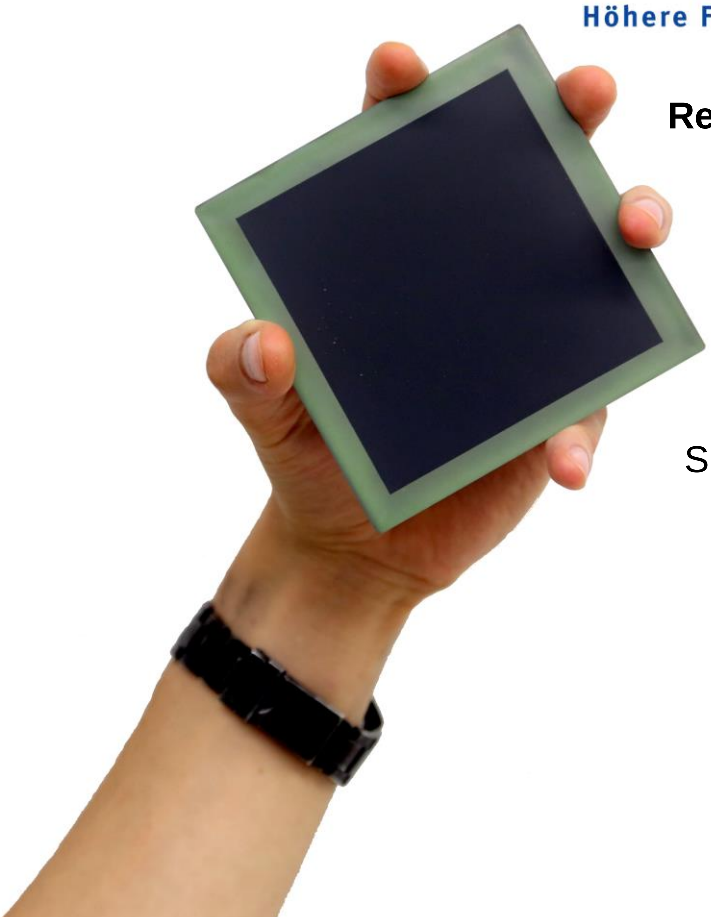
Fuel Cells:

A Feasible Regenerative Energy Technology



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Renewable Energies

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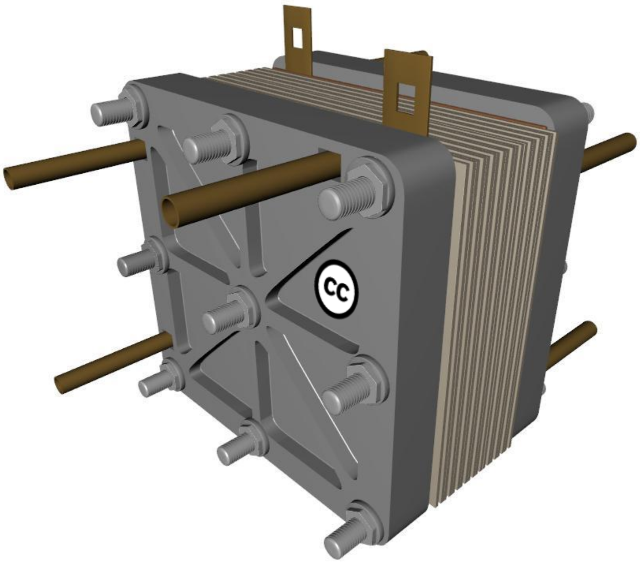
Signed: Kartik Isaac   Dated: 05.05.2015

Acknowledgements

I would like to express my sincere gratitude to Mr. Alex Fuchs who was my supervisor and provided me with guidance throughout the duration of the project. Many thanks to Mr. Mario Pagliaro, author of "Solar Hydrogen: Fuel of the Future" and founder of Sicily's Solar Pole for his role as external reviewer and for providing his valuable insights on solar hydrogen. Thanks to Mr. Ottorino Veneri, co-author of "Hydrogen Fuel Cells for Road Vehicles" for providing his valuable feedback on the auxiliary requirements of fuel cells. Acknowledgement also goes to Wyndham for his support in proof-reading and for his interesting feedback regarding hydro power. Last but not least I would like to thank my beloved partner Kira for her inspiration, constant support and valuable assistance.



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1. Abstract

Renewable energy systems are becoming an increasingly popular solution for grid integrated, as well as for off-grid solutions around the world. However, the autonomy permitted by such systems is often limited by the necessity for fossil fuels for backup generators and for transportation. The implementation of hydrogen fuel cells (FCs) in combination with a feasible hydrogen storage system could in many cases, enable the final leap towards a fully autonomous solution. Furthermore, if the energy used for hydrogen production through electrolysis is produced by regenerative sources, this type of system offers a 100% clean, reliable and attractive solution. Another added benefit of a hydrogen system is that it greatly minimizes strain on the grid and can balance out the supply and demand imbalance problem by the nature of its functionality. Excess energy production on sunny and windy days can easily be stored indefinitely and with relatively good efficiency for use in times of low energy production, either for direct power generation or for other applications such as power to gas. Fuel cell technology is rapidly improving in performance and efficiency and due to its numerous benefits it will inevitably make a breakthrough in the near future.

The focus of my research was concentrated on the most promising hydrogen fuel cell technologies available today. All the data gathered was thoroughly assessed and the most valuable information was condensed into this technical paper. The research methods used were largely online inquiries through credible internet sources, as well as numerous undocumented discussions, viewing of documentaries and blogs by fuel cell enthusiasts.

The findings of this research, as well as the documentation process was very rewarding to me personally, and has proved to be a very steep learning curve in the field of hydrogen technologies. Some of the more in-depth information had to be abridged in the interest of maintaining a broad overview of fuel cells, while remaining inside the volume prerequisites. However, if circumstances allow, I will provide a more comprehensive insight on a particular hybrid fuel cell system in my thesis work.

The biggest challenge of this documentation was researching and evaluating the conflicting and partially biased data available on the fuel cell technologies as a viable alternative to the conventional power supply systems in use today. This is due to the fact that it is still a small niche market, and is kept at bay by Big Oil and nuclear lobbyists and other profit-driven corporations that have no interest in seeing this kind of technology bloom. However, for people with a sense of responsibility and a healthy curiosity, there is plenty of useful information out there. And I would recommend that you do your own further research and look into fuel cells as a viable energy solution with huge potential in the near future. When it comes to hydrogen- the most abundant element in the universe, the possibilities are truly endless. Here’s one; you can build your own affordable, clean and regenerative “refinery” in your backyard. Sounds like a far-fetched tall story? Actually, hybrid solar-hydrogen systems already exist for private off-grid homes, and offer a truly independent source of secure energy. And with a little push in the right direction, this kind of technology could become the primary source of energy for decentralized smart-grids in the coming decades.

2. Glossary of terms

AFC	Alkaline fuel cell
A_I	Inherent Availability
APU	Auxiliary power unit
BPD	Barrels per day (158.9873 litres of crude oil per day)
CH_4	Methane - a chemical compound, main component of natural gas
CH_3OH	Chemical formula for methanol, aka methyl alcohol or wood alcohol
CHP	Combined heat and power
CO_2	Carbon dioxide - a naturally occurring chemical compound
CAPEX	Capital expenditure
DC	Direct current
DMFC	Direct methanol fuel cell
FC	Fuel cell
FCV	Fuel cell vehicle
GPU	Ground power unit (aviation)
H	Hydrogen - chemical element with symbol H and atomic number 1
H_2	The chemical formula for hydrogen gas
H_2O	Water - chemical substance
ICE	Internal combustion engine
LED	Light emitting diode
MCFC	Molten carbonate fuel cell
O	Oxygen - chemical element with symbol O and atomic number 8
O_2	The chemical formula for oxygen gas
O_3	Ozone - an inorganic molecule
OPEX	Operating expense
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
POC	Proof of concept
Pt	Symbol for platinum - a chemical element with atomic number 78
Ru	Symbol for ruthenium - a chemical element with atomic number 44
SOFC	Solid oxide fuel cell
WBS	Work breakdown structure

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Figure 2 *– A 132 kW automotive Fuel Cell from Nuvera*

3. Introduction

It is common knowledge that our planet is facing huge environmental problems and that our present course is unsustainable and irresponsible. Our ever-growing demand for energy is probably the main catalyst in the global warming issue as well as the pretext for the devastation and abuse of earth's fragile eco systems.

Our addiction to fossil fuels, like any destructive habit, brings with it a slew of negative side effects. Recent conservative studies show that we have already reached peak oil, and are now heading on a downward spiral that is leading to an energy crisis and causing widespread damage of our planet.

Many innovative methods of harvesting and storing nature's abundant and clean energy sources in a sustainable way already exist today. But there is no one-size-fits-all, clear-cut solution to the energy problem. The technology is out there, and it's just a question of using and combining this technology in the right way and in the right places.

Fuel cells are a very feasible part of the solution in the search for alternative energies in the present energy crisis. There is unfortunately, however, little interest to make the information in this field available to the general public. My goal, hopefully, is to contribute to the further research and development of the fuel cell technologies, and thereby aid in making it a convincing and attractive solution in the near future.

My previous knowledge of fuel cell and hydrogen technology was somewhat limited to watching educational documentaries and reading technical papers. It is a very interesting technology with great potential, and I am grateful for this opportunity to acquire a deeper knowledge in the process of writing this paper.

The first section of this paper looks at our present energy crisis and highlights sustainable solutions with the use of two best-practice alternative energy sources i.e. solar and wind power. The section covering the different types of fuel cells, including their history and functionality is briefly described. The two fuel cells (polymer electrolyte membrane fuel cells – PEMFCs and direct methanol fuel cells – DMFCs) with arguably the biggest potential are described in detail. Together with the fuel cell types, the storage and the supply challenges of hydrogen gas make up the main focus of this paper and are described in detail. The final section explores the engineering benefits of fuel cells, and examines how they compare against other power generation technologies. The obstacles that researchers face in the development of practical and affordable fuel cells for everyday use are discussed and a recommended system configuration is presented.

3.1. Motivation

One rarely hears about fuel cells and their numerous applications for a low carbon society, and when one does, it is often tainted with misaligned safety-hazard concerns and copious scepticism.

On the one hand, I felt the need to better educate myself on this subject, and on the other, to make this information available to the public in an easily understandable and freely available way. I promote the freedom to use, study, copy, modify, and redistribute this documentation (with respect for the materials created by others) and am an avid supporter of open source and copyleft works and licenses. I am henceforth releasing this pre-thesis under the Creative Commons Attribution-ShareAlike 3.0 International License.

3.2. Project outline

All technical information has been found through the Internet, as well as print copies at the ETH Grüne Bibliothek. All respective sources have been explicitly listed the 13. References section.

I have purchased a hydrogen powered model car for demonstration and learning purposes. The model will also serve as a proof of concept in my presentation of this pre-thesis, demonstrating the basic principles of a completely clean hydrogen system for automotive application.

3.2.1 Target/actual performance comparison

The brainstorming and project planning did not require much time, as I already had some ideas and a rather clear picture of what I wanted to achieve. Given the fact that this is a topic that fascinates me, has made the entire process more creative and very rewarding. I've therefore been able to do much of the research and writing of this draft with relative ease. The initiation, planning, execution, the control and closeout phases, and all the milestones I had set, were all achieved in ample time (Figure 4).

3.2.2 Lessons learned

As is often the case with a pending project, I was a little overwhelmed with the sheer volume of work awaiting me. But breaking the project down into smaller, more manageable work packets made it a lot easier (Figure 3). As I do not like to keep work open till the last moment I remained consequent with my initial planning and was able to achieve all my goals without stress. The experience has reinforced my self-confidence in my own time management skills and has convinced me that even larger projects can be successfully completed, provided the planning phase is carried out earnestly – and the individual tasks have been well defined.

