. Total life capacity is 108 MWh. Considering an average consumption of 0,25 kWh/km, battery life can be theoretically more than 400.000 km. Unfortunately, life is dependent on many factors like the way of charging the battery, temperature, usage of the car. So the real life is much lower and for example Tesla guarantee up to 190.000 km the life of the battery. Fuel cell lifetime can be more than 4 years of continuous use which will be much more than the one with Lithium battery for a fraction of weight. In case of use of stationary application with high energy it is clearly better to use Fuel cells

It is interesting to compare Fuel cell vs lithium battery and standard diesel car.

		Tesla model 3	Toyota Mirai	BMW serie 3
Initial cost	(€)	58.479	66.000	45.500
Capacity	(kWh)	75		
	(kg)		5,6	
	(l)			59
Cost per km	(€/kWh)	0,79		
	(€/kg)		10,00	
	(€/l)			2,00
Contained energy (kWh)		87	220	590
Price to fully charge (from 0% to 100%)	(€)	59,25	56,00	118,00
Range	(km)	349	1360	1054
Effective consumption	(kWh/km)	0,25	0,16	0,56
Unit cost	(€/km)	0,17	0,04	0,11

Table 5-3 – Comparison of various propulsion systems

It is interesting to notice the row of contained energy, representing total potential or used energy to fully charge the vehicle. Clearly more is the contained energy value at parity of km, less is the efficiency of the vehicle. In this way a standard ICE[5] car is the least efficient, even though at current price for normal usage it is the cheapest to use.

[5] Internal Combustion Engine

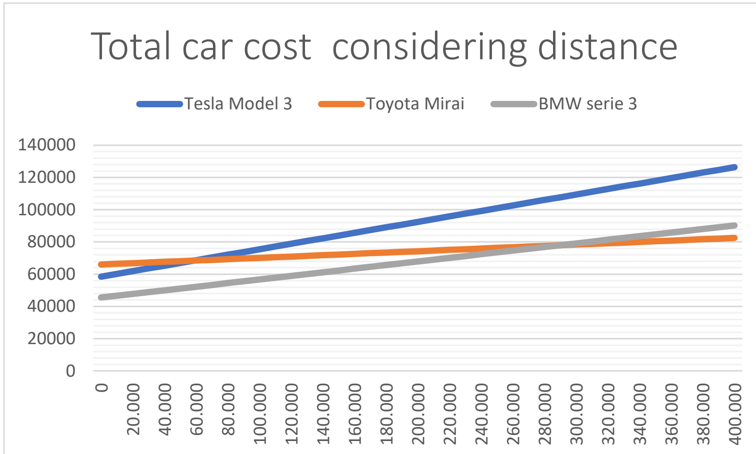

Figure 5.5 - Total cost comparison

The hydrogen production is not that efficient like recharging a Lithium-ion battery, but there is a big advantage on Fuel Cells. They do not require high power at the time of recharging like supercharges. Hydrogen can be produced with photovoltaic panels or wind turbine. The size of the production of photovoltaic panel can match average H2 requirements or use the electricity from the grid during lower price time and distribute it to the user. The cost of green Hydrogen can be even lower than the present 10€/kg even to 1 €/kg according to IEA by 2030 and this fact will make Fuel Cells much more convenient. It is also possible that increasing production of Fuel Cells vehicles, the price will be much lower, even the same as standard Internal Combustion Vehicles (ICV). Fuel cell transport has also the advantage of reducing lead time between charging, which is a big problem for lithium battery. A lithium-ion battery charging has a minimum of 30 min to a maximum of more than 8 hours. In that time, it is not possible to use the vehicle. By opposite a Fuel cell vehicle is filled in few minutes which make it similar to conventional ICE.

It is essential to increase the number of refuelling stations to increase the number of vehicles. The price of Hydrogen and the fuel price will become much cheaper with diffusion and there will be illimited power available thanks to the usage of renewable energies. All this consideration made for standard car can be done for any means of transport. It is possible to convert them to use Fuel Cells and this will reduce the price of green Hydrogen.

6. Conclusions

The advantages of hydrogen as energy storage system have been identified. A lot of research is ongoing to improve efficiency of the system. It is a big challenge since the new agenda of climate change is imposing to phase out all non-renewable fuels, which intrinsically are storing energy, for this reason it is essential to use renewable energy which require a storing system and it is ongoing a competition between fuel cell energy storage and lithium batteries. Apparently, the higher efficiency of lithium batteries tends to push on this system for all future applications, but as this module showed, fuel cells can compete with lithium batteries and at the moment the main difficulty is the limited diffusion of refueling station and limited means of transport. With increasing diffusion of hydrogen system all cost will be much lower and for sure there is a bright future for Hydrogen in fuel cells.