Solar Hydrogen Systems

for Off-grid Energy Generation

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of the requirement for the degree in Dipl.
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To the men and women who believe in a better future and who make a difference by being the change they want to see in the world, and to the children who will not have the benefit of two billion years' worth of accumulated energy reserves.

~

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Signed: Kartik Isaac   Dated: 01.03.2016

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Foreword

The thesis of *Mr. K. Isaac* describes an issue of fundamental importance. The research and development in renewable energy has been neglected for many decades and thoughtless consumption of fossil resources has caused unfathomable damages to our planet. A paradigm shift is urgently needed, and in it, renewable energies will play a very significant role in the shift to a clean energy future. *Mr. K. Isaac* has chosen to work on solar hydrogen systems and his thesis makes a useful contribution to further understanding this outstanding technology.

The presentation structure of his work, with the six main chapters (solar energy, hydrogen, current status of solar hydrogen systems, solar hydrogen systems for residential application, proof of concept model) presents the reader with an excellent insight in this technology. The very interesting discussion section provides an objective and critical analysis of today's situation and ends with an inspiring call to action. In this paper, *Mr. K. Isaac* has succeeded in realising a vivid and exciting "journey" through the complex and fascinating field of solar hydrogen.

It would be very gratifying if this thesis would find many readers outside the *HBU*.

Prof. Dr.-Ing. Wolfgang Rienecker
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I. Abstract

Interest in solar hydrogen is on the rise, and it is beginning to shake up the energy and automotive industries. This disruptive technology could eventually displace established technologies and offer ground-breaking products that create a completely new industry. Its true potential will, however, only really be seen when fuel cell vehicles and hydrogen infrastructure capture a sizable share of the automotive and energy markets. Although fuel cell technology has experienced rapid progress in the past years, there are still challenges to overcome, such as the lack of hydrogen infrastructure and the political resistance from multinational interests that control the production and distribution of petroleum (*Big Oil*), before this technology reaches widespread adoption.

It is therefore necessary to circumvent these obstacles and to develop decentralised and off-grid solar hydrogen systems, both for generating heat and electric energy, as well as the energy needed for transportation in an affordable, clean and sustainable way. The process described in this paper explores the harnessing of the sun's energy (the most abundant source of energy on earth) and the storage of this energy in a power-dense and efficient way using hydrogen (the most abundant element in the universe).

One thing is clear; it is time to give up on fossil fuels and to embrace new technologies, and solar hydrogen systems could be the catalyst for a paradigm shift towards clean and affordable energy. This regenerative energy solution could potentially free us from finite and unstable fossil fuel dependency.

This thesis is a continuation of my work and research in the field of hydrogen technology and it consists of two papers describing clean hydrogen production, storage and distribution as well as power generation with fuel cells. The first paper *Hydrogen Fuel Cells: A Feasible Regenerative Energy Technology* (pre-thesis) [1] describes fuel cells as a regenerative energy technology and discusses their feasibility and integration in the future energy market. The second paper (this thesis) presents solar hydrogen technology for decentralised and off-grid power generation.

The two papers compose a synthesis of a broad array of research and findings, offering a viable and practical solution for a cleaner and more efficient energy alternative to the already existing ones. They comprise an analysis and review of the presently available literature on this technology. Scaled-down models of these systems are demonstrated alongside the documentations.

A choice was made to make the product of this thesis an easy to read paper in order to make it more accessible to the public and in particular to the creative and curious individuals in the open source grassroots movement. I worked closely with like-minded individuals to tailor my writing style and refrained from using too much technical jargon to suit this audience. In doing so, I have explained solar hydrogen technology in such a way that it can be easily understood by people without any background or technical understanding of it.

Both papers contribute to the research and development of solar hydrogen technologies for decentralised and off-grid energy generation, as well as in making these an interesting and attractive solution in the near future.

With the intention to share this knowledge and make it openly available to everybody, this paper has been released under the *CC Creative Commons License* and the *GNU Free Documentation License*.

Keywords: Solar hydrogen, photovoltaic, wind turbine, hydrogen, electrolyser, fuel cell, decentralised, off-grid, µ-CHP, micro-CHP, smart home.