3.2.3 Work breakdown structure (WBS)

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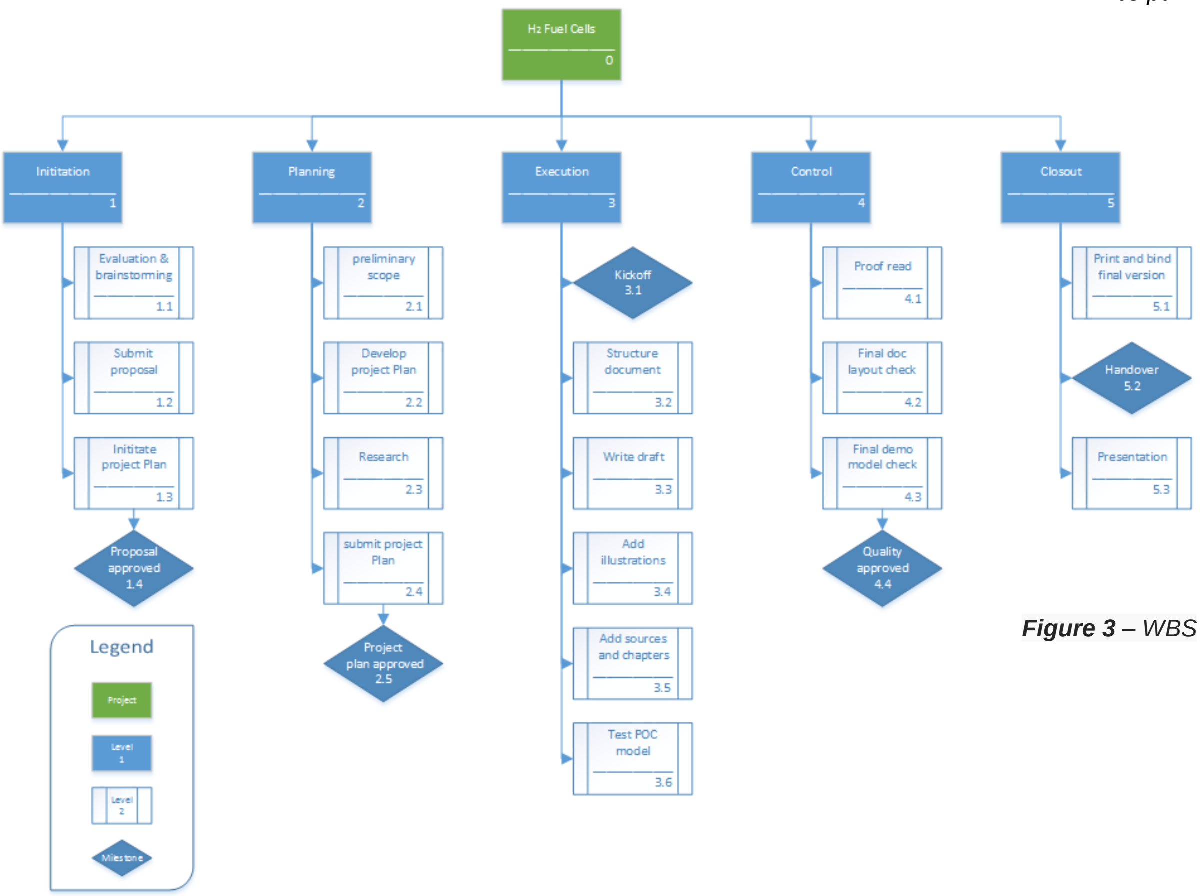


***Figure 3** – WBS*

3.2.4. Project plan

pp.pdf [3]

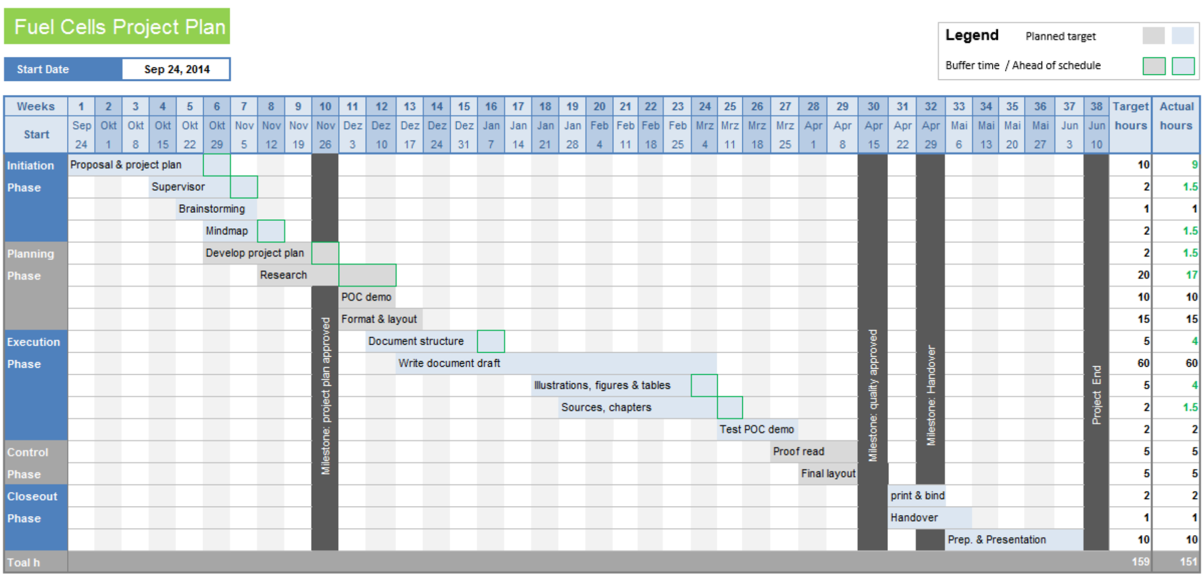


***Figure 4** – Project Plan*

[2] https://drive.google.com/file/d/0BxLJh12BbrzAeFJLT2NYTG01Unc/view?usp=sharing
[3] https://drive.google.com/file/d/0BxLJh12BbrzAUFczS1ViZE5UUVE/view?usp=sharing

4. Our energy crisis

4.1 Fossil fuels

Most people take it for granted that we have access to energy produced with fossil fuels, while the more concerned people are worried about the finite amount of remaining fuels to exploit. These fossil fuels (oil, gas and coal) have existed long before we came to live on this planet - we only began using them as a source of energy at the end of the 19th century.

It is during the past eight decades that our ever-growing consumption of these finite resources has grown exponentially to the extent that our oil, coal and gas reserves may not last for another two decades. Our fossil-fuel-age will likely not last another century of human existence on planet earth. 2013 saw a new global record in oil production and consumption, reaching an all-time high of 86.8 million barrels per day. This is partly due to the fracking boom that began in mid-2011 in the US. Unless we seriously rethink our energy strategy and actively change the course of this trend, the brief time window that may become known as the fossil fuel era, is rapidly coming to an end.

4.2. Greenhouse effect

Joseph Furier first observed the greenhouse effect in 1924. The greenhouse effect takes place when greenhouse gasses in the atmosphere allow the energy from the sun in the form of infrared and ultraviolet radiation to reach the earth's surface but reflects and scatters the heat emanated from the earth. Most of this heat remains within the atmosphere and warms up earth to a temperature by which flora and fauna are generally accustomed (Figure 5). Without this naturally balanced greenhouse effect, the temperature on earth would drop as low as minus 18°C.

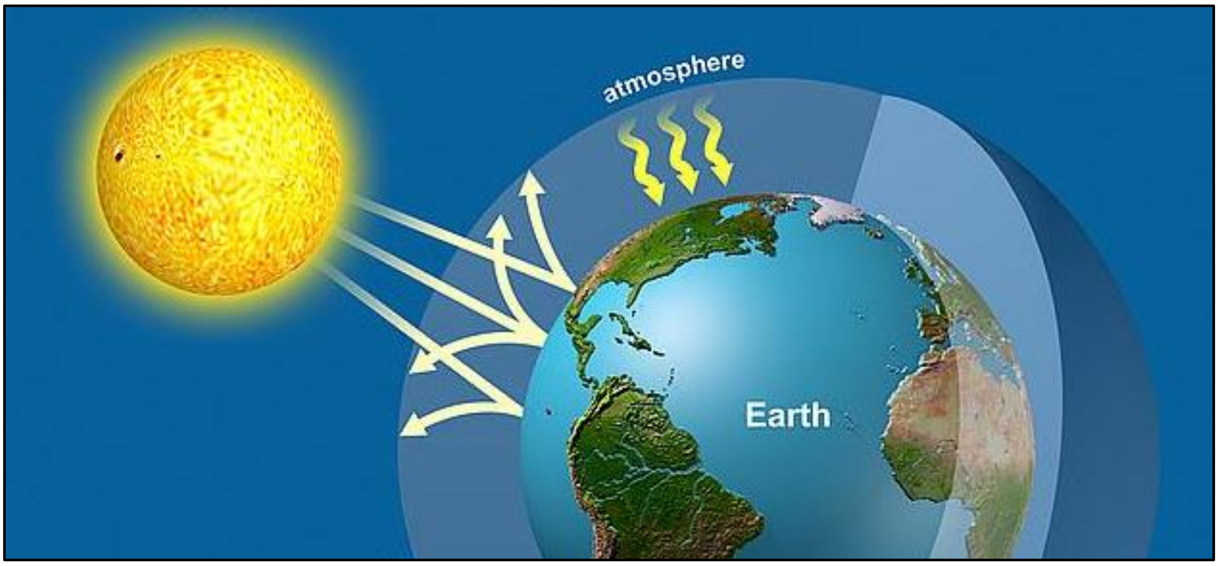


Figure 5 *- Diagram of the greenhouse effect*

Greenhouse gases in the atmosphere occur naturally and are extremely important for life on earth. Below are the main greenhouse gases listed by their percentage-contribution to the greenhouse effect.

- H_2O-vapor 36–70%
- CO_2 9–26%
- CH_4 4–9%
- O_3 3–7%

Water vapour (H_2O) and carbon dioxide (CO_2) are the most critical of these gases and constitute a large part the earth's atmosphere. They are also the predominant gases produced by the combustion of hydrocarbon fuels in internal combustion engines.

It is only in the past twenty years that people have become concerned that these man-made gases are interfering with the atmospheric balance and thus affecting the earth's climate. Unsustainable and destructive human activity generates vast amounts of these gases and thus amplify the greenhouse effect by additionally absorbing and storing radiation, and heating up the earth.

The combustion of hydrocarbons is the primary source of human CO_2 Emissions and accounts for over 70% of these greenhouse gases (Figure 6). Fossil fuel combustion also produces other greenhouse gases such as methane and nitrous oxide.

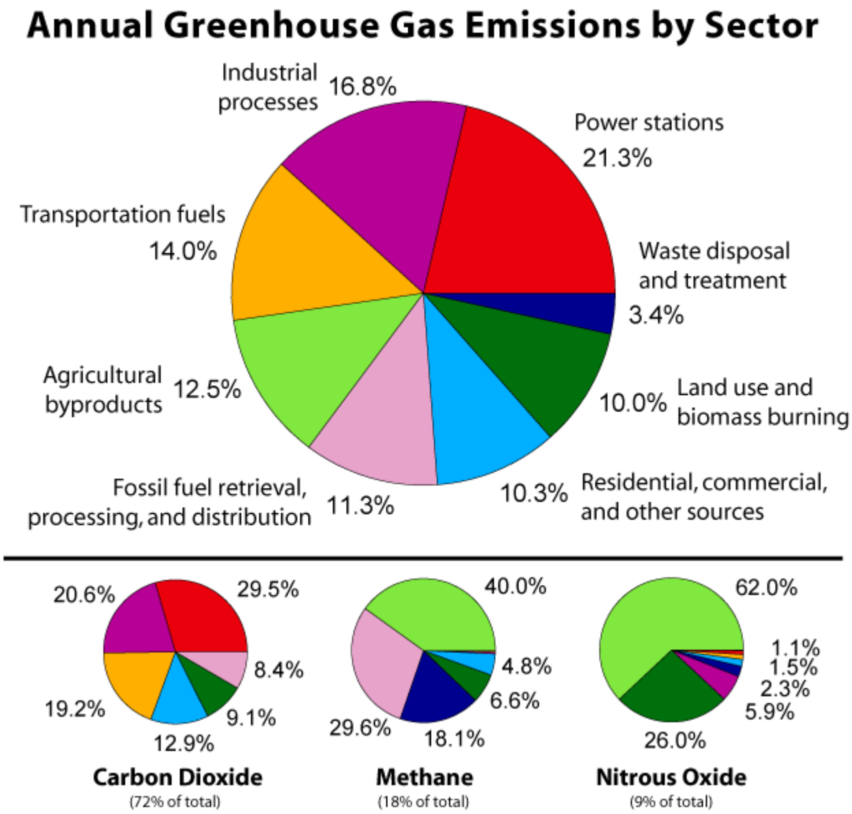


***Figure** 6 - Relative fraction of greenhouse gases produced by sector, as estimated by the Emission Database for Global Atmospheric Research, fast track 2000 project.*

There are several strategies to reduce the global carbon footprint and perhaps reverse the negative effects of climate change; switching from hydrocarbons and nuclear to clean and more sustainable energy sources, improving the efficiency of energy systems and greatly expanding the use of sustainable and alternative energy sources worldwide. These energy-strategies backed up by political legislation, would make the much needed energy revolution happen.

4.3. Renewable energy sources

Renewable energy sources (those without undesirable consequences and that are replenished on a human time scale) exist everywhere in the world. These are unlike the conventional finite energy sources, which are generally concentrated in few select and unstable regions. Due to the threats of global warming as well as economic benefits, energy security and autonomy, renewable sources are increasingly being deployed with more efficient technologies. They all have much lower CO_2 emissions and are a “free” and abundant resource with comparable or better performance. These include geothermal, hydro, biomass, wind and solar energy. The latter two will be briefly discussed, as these forms of power make more sense in combination with hydrogen production and storage.

4.3.1. Wind and solar power

Wind and solar power stations never cause widespread catastrophic accidents, as can be the case with other types of power stations. They therefore are not at risk of being taken off the grid for security reasons. An oil spill or a nuclear meltdown causes unfathomable damage and has long-term repercussions for future generations. Using solar in the equation, the analogy of a huge solar radiation spill paints a much brighter picture - we simply call it a nice sunny day!

From an environmental point of view, solar thermal and photovoltaics are the most feasible clean energy solutions available. Photovoltaic is presently experiencing the fastest growth rate of all the renewables. And thanks to the sinking prices of photovoltaic modules and inverters we are seeing more and more applications. In recent years most of the European rooftop-mounted modules were exclusively placed at southern inclinations, but now, the cheaper module market is capturing complete roofs (roof integrated photovoltaic modules), roofs with east and west inclinations. This contributes to a more balanced energy production profile the entire day in any season.

Wind power is also experiencing a rapid growth rate; the worldwide capacity of installed wind power stations has doubled every three years since 1995. This growth rate has surpassed all official think tank predictions. And the outlook according to BTM Consult[4] for total performance output of wind turbine energy is forecasted to increase to 1100 GW by the year 2020.

[4] BTM Consult is the leading independent market analysis and consulting company for renewable energies. Their prognoses have always been conservative.

4.4. Global trends

Many mainstream media distribution channels and big investors have regarded renewable energies as a weak and overpriced niche market that offers no competition for the conventional energy sources. These global players would like us to believe that serious investments in the energy sector are to be made in traditional technologies such as the petroleum, gas and coal branches. The real potential however, is pointing in a completely new direction.

The above-mentioned energy sources are losing their momentum and market shares, but they are backed by very powerful lobbies in the government and Big Business, receiving subventions to keep them afloat. These big companies are not speaking of the decline in interest towards these sources of energy and are doing their best to maintain large and profitable fuel companies. In spite of this, there are three new trends that are clearly visible:

1. The oil price is the lead “currency” in our energy market and it is steadily rising in the long run - in fact it has tripled in most currencies. And when it comes down, it is a result of temporary market manipulation and will not stay there. Most existing oil fields are declining in their production to a tune of at least 4% per year. These losses are hardly compensated with new and more expensive production methods.

2. Nuclear energy is experiencing a substantial setback in the aftermath of the Fukushima catastrophe. Trust and faith in this technology has been lost, and its market share is steadily sinking. Numerous big global companies are opting out of the nuclear energy sector and polishing their images, investing in more sustainable and renewable energies.

3. Solar and wind power are on an impressive growth path, becoming a convincing source in today’s energy mix. They have undeniably established themselves and are coming out on top as a competitive, clean and long term energy solution. In their current trajectories, these energy sources will soon become the cheapest and most sensible choice, and are paving the way for the replacement of fossil fuels.

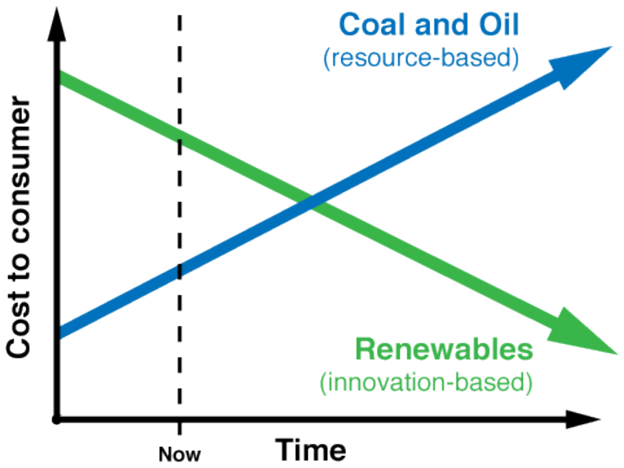


Figure 7 *– A graph depicting resource-based energy getting more expensive vs. innovation based energy getting less expensive in time.*

5. What are fuel cells?

Fuel cells are electrochemical energy conversion devices that convert chemical energy from a range of fuels into electrical energy through the chemical reaction of an oxidizing agent such as oxygen.

A more commonly known electrochemical device is the battery. Batteries store the chemicals needed for the chemical reaction inside a casing, producing electrical energy. When the electrical energy is discharged, the battery either needs to be disposed of, or recharged electrically to restore its capacity.

Fuel cells rely on a continuous external flow of chemicals into the cell (usually oxygen/air and hydrogen) to sustain the chemical reaction and convert the chemical energy into electrical energy. Therefore as long as a chemical fuel flows into the FC it will produce electricity.

There are several types of FCs and each operates slightly differently. However, all of them consist of a cathode (negative electrode), an anode (positive electrode) and an electrolyte (ionizing solution that allows a charge to be conducted between both electrodes).

The most common fuel used in fuel cells today is hydrogen separated from hydrocarbons by means of steam reforming. A higher efficiency can be achieved by directly feeding fossil fuels such as methane into the system. Both of these methods produce greenhouse gases but have many advantages over internal combustion engines.

When using hydrogen, a fuel cell generates power efficiently and quietly, with the only by-products of the system being water and heat, which can be additionally used for room heating purposes. Moreover, if the hydrogen is produced from a renewable source, the system is CO_2 neutral and completely clean. This makes fuel cells a most promising clean technology that governments, corporations and universities are collaborating to research and develop.

To obtain their electrochemical reactions, most fuel cells need auxiliaries. These auxiliaries generally require a proper design and sufficient power. For this reason some applications need to take into proper consideration the amount of power to run the auxiliaries, such as the air compressor, to evaluate the real advantage of using a fuel cell system instead of other conventional energy solutions.

Fuel cells have many applications for primary and backup power solutions in buildings and in remote areas where off-grid systems are used. Their ability to produce energy with virtually no pollution, vibration, noise or heat makes them an indispensable niche market for military and space use. They are also becoming an emerging technology to power FCVs (fuel cell vehicles) such as cars, buses, forklifts, boats and submarines.

The market for FCs is steadily growing, and according to an estimation made by Pike Research, stationary FCs will produce 50 GW by the year 2020.

6. History of fuel cells

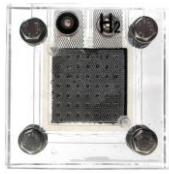
Figure 8 *– Timeline*

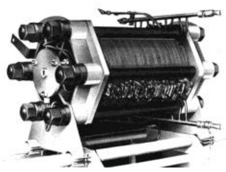
1801
Humphry Davy demonstrates the electrochemical principle of fuel cells.

1839
William Grove invents the first fuel cell. Then known as the “gas battery”.

1889
Charles Langer and Ludwig Mond develop Grove’s invention and rename it the fuel cell.

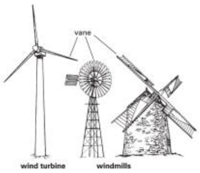
1950s
GE invents the PEM fuel cell.





1959
Francis Bacon develops a 5 kW alkaline fuel cell.

1960s
NASA starts using fuel cells in rockets.



1970s
The oil crisis triggers the search for alternative energy technologies

1980s
US Navy starts using fuel cells in submarines.

1990s
Big scale fuel cells are developed for alternative power supplies.

2007
Fuel cells are available commercially as APUs and standalone backup power supplies.

2008
Honda builds a fuel cell powered electric car.

2009
Residential FC power units & portable FC battery chargers become widely available.

2010
Bloom Energy launches the Bloom Energy Server (the Bloom Box).

2013
FuelCell Energy reaches milestone of 2 billion kWh of ultra-clean power produced since 2003.

2014
Hyundai, Audi, Honda and Toyota unveil their new Fuel Cell Vehicles.

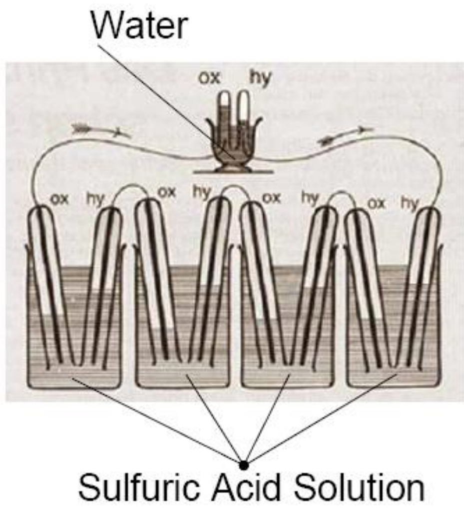


***Figure 9** – A diagram of the first "gas battery" fuel cell invented by William Grove.*

The first reference to fuel cells goes back as early as the beginning of the 19th century when British physicist and chemist Humphry Davy demonstrated the concept of the electrochemical reaction that takes place in fuel cells. His research and development was based on the earlier work of the German chemist Christian Schönbein. In 1939 William Grove managed to demonstrate that the electrolysis of water was a reversible process and went on to developed his "gas voltaic battery" (Figure 9). This was the first big step to the fuel cell discovery, and he was credited with the invention of the fuel cell. His fuel cell was based on reverse electrolysis, with the reasoning that if water can be separated into oxygen and hydrogen using electricity, then the reverse process should hold true. It consisted of platinum electrodes in two test tubes, which were immersed in an electrolyte solution of water and sulphuric acid. This type of cell could generate a small voltage, and by connecting several cells in series, his gas battery device could generate significantly higher voltages.

In 1889 Ludwig Mond and Charles Langer further developed and refined Grove's design, and renamed it the fuel cell.

Towards the end of the 1950s, Tomas Grubb and Leonard Niedrach from General Electrics invented the proton exchange membrane (PEM) fuel cell. Their fuel cell excelled in durability, efficiency and performance, and went on to be the most widespread type of fuel cell in use to date.

1959 saw the conception of a 5kW alkaline fuel cell (AFC) by British inventor Francis Bacon. The AFC, later also known as the Bacon fuel cell, had the potential to reach 60% efficiency and was one of the most developed FC technologies. NASA used the AFC in their space missions and on their shuttles since the 1960s.

With an ever increasing awareness of environmental consequences emerging in the 1970s, governments in the US and in Europe passed legislation with the goal of reducing harmful exhaust gases. Many countries soon adopted this clean air legislation. The 70s was also the time of oil embargoes, which consequently pushed the necessity and awareness for clean energy and efficiency. These two factors were to become the main drivers for the interest and development of FCs, as well as an increased concern about global warming in the following decades. This drove automobile manufacturers to experiment with and develop hydrogen-powered vehicles, most demonstrated some sort of PEM fuel cell stack, while others converted conventional internal combustion engine to run with hydrogen. In the following decades, with the result of this early effort, all the large automobile manufacturers had developed prototypes of hydrogen fuel cell vehicles, which produced zero emissions.

Development and commercial interest continued into the 80s, especially in the Phosphoric acid fuel cell (PAFC) technology for stationary as well as for transport applications. The US Navy also saw the operational benefits of highly efficient, practically silent and emission free fuel cell technology, and conducted research and development work for the application of fuel cells in military submarines.

In the following decade, the focus turned more towards solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEMFCs), especially for more compact uses such as backup power units and powertrains. A great advance was made when PMFCs were modified to run directly from methanol. These early direct methanol fuel cell (DMFC) prototypes were engineered to power small devices such as notebooks and cell phones.

An increasing awareness and concern about greenhouse gas emissions, as well as energy security and efficiency, grew ever stronger into the early 21st century. This once again led to the search for cleaner and more sustainable alternatives, and research and development of the fuel cell technologies was given new light and energy. Private and government research and funding greatly increased in the past decade, especially in the areas of cost reduction of catalyst technology and performance. A great deal of interest in FC technology was also shown worldwide by car manufacturers; the clear advantage in running time, simplified and quicker refuelling as well as greater efficiency compared to conventional technologies all went to promote an even more widespread adoption of FCs.

In 2006 the HyFLEET:CUTE project set out to test the hydrogen fuel cell capabilities involving 10 cities across Europe, China and Australia, where hydrogen powered buses were tested and studies on the long term use and efficiency were conducted (Figure 10).

Figure 10 *– A HyFLEET:CUTE Global Hydrogen Research ecobus at a hydrogen fuelling station.*

The hydrogen ecobus development and testing continues around the world today.

In the years following, fuel cells for use in a variety of applications became readily available commercially and began to meet the required standards and regulations for commercial use. As a result, a large number of PEMFCs were sold for the use in private applications such as campers, boats and off-grid homesteaders. Similarly, a niche market demand for very small and compact fuel cells for concept models and experiment kits was created.

Over the past several years, the advance in low or zero CO_2 emission, high efficiency, compact size and low cost are some of the characteristics that goes to show that fuel cells really do represent a viable and proven alternative clean energy solution to our energy crisis and race against a climate change point-of-no-return.

6.1. Recent advances in fuel cell technology

In the autumn of 2009 a Swiss collaboration of Paul Scherrer Institute (PSI), Empa, Bucher Schoerling, Proton Motor, BRUSA Elektronik AG and Messer Schweiz developed the CityCat H2, the world's first municipal utility vehicle powered by hydrogen fuel cells (Figure 11).

Figure 11 *– CityCat H2, the first hydrogen driven municipal utility vehicle in the world*

The pilot project took place on the streets of Basel, where the CityCat H2 was tested under real world conditions. The test results were very promising regarding energy efficiency and carbon footprint. Some issues related to the fuel cell's ability to perform under the sub-zero conditions of the Swiss winter were identified and the project team is presently working hard to correct the problems. So in the near future this clean green cat may make its way into mass production and be a common sight in Switzerland.

Another interesting recent development in Switzerland is the "Fuel Cell Postbus" project with five hydrogen buses in operation in and around Brugg. All of the hydrogen fuel used to power these buses is obtained from renewable energy sources such as hydro, wind, and solar power.

There are over twenty types of FCVs that have been released since 2009, and several large automobile manufacturers have announced ambitious plans of a production model for release in the coming years. As of early 2014, the infrastructure for hydrogen cars is limited; with ten fuelling stations in the US and a few prototypes in Europe. However, along with the new momentum caused by the rollout of new high tech FCVs, more stations are planned for the US, Japan and Germany. The next few years will show whether or not FCVs can prove to be a cost effective and efficient solution for automobiles, and if they can compete with other zero emission vehicles i.e. hybrids and EVs.

Perhaps one of the most significant advances in the automobile sector is Toyota's recent announcement to make all of its 5700 hydrogen technology patents open to the world, for royalty-free use. This move goes to show that Toyota is hedging its bet on the future of hydrogen technology and is reaching out for "open source" support in the further development of this technology.

Figures 12, 13 & 14 below depict some of the most promising new FCVs.

Figure 12 *- The Hyundai ix35 FCV is the first ever to go into mass production. A first small batch was started in 2013, and in 2015 the production of ten thousand units will commence. These units will be delivered to the EU as well as fifteen countries around the world.*

The powertrain generates an output of 100 kW with 300 Nm of torque. The 700 bar pressurized hydrogen tank has a capacity of 5.64 kg that permits a range of about 600 kilometres.

Figure 13 *– The Toyota Mirai FCV is scheduled for commercial mass production in 2015. The fist batch of 700 units will be sold worldwide at a price of 60,000 Euros (in Europe).*

The four-door sedan is refuelled in 3-4 minutes and has a range of 480 km on a full tank of hydrogen. Its powertrain delivers 113 kW and 335 Nm. The Toyota FC system is more efficient than an ICE and produces no CO_2 (at operation point). For every 4 km of driving, the car emits an exhaust of 240 ml H_2O.

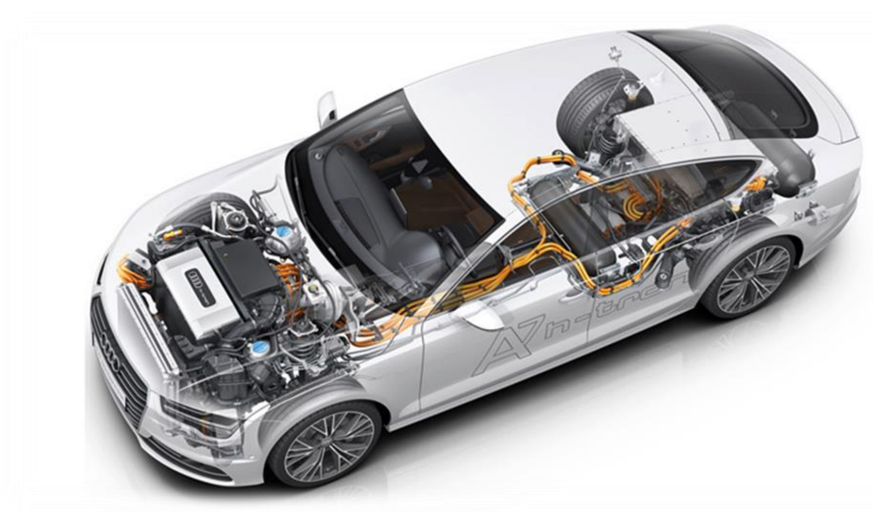


Figure 14 *– The Audi A7 h-tron Quattro is Audi's sporty and luxurious performance FCV answer to the FCV competitors.*

The turbocharged powertrain (which forces air into the fuel cell) holds a 300-cell stack and delivers 170 kW with 540 Nm. The hydrogen tank takes 3 min to refill and has a capacity of 5 Kg, giving it a range of more than 500 km.

The PEM fuel cell operates at around 80 °C and achieves an efficiency as high as 0.6 which is far greater than ICEs. By using the clean hydrogen produced by Audi's renewable wind-powered pilot plant, this car truly can operate as a zero emission vehicle.

7. Types of fuel cells

There are several different types of fuel cells and each of them operates with a different electrochemical reaction to generate electrical energy (Figure 15). They are classified by their operating temperature and by the electrolyte used. Some are more suited for stationary power plant use, while others work better for more compact and mobile applications or for powertrains in transportation. The main types of FCs are included below:

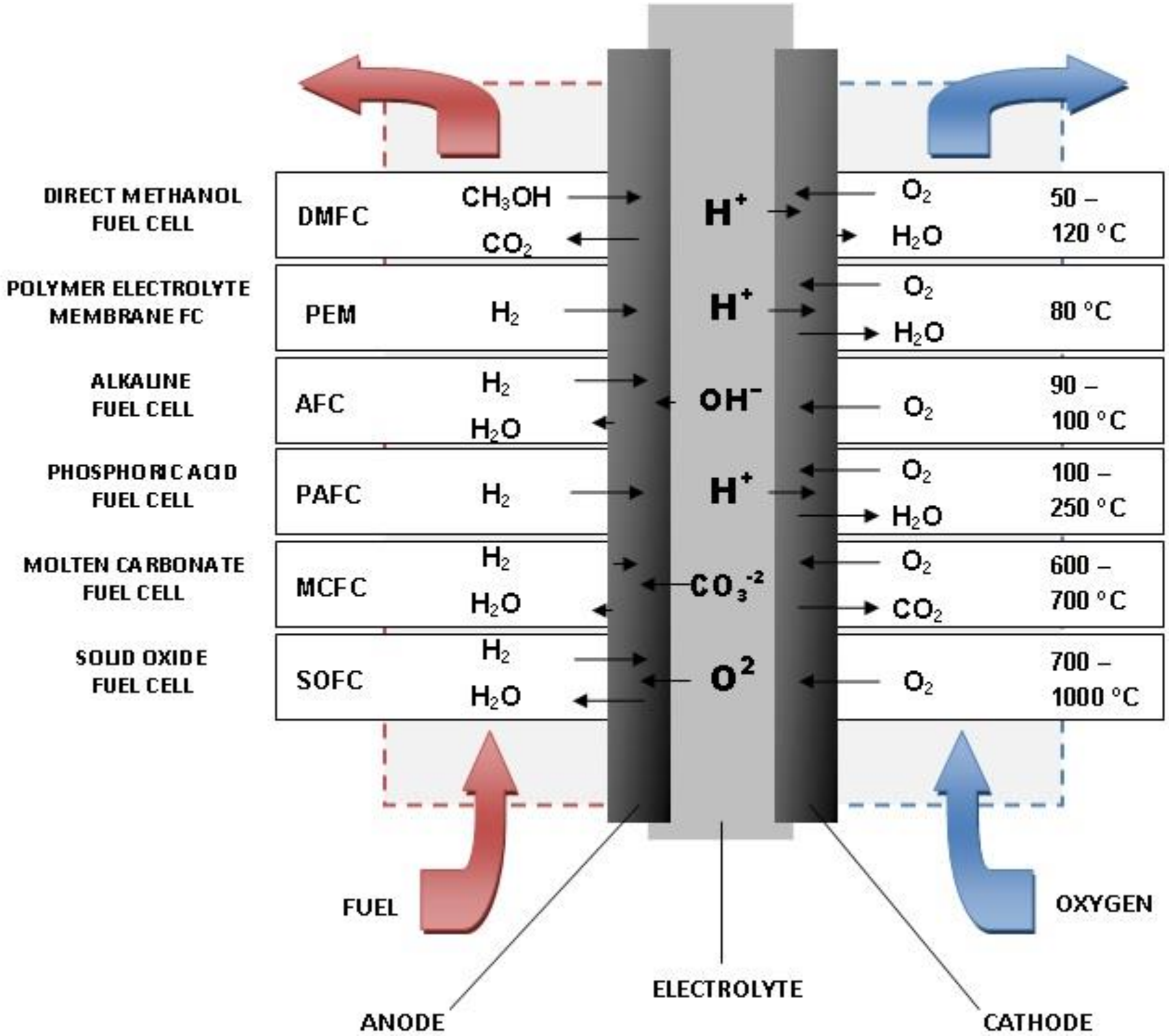


***Figure 15** – A diagram depicting the basic function of the most common types of FCs*

The fuel cells with most potential and the most prevalent to date are the proton exchange membrane fuel cells and the direct methanol fuel cells. These two types are described on the following pages.

7.1. Proton exchange membrane fuel cells (PEMFCs)

Also known as polymer electrolyte membrane fuel cells, PEMFCs are a type of fuel cell that operates at relatively low pressure and temperature, and has high power density[5]. Their development in the fields of compact transportation, stationary and mobile applications has come a long way over the years and is continuously being used in new and innovative ways. They are well suited to deliver power where a rapid power start-up and dynamic power output is demanded, such as in forklifts and road vehicles.

As with all fuel cells, PEM fuel cells do not combust a fuel (usually hydrogen and oxygen) in order to generate thermal energy; instead they directly transform chemical energy released in the electrochemical reaction, to electrical energy.

These cells use a water based polymer electrolyte membrane sandwiched between two electrodes typically made of platinum (Pt), a highly corrosion-resistant noble metal and an excellent catalyst. Pressurized hydrogen gas is supplied to an inlet, wherein it reacts with the platinum catalyst at the anode side of the cell. The hydrogen electrons are separated from the protons and are forced to take the detour (passing through an external electric circuit), while the protons are able to pass freely through the proton exchange membrane. This half-cell reaction is called an oxidation.

Oxygen (either in pure form or as air) is fed through an inlet on the cathode side of the cell. After passing through an external load circuit, the electrons are conducted back to the cathode. There they react with the oxygen molecules and with the newly formed protons that permeate through the membrane, this reaction forms water vapour. This half-cell reaction is called a reduction and it generates heat, which can be utilized in a combined heat and power (CHP) system to further improve the overall efficiency of a hydrogen system i.e. for room heating.

The overall cell reaction is called a redox reaction and is reversible. This means that the process of a PEM fuel cell can be reversed to run as an electrolyser to split oxygen and hydrogen from water using an electrical current. Usually a high performance PEMFC is optimized for operation in fuel cell mode only, and will not perform efficiently as an electrolyser. However, there are purpose-built reversible PEMFCs that perform relatively well in both modes. When the FC is operated in reverse mode (as electrolyser), the anode and cathode are also reversed, so the electrolyser generates hydrogen at the cathode and oxygen at the anode with a ratio of 2:1.

Each individual cell generates a relatively low voltage of approximately 0.7 volts. The desired voltage is obtained by stacking cells together, thus increasing the electrical potential. An increase in the number of individual fuel cells increases the overall voltage, and an increase in the electrode surface area of the individual cells increases the overall current. These PEM fuel cell assemblies are called stacks, and come in many sizes ranging from several watts to several hundred kilowatts. Water management is an important factor to the efficiency and performance of these cells; running them too dry will damage the membranes and running them too wet will flood

[5] The amount of power generated per unit volume expressed as W/m^3

them. The components of a PEMFC and the reactions that take place therein are illustrated below in Figure 16:

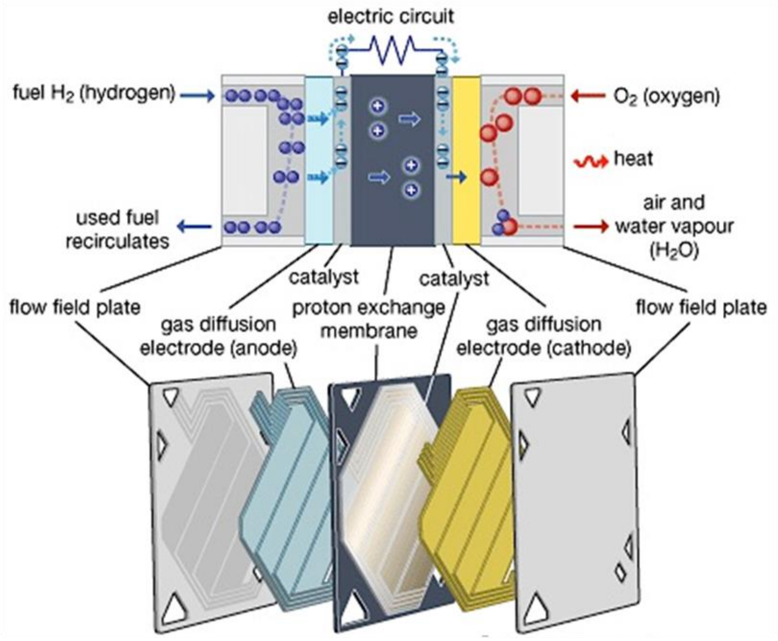


***Figure 16** – Exploded view drawing of a PEMFC showing the components and chemical reaction.*

The chemical reactions that take place inside a PEMFC are as follows:

Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$	***Ox**idation reaction*
Cathode reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	***Red**uction reaction*
Overall cell reaction: $2H_2 + O_2 \rightarrow 2H_2O$ *+ energy*	***Redox** reaction*

Catalyst: mostly platinum, sometimes cerium oxide as a cheaper alternative

Electrolyte: Solid polymer membrane

Operating temperature: Ca. 80 °C

Cell efficiency (η): 40 - 60 % (can reach 90% by using waste heat in CHP systems)

***Figure 17** – A 5 kW PEM fuel cell stack consisting of 120 cells with a rated performance of 72V @ 70A. The stack measures 350 x 212 x 650 mm and weighs in at 30 kg including cooling fan and aluminium casing.*

7.2. Direct methanol fuel cells (DMFCs)

The DMFC shown in Figure 18 is a subcategory of the PEMFC; both of these fuel cells function with a solid polymer membrane as an electrolyte to enable the required chemical reaction. With the DMFC however, the platinum and ruthenium (PtRu) catalyst at the anode side of the cell directly extracts hydrogen from liquid methanol. Directly powering the fuel cell with a hydrogen-rich fuel increases the overall system's power density, and eliminates the need for pure hydrogen generation and storage.

A mixture of water and methanol is supplied to the anode side of the fuel cell; this causes an oxidation on the PtRu catalyst, consuming H_2O and releasing CO_2. The protons *(H^+)* are able to pass through the proton exchange membrane, while the free electrons *(e^-)* are forced to flow through an external circuit providing electrical power to the devices in the circuit. The protons that enter the cathode side of the cell through the PEM then react with the oxygen from the air and are reduced into water. Most of this water is recycled inside the cell and the excess is released as water vapour.

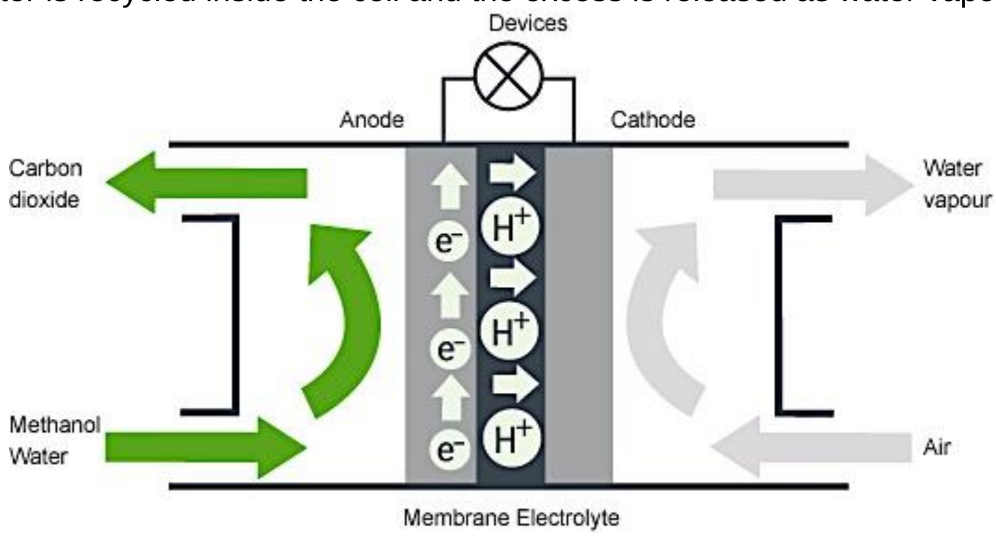


***Figure 18** – Diagram showing the electrochemical reactions inside a direct methanol fuel cell with inputs and outputs.*

The chemical reactions that take place inside a DMFC are as follows:

Anode reaction: $CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$ — ***Ox**idation*

Cathode reaction: ${}^3/_2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$ — ***Red**uction*

Net reaction: $CH_3OH + {}^3/_2O_2 \rightarrow 2H_2O + CO_2$ + energy — ***Redox** reaction*

Catalyst: usually platinum and ruthenium

Electrolyte: Solid polymer membrane

Operating temperature: 50 - 120 °C

Cell efficiency (ɳ): approximately 30 - 40 %

The advantages of using methanol rather than hydrogen as a fuel are its (still) relatively low cost and availability. Methanol's energy density is also relatively high without the need for compression, this makes it easy to store and tank up. A methanol tank can quickly be refuelled without special equipment, and for smaller applications, a disposable cartridge is replaced in seconds.

The disadvantages compared to hydrogen PEMFCs are lower cell voltage and current density resulting in a lower cell efficiency of up to 40%; this makes DMFCs suitable only for smaller applications. Also, the CO_2 emissions of the exhaust contribute to the greenhouse effect.

Since the efficiency of these cells is relatively low, they are targeted at smaller mobile applications where energy density is more important than efficient performance. DMFCs are able to generate a small amount of energy for long periods of time; this makes them well suited for small and compact applications. These include small vehicles such as golf carts and forklifts, electronic devices such as notebooks and cell phones as well as for backup power supplies, chargers and APUs (Figures 19, 20 & 21). They are usually coupled with a battery so as to enable a flexible and dynamic energy demand profile. These types of units usually range from a few watts up to 5 kW, and can supply power for up to one hundred hours without refuelling.

Figure 19 *– Samsung's lightweight military power supply for soldiers. The rugged enclosure weighs just 1.8 kg and includes a DMFC with 25W nominal and 55W peak power, a methanol cartridge and Li-ion battery. The unit together with 8 spare fuel cartridges weighs 3.4 kg and is capable of powering a soldier's electronics (i.e. laptop, radio etc.) for a 3-day mission.*

Figure 20 *– The EFOY Pro 2400 off-grid DMFC power unit from SFC Energy. The 110W unit is capable of supplying power for long periods and is completely maintenance free. It consumes methanol at 0.9 l / kWh and produces relatively low amounts of CO_2, about the equivalent of a baby's breath.*

Figure 21 *– The EFOY ProEnergyBox, a rugged all-in-one off-grid power supply designed for extreme conditions. The unit includes a battery and houses two methanol cartridges. The hybrid system can be coupled with a photovoltaic module out of the box.*

7.3. Comparison of fuel cell technologies

Type	Power	Temperature	η Cell	Applications	Advantages	Disadvantages
PEMFC [6]	1 W - 500 kW	Ca. 80 °C	40-60 %	-EVs -APUs -Portable power -Backup power -Transportation	-High efficiency -High power density -Lightweight -Low operating temperature -Quick start-up -Solid electrolyte	-Expensive catalyst materials -Sensitive to fuel impurities
DMFC [7]	100 mW - 5 kW	50-120 °C	30-40 %	-APUs -Portable power -Backup power -Electronic devices	-High power density -Lightweight -Low operating temperature -Solid electrolyte	-Expensive catalyst materials -Low efficiency -Slow start-up
AFC [8]	10 - 100 kW	90-100 °C	60 %	-Space -Military	-High efficiency -Quick reaction -Low cost	-Sensitive to fuel impurities
MCFC [9]	100 MW	600-700 °C	45-50 %	-Power stations	-Fuel flexibility -Catalyst flexibility -CHP possible	-High temperature -Slow start-up -Low power density
PAFC [10]	< 10 MW	100-250 °C	40 %	-Power stations	-Tolerant to fuel impurities	-Expensive catalyst materials -Slow start-up -Low power density
SOFC [11]	1 kW - 2 MW	700-1000 °C	60 %	-APUs -Power stations	-Fuel flexibility -High efficiency -Catalyst flexibility -CHP possible	-High temperature -Slow start-up

***Figure 22** – Fuel cell comparison*

[6] Proton exchange membrane fuel cell
[7] Direct methanol fuel cell
[8] Alkaline fuel cell
[9] Molten carbonate fuel cell
[10] Phosphoric acid fuel cell
[11] Solid oxide fuel cell

8. Proof of concept model

8.1. H - Racer 2.0

H-Racer guide.pdf [12] *H-Racer manual.pdf* [13]

Powering a drivable car with 100% clean hydrogen fuel cells poses its challenges. Some issues with clean hydrogen production and storage still need to be addressed before we'll see FCVs hit our roads in a big way. But powering a little RC car is already well within reach!

The POC model H-racer 2.0 hydrogen car presented with this paper is an educational kit that contains all of the components needed to produce climate friendly hydrogen from solar energy, to store this hydrogen and then to drive a scaled down model hydrogen fuel cell car (Figure 23). This model works on 100% clean hydrogen produced by a 10-cell solar module powered fuelling station.

The hydrogen fuelling station's PEM electrolyser converts distilled water to hydrogen and oxygen using solar energy. The oxygen is released into the atmosphere, and the hydrogen is transferred to a balloon H_2 tank via a hydrogen refuelling valve system in the car. The 15 cm long H-Racer contains a PEM fuel cell that converts the hydrogen and oxygen from the air back into electricity to power a motor to drive the car.

One tank of hydrogen suffices to drive the car approximately 100 meters at a speed of up to 25 meters per minute and to power the on-board LEDs.

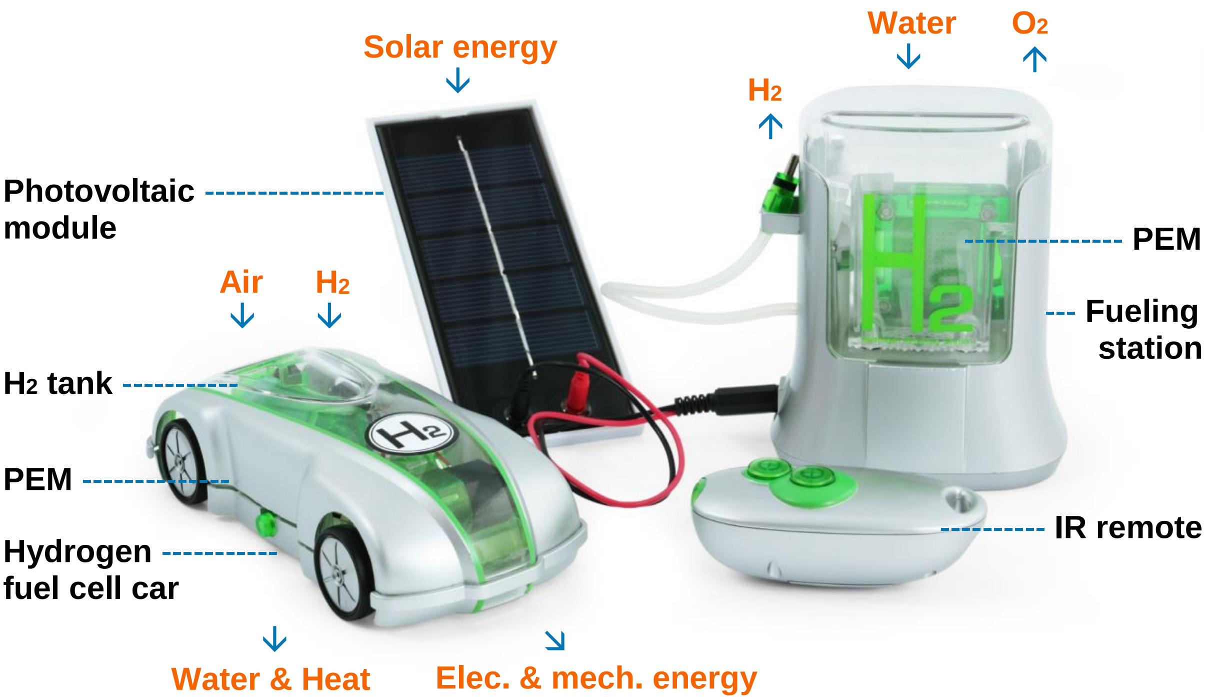


Figure 23 *– The H-Racer 2.0 demonstration model showing the main components as well as the inputs and outputs of the system.*

[12] https://drive.google.com/file/d/0BxLJh12BbrzAdEswSzZVclJRemM/view?usp=sharing
[13] https://drive.google.com/file/d/0BxLJh12BbrzAaG5xYkFpQ0V3d28/view?usp=sharing

9. Hydrogen

Hydrogen (H) is the lightest element and the most abundant substance in the universe, constituting approximately 74% of it. At ambient pressure and temperature and in its diatomic molecular state (H_2), hydrogen is an odourless, tasteless, colourless and non-toxic yet extremely energy dense and flammable gas.

9.1. Hydrogen as an energy carrier

The need for a clean, renewable and abundant energy carrier has since long put hydrogen in the spotlight. The international scientific community has made big advances in hydrogen technologies, and has laid down the foundation for a possible future global hydrogen economy. The key factors for a global adoption of this brave new technology by the energy markets are the cost and efficiency of hydrogen production, storage and distribution. At the moment these costs drop lower than that of fossil fuel production, the Big Oil lobby will lose its leverage and control on the energy markets. This shift would then unleash the true potential and the massive diffusion of hydrogen as an energy carrier.

Hydrogen's energy content per unit mass is greater than any other chemical fuel. It has a specific energy of 142 MJ/kg, which is about three times greater than that of diesel and petrol. In nature however, hydrogen is only found bonded with other elements such as carbon and oxygen in the form of molecules and compounds. And in order to tap into its potential energy, it first needs to be separated from these bonds.

9.2. Hydrogen production

Any primary source of energy (i.e. hydrocarbons, nuclear energy, as well as the renewables; wind, solar, biomass etc.) can be utilized to produce hydrogen. And hydrogen gas can be extracted from any molecule or compound containing hydrogen atoms, to be used as an energy carrier with virtually no polluting emissions. The most common ones are hydrocarbon fuels, water and biomass. Some are clean and renewable while others are more efficiently extracted, but all of them can be used to produce the energy-dense and ultimate clean energy carrier - hydrogen.

Today a large amount of the hydrogen is produced by catalytic steam reforming fossil fuels, this equates to approximately 48% of the global production. This is the most economical process to date, but unfortunately it has a negative impact on the atmosphere and is dependent on finite resources.

The technology we need to focus on is fuel cells using solar hydrogen, namely from water electrolysis using clean electricity. If said clean electricity is obtained through photovoltaics, wind or hydro energy, the sun is responsible. Hence, it is all solar electricity.

9.2.1. Electrolysis of water

Electrolysis is the process of splitting water molecules (H_2O) into its constituents; hydrogen (H_2) and oxygen (O_2) using an electric current (Figures 24 & 25). This electrochemical reaction produces two parts hydrogen at the cathode and one part oxygen at the anode. Any source of electricity can be used to produce hydrogen this way, but renewable sources of energy such as wind and solar power offers the cleanest pathway to sustainable and environmentally friendly hydrogen production.

Industrial scale production of hydrogen can be achieved with polymer electrolyte membrane (PEM) electrolysis. This method utilizes a PEM electrolyser, which is basically a reverse PEMFC designed to produce hydrogen and oxygen at a high rate. With quick response time, high efficiency and gas purity, PEM electrolysers are an attractive solution for energy storage.

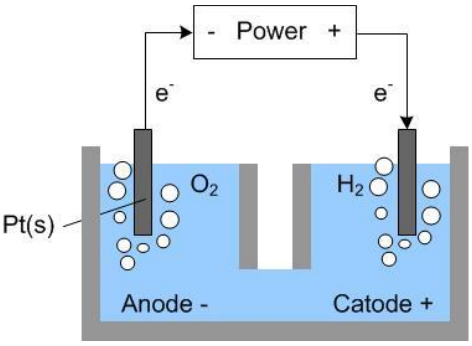


Figure 24 *– A simple demonstration diagram for water electrolysis.*

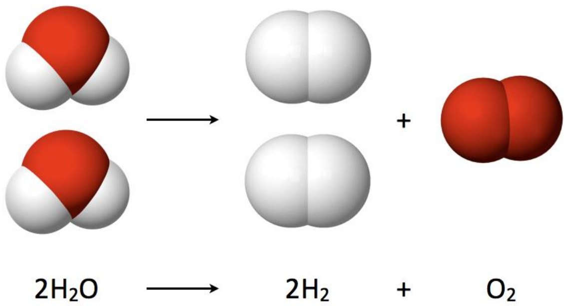


Figure 25 *- The chemical equation of splitting water into hydrogen and oxygen.*

Storing surplus electric energy from wind turbines, photovoltaic arrays or other sources of power with hydrogen as an energy carrier can greatly improve the overall efficiency of a smart energy production, storage and distribution system. This solution provides electrical grid stabilization from the above-mentioned dynamic renewable sources as well as stored hydrogen for later use in fuel cell applications such as APUs and FCVs.

9.3. Hydrogen storage

Hydrogen can be stored in gas or liquid form as well as in solid materials. Storing hydrogen in liquid form however requires cryogenic storage and boils at −252.9 °C. This requires a large amount of energy and is impractical for most applications. Hydrogen is therefore usually stored as a compressed gas in large tanks above or below ground for long-term storage. For short term storage and high-cycle use, small quantities of hydrogen are usually stored in compressed form or in metal hydrides.

9.3.1. Compressed hydrogen

Hydrogen gas has high energy density per unit mass, but low energy density per unit volume when compared to fossil fuels such as diesel and petrol. This means that compressed hydrogen storage requires bigger tanks to store the same amount of energy. This problem can be overcome by increasing the storage pressure, but at an additional energy loss in the compression step.

Smaller tanks for mobile applications are made of aluminium or stainless steel alloy cylinders capable of holding hydrogen safely at 200 bar. More recent advances in storage technology have permitted compressed hydrogen to be stored safely and reliably at 700 bar using lightweight composite materials (Figure 26). These cylinders are usually constructed of three layers; a polymer lining on the inside, a carbon fibre layer, and an outer layer made of Kevlar. These types of tanks display extremely high tensile strength and elasticity, and are capable of withstanding huge mechanical impacts as well as extreme thermal and corrosive conditions.

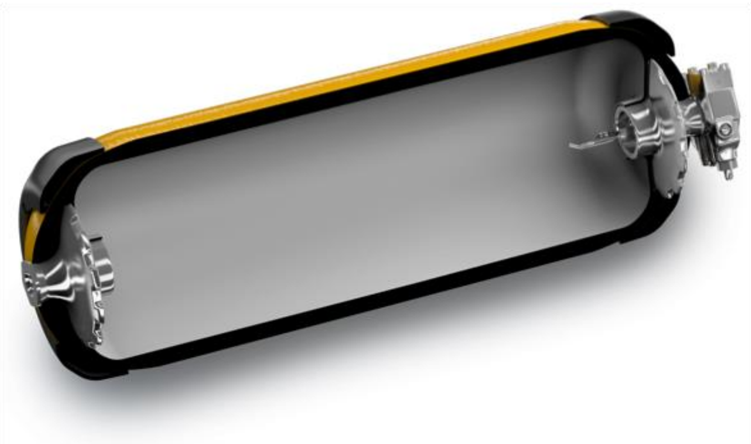


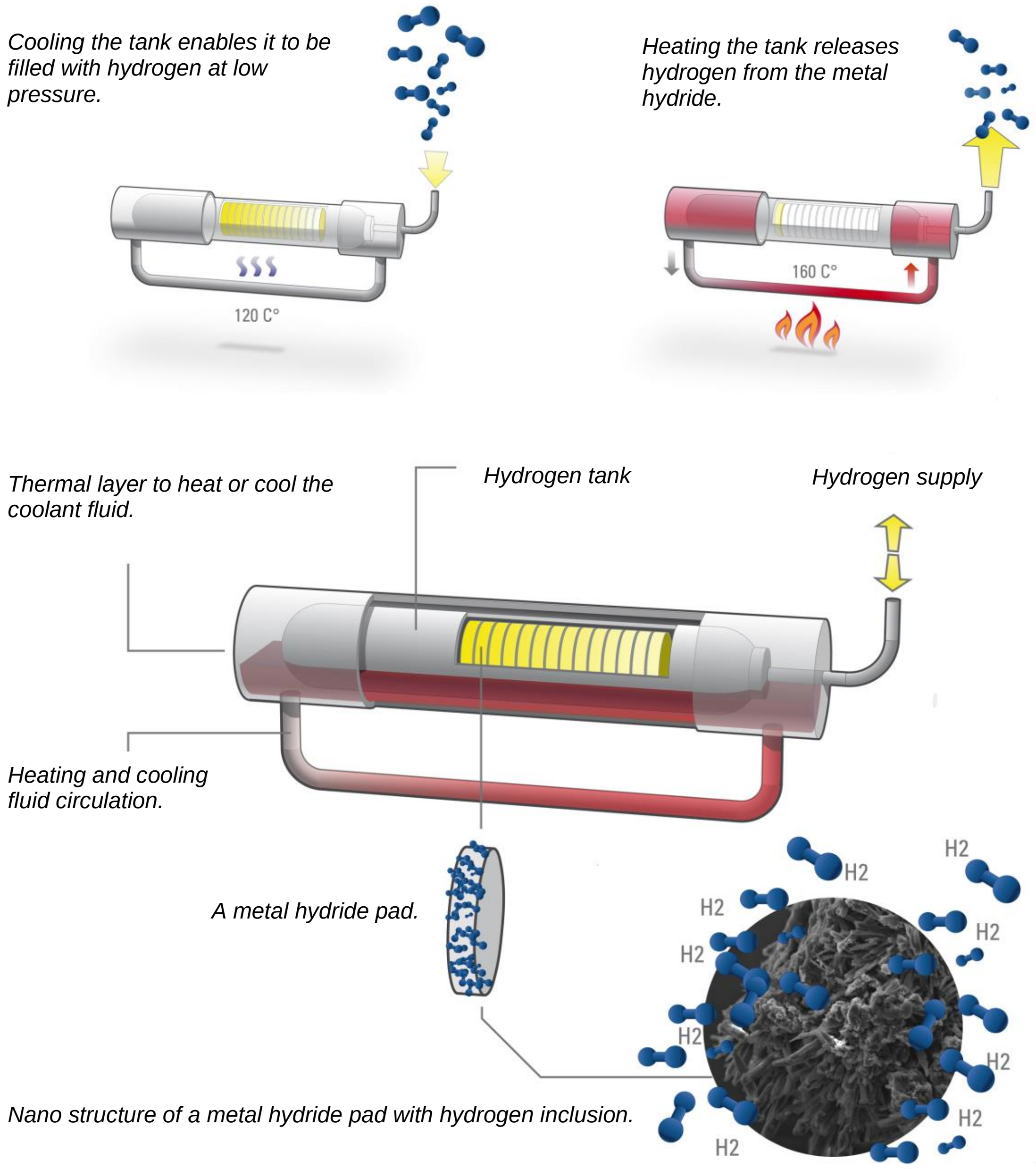
Figure 26 *– Image showing the cutaway of a composite hydrogen tank used in the Toyota Mirai FCV.*

9.3.2. Metal hydrides

The storage of hydrogen in pressurized gas or cryogenic liquid form does not match the storage advantages of tanking liquid fossil fuels. However, a very promising alternative is the use of metal hydrides to increase storage density and safety (Figures 27 & 28). These are materials that bind with hydrogen atoms and thereby act as a chemical sponge capable of absorbing large amounts of hydrogen within a compact canister or cylinder. The metallic powders inside the cylinder chemically bind with hydrogen forming a new compound. This enables hydrogen to be stored at low pressure and ambient temperature with a very high storage density (more dense than hydrogen in its liquid form). The hydrogen is released from the chemical bond by means of heating the metal hydrides from the inside. The pressure and flow rate is controlled by increasing or decreasing the temperature accordingly. Apart from the high storage density, another advantage of using metal hydride tanks for hydrogen storage is the safety aspect. A mechanical failure, or damage to the tank as a result of a collision, would pose no serious fire hazard because hydrogen gas would remain bonded with the metal hydrides and would just smoulder and glow like a cigarette if ignited.

Figure 27 *– Above: A 3 kg stainless steel metal hydride tank with a storage capacity of 300 l and a flow rate of 2-3 l/min.*

Figure 28 *– Below: Diagram showing the function of a metal hydride tank for use in FCVs.*



9.4. Hydrogen safety

Due to incidents like the Hindenburg zeppelin tragedy of 1937 and the Challenger Space Shuttle disaster of 1986, hydrogen has been portrayed as a dangerous fuel in the mainstream media. However, using tried and tested technologies and early warning systems mitigate most risks posed by using hydrogen as a fuel. Here are the facts:

Hydrogen is a very buoyant gas that ignites readily and will combust at a wide range of fuel to air ratios. It is also colourless, tasteless and odourless, so leaks in a hydrogen system cannot be detected by human senses. These properties pose some technological challenges to ensure safe and reliable operation of hydrogen systems.

Modern hydrogen systems are monitored and regulated using sensors and security shut-off valves. Due to the buoyant nature of hydrogen, indoor systems need special monitoring and ventilation systems to detect any leaks and to remove any hydrogen accumulation at the ceilings and overhangs where it would pose an explosion hazard. In the event of a leak outdoor, hydrogen by its nature will rise very rapidly and disperse into the atmosphere. This prevents a dangerous accumulation of highly flammable fuel at the site of an accident.

Studies have shown that a gasoline fire in a car causes far greater damage in contrast to a hydrogen fire in an FCV, where the hydrogen rises and burns up resulting in very little damage (Figure 29).

Figure 29 – *Time-lapse video frames of an experiment conducted where two car fires were simulated, on the left an FVC with a pressurized hydrogen tank, on the right a conventional car with gasoline tank.*

Frame 1: 0 seconds - FCV on the left, gasoline car on the right.
Frame 2: 3 seconds - Ignition of both cars' fuel tanks take place.
Frame 3: 60 seconds - Hydrogen fire is subsiding, gasoline car fire grows.
Frame 4: 90 seconds - Hydrogen fire almost out, gasoline car engulfed in flames (zoomed in to large view).
Frame 5: 140 seconds - Gasoline car being consumed by fire (zoomed in to full screen view).

For the past four decades, industry and space research has developed technologies for safely and reliable production, storage, distribution and usage of hydrogen. These advances have brought hydrogen technology to a manageable standard and a safe alternative to hydrocarbon fuels, making it neither more nor less dangerous. As described above, some of hydrogen's properties actually make it a safer solution for transportation, provided its behaviour is understood and it is handled with appropriate safety measures.

10. Engineering properties of fuel cells

10.1. Performance

Fuel cells can be operated at very low temperature (low heat energy loss), and can very quickly adapt to the output power demand. They offer a high power density, and due to rapidly developing and innovative research in the field, these numbers continue to grow and outperform comparable alternatives. Their very low start-up time makes them ideal for use in vehicles and other applications where quick response power delivery is needed.

10.2. Fuel flexibility

FCs are capable of running either on pure hydrogen, impure hydrogen and hydrogen reformed from any hydrocarbons. The ability for some fuel cells to run directly from hydrocarbons such as methanol makes them a very attractive and much more efficient powertrain or APU/GPU when compared to ICEs.

10.3. Usage flexibility

Due to their inherently quiet and vibration free operation, low operating temperature, low to zero CO_2 emissions and high power density, FCs can be used in a large variety of environments and applications.

10.4. Reliability and life expectancy

Fuel cells have very few moving parts and are essentially a very simple design. Bigger systems do have some moving parts such as pumps, valves and cooling fans, but the limited amount of these moving parts greatly reduces the risk of mechanical failure. This results extremely high reliability, higher uptime and lower maintenance costs compared to classical technologies.

The main factor governing FC durability is voltage degradation. This happens over time, as oxygen and hydrogen or methanol react with the catalyst in the cell, wearing it down and degrading its electrochemical-reaction ability. This degradation process is similar in batteries and other galvanic systems where an electrochemical reaction takes place.

10.5. Efficiency

The energy efficiency of fuel cells is measured by the usable output to the input energy ratio, in practical applications this is usually between 40-60% (Figure 30). This is a lot higher than the efficiency of heat engine systems such as the conventional internal combustion engine, which converts chemical energy to thermal and mechanical energy at an efficiency of about 25-35%. Some fuel cells operate at high temperatures, where combined heat and power makes sense. In these CHP systems, the heat emitted from the fuel cell is used for heating instead of being a wasted by-product, and thus increases the overall efficiency of the system to about 90%.

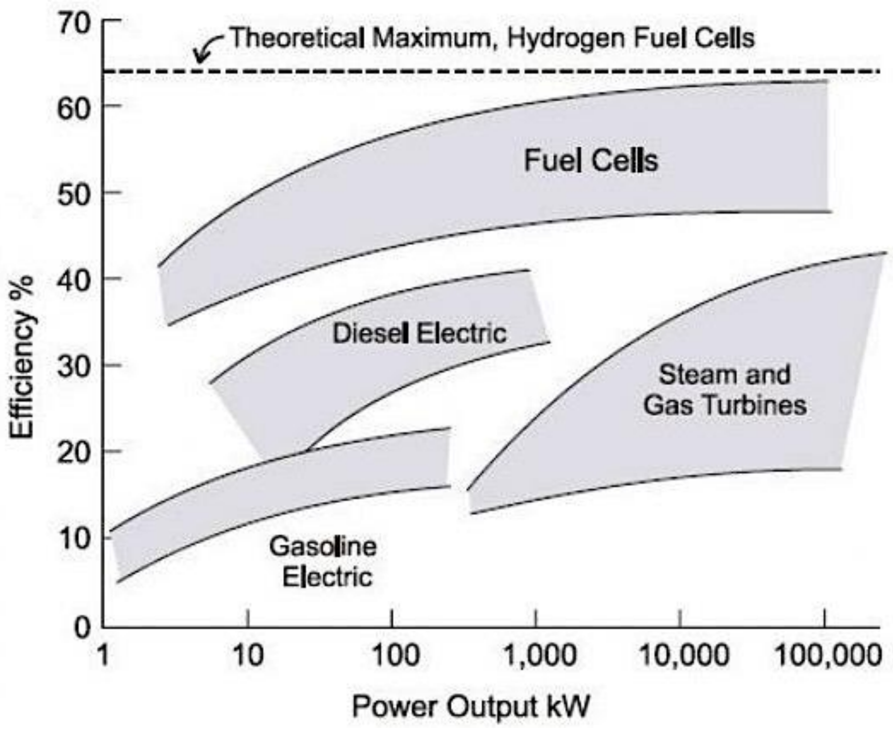


***Figure 30** – FC efficiency in comparison with conventional ICEs and hybrids.*

10.6. Economics of fuel cells

A very common question concerning fuel cells is “What does it cost?” The answer to this question depends on range of factors and each case needs to be studied individually in order to calculate realistic figures.

Firstly, CAPEX (capital expenditure) costs of fuel cell systems greatly differ depending on the type of fuel cells used. Also, since each type of system is only available in a certain capacity range, it is not possible to compare them directly.

Secondly, OPEX (operation expenditure) costs are again different. These running costs depend on several factors including type of fuel cells, fuel type, fuel availability and climate.

So when looking at costs, it is important to differentiate between lifetime, OPEX and CAPEX costs. And so the conventional way of looking at the price per kilowatt costs (where conventional technologies only differ by a few per cent depending on manufacturer) needs to be individually calculated for fuel cell type, system size and production volume.

Pike Research made a study in 2012, where data from the leading PEMFC manufacturers was gathered in order to calculate the actual average costs for these types of fuel cells (Figure 31). The price for PEMFC stacks range from 1,700 to 2,645 dollars per kW, however, these manufacturers are also experiencing a degressive "learning curve" of 10 – 20 %. This means that fuel cell costs drop by 10 to 20 per cent with every doubling of manufacturing volume (GW Installed).

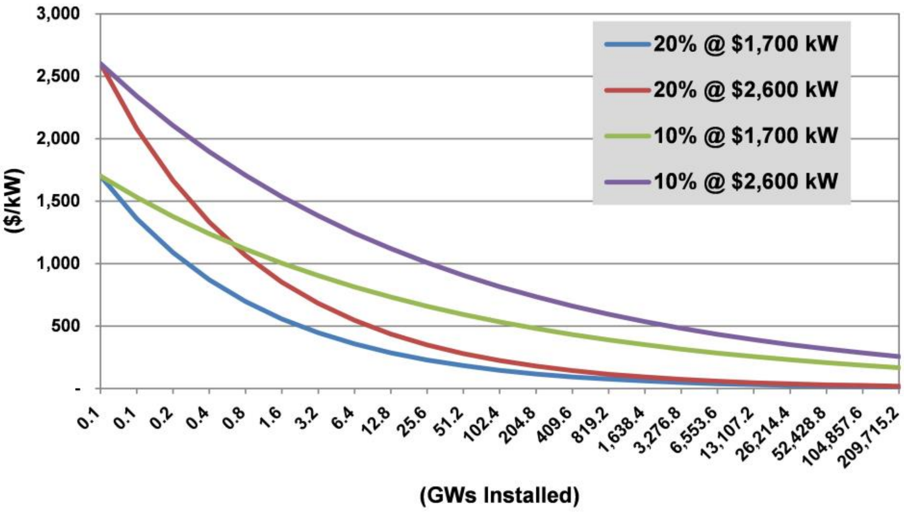


Figure 31 *– Graph showing PEMFC price per kW dropping in relation to the manufacturing "learning curve" made by Pike Research in 2012.*

These dropping PEMFC manufacturing costs are resulting in an overall price reduction for fuel cell systems in the long run. And when combined with the significantly lower OPEX costs than that of conventional technologies, the lifetime costs for fuel cell systems in many applications have already dropped lower than the lifetime costs for traditional power supply systems.

11. Recommended configuration for a small community

There are several small-scale renewable hydrogen systems in service today that deliver the energy needs of islands, small villages and off-grid communities. These types of systems are perfectly capable of supplying 100% clean energy with relatively high efficiency. So far most of these systems have been applied for single-family homes and for small communities, but they are scalable and could be expanded to fit the needs of a larger smart grid. The basic configuration for a bivalent clean hydrogen system is illustrated in Figure 32, and comprises the following elements:

Renewable energy sources

Solar and wind energy is used to generate electricity, which is then fed directly to the micro- or off-grid system. The excess energy (including production peaks and surplus energy during low-demand hours) is used to charge a battery bank, and after fully charging the batteries, to produce hydrogen gas. Biogas from agricultural waste and landfills can be directly converted to hydrogen by means of methane reforming.

Batteries

The battery bank serves as an energy buffer and can deliver high loads for short durations during peak demand. Once the batteries have been fully charged, the excess energy is routed to the electrolyser for hydrogen production.

Electrolyser

One or more electrolysers convert the excess electric energy into hydrogen to feed it to a compressor.

Compressor

A hydrogen compressor compresses the hydrogen at a high pressure for storage in tanks.

Storage tank

The pressurized hydrogen is stored in large tanks and serves as the main energy storage for later use. This can be a cylindrical or spherical stainless steel tank above the ground, or for larger scales, underground caverns and salt domes can be used.

Fuel cells

The fuel cells use the stored hydrogen to produce electric energy on demand. In a combined heat and power setup, the heat generated by the cells is used for room heating. The water from the fuel cell exhaust can be re-mineralized and used for drinking.

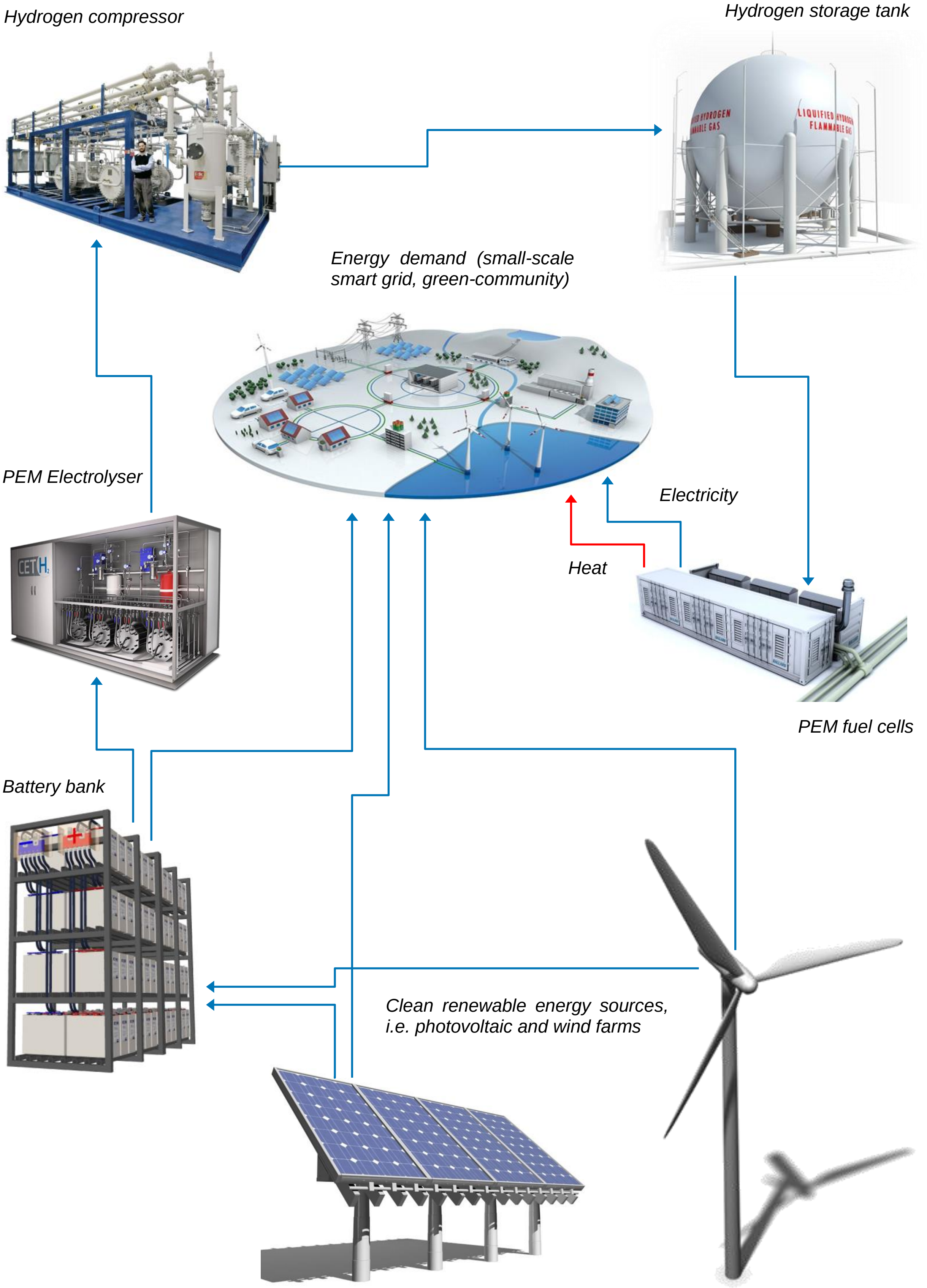


Figure 32 *- Simple representation of a clean hydrogen system*

12. Discussion & Conclusion

A hydrogen economy is conceptually a great and much needed part of the solution to today's energy crisis. In reality however, it faces major challenges and obstructions. A hydrogen economy in the transportation and energy sectors poses the chicken-or-the-egg causality dilemma. These big industries are reluctant to invest heavily into hydrogen technology because no infrastructure is available to produce and deliver hydrogen gas cheaply to power fuel cells. On the other hand, this infrastructure is not available because there is insufficient demand for hydrogen gas. So the question remains; what is needed for this type of paradigm shift in the energy sector? Some of the aspects that need addressing in order to facilitate this shift are a strong political promotion along with the passing of legislations in favour of hydrogen technology. Advances in hydrogen technology, fuel cell technology as well as in the transportation and the storage of hydrogen also need to be made. These are still fundamentally unresolved issues to date. However, the global boom in renewable energy demands efficient energy storage, and solar hydrogen obtained from water electrolysis, coupled to fuel cells to efficiently generate power when needed, is the right technological answer. Solar hydrogen is reaching maturity and the production costs are steadily dropping. The energy crisis unfolding with the end of "tight" (shale) oil by 2020 requires massive adoption of solar and wind energy, which in turn requires the use of FCs. Fuel cells are ready. The expensive Pt catalysts will be replaced by much cheaper metals, and the technology will shortly boom. Therefore, a realistic forecast would be five to ten years for the adoption of hydrogen technology on a big scale to become a reality.

With a shorter timespan in a smaller scale and with a more decentralized off-grid energy production strategy in mind, more and more people are already looking towards innovative technology such as hybrid hydrogen energy systems as this technology becomes cheaper and more widely available.

As discussed on page 13 of this paper (4.4. Global trends), the global energy trends indicate that fossil fuels are becoming scarcer and are making us increasingly dependent on unstable foreign countries. Thereby resulting in market price manipulation and offering us low "energy security". Additionally, nuclear has proved time and again to be a completely unsustainable and a hazardous option, and people are increasingly losing trust in this technology. This is driving more and more people towards the innovative and regenerative technologies such as solar, wind and hydrogen, for a clean, secure and affordable alternative. This is a slow process but it is gathering momentum and I am confident that we will be seeing exponential growth of these technologies in the coming years.

However, we cannot be naïve or take the stance of "Renewable energies - yes please, just not in my back yard" (NIMBY). We need to be realistic and consequent and realise that our good intentions can save some of our rainforests, offset some of our greenhouse gas emissions, but the old trends will not magically turn around until the capitalist model of growth and profit is terminated by the lack of energy and resources. The inevitable collapse of the petro-industry will eventually take care of this - but after how much damage to our planet? This is why we, the people, need to be the change we want to see in the world, rather than just sitting back and waiting for governments and corporations (or some old-politics revolution) to make things right again - the people in power in our present system will not do it because of the deep-seated human tendency to give in to the corruption and the greed.

Most of the solutions presented in this paper are industrial and technological in scope, designed to replace conventional power sources with solar, wind and hydrogen technology. But as we look deeper at the underlying problems, it becomes obvious that our irresponsible and unsustainable behaviour is determined by corporate grids of electricity, by resource usage, by transportation, by food availability, by material products, and so on. Perhaps what we really need first and foremost is a promotion for behavioural change. For local farming and agriculture. For small-scale sustainable off-grid communities. For vegetarian diets. For thinking outside of the box. For breaking free from the moulds of the established patterns of behaviour and becoming more conscious, and paying attention to the here and now. And all the rest will fall into place.

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Figure 8: Fuel cell timeline – Diagram:

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14. Appendices

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