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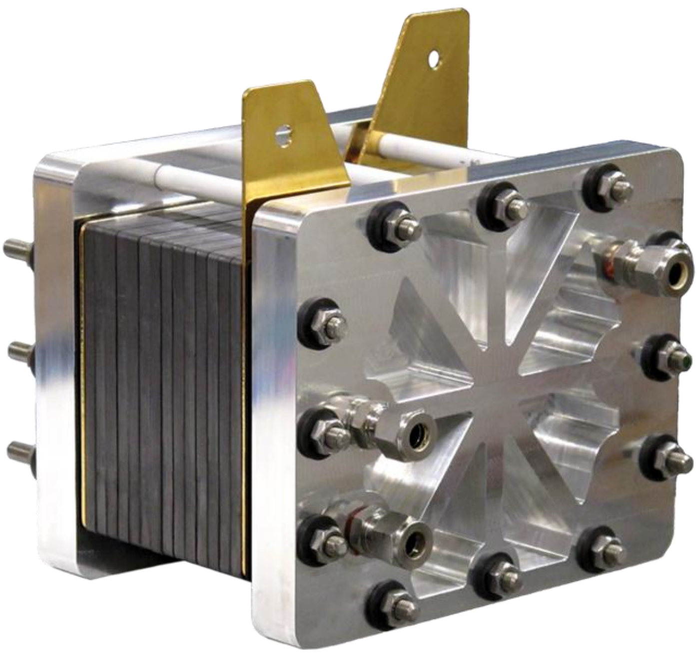


II. Glossary of terms & SI units

A	Ampere - SI unit of electric current [I] ($A = \frac{C}{s}$)
AC	Alternating current ∿
APU	Auxiliary power unit
bar	metric (not SI) unit of pressure [P] (1 bar = 100 000 Pa)
BEV	Battery electric vehicle
C	Coulomb - Si unit of charge [Q] ($C = A * s$)
CH_4	Methane - a chemical compound, main component of natural gas
CHP	Combined heat and power
CO_2	Carbon dioxide - a naturally occurring chemical compound
DC	Direct current ⎓
DMFC	Direct methanol fuel cell
EL	Electrolyser
EV	Electric vehicle
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FCV	Fuel cell vehicle
GHI	Global horizontal irradiation
H	Hydrogen - chemical element with symbol H and atomic number 1
H_2	The chemical formula for hydrogen gas
H_2O	Water - chemical substance
Hz	Hertz - SI unit of frequency [*f*] ($f = \frac{1}{T}$ where *T* is the period of one cycle)
ICE	Internal combustion engine
J	Joule - SI unit of energy [E] ($J = W * s = N * m = \frac{kg * m^2}{s^2}$)
K	Kelvin - temperature [T] unit based upon an absolute scale (0 K = −273.15 °C)
m	Metre - SI base unit of length [l]
MPPT	Maximum power point tracking
N	Newton - SI derived unit of force [F] ($N = kg * \frac{m}{s^2}$)
Nm^3	Normal cubic meter - temperature: 0 °C, pressure: 1.01325 bar
O	Oxygen - chemical element with symbol O and atomic number 8

O_2 The chemical formula for oxygen gas

O_3 The chemical formula for ozone - an inorganic molecule

P&ID Piping and instrumentation diagram

Pa Pascal **-** SI Unit of pressure [P] (1 bar = 100 000 Pa) ($Pa = \frac{N}{m^2}$)

PEMFC Proton exchange membrane fuel cell

POC Proof of concept

R&D Research and development

s Second - SI base unit of time [t]

SI International system of units (French: **S**ystème **I**nternational d'Unités)

SOFC Solid oxide fuel cell

STP Standard temperature and pressure

V Volt - SI derived unit for electric potential [V,U] ($V = A * \Omega = \frac{W}{A} = \frac{J}{C}$)

W Watt - SI derived unit of power [P] ($W = \frac{J}{s} = \frac{N*m}{s} = \frac{kg*m^2}{s^3}$)

WBS Work breakdown structure

W_p Watt-peak - nominal power [P] (photovoltaic)

Ω Ohm - SI Unit of resistance [R] ($\Omega = \frac{V}{A}$)

II.I. Table of unit prefixes

Prefix	Symbol	Factor	Example
pico	p	10^{-12}	1 pm = 10^{-12} m
nano	n	10^{-9}	1 nm = 10^{-9} m
micro	µ	10^{-6}	1 µA = 10^{-6} A
milli	m	10^{-3}	1 mA = 10^{-3} A
kilo	k	10^{3}	1 kW = 1000 W
mega	M	10^{6}	1 MV = 10^{6} V
giga	G	10^{9}	1 GW = 10^{9} W
tera	T	10^{12}	1 TB = 10^{12} B

1. Introduction

Our planet is presently facing an accumulating effect of multiple problems such as climate crisis, resource wars, economic meltdown, terrorism, oil spills, ecosystem breakdown, greenhouse gases, water shortages and smog happening at once. All of these problems have one common denominator; they are all the result of a total fossil fuel addiction. This crisis is evolutionary in nature, concealing in it a choice of destiny, and if the human species wants to survive on this blue planet, it asks of us to make a quantum leap forward.

The industrial revolution, which has made us increasingly dependent on a small number of large industries, is not working for the common good. It is consuming the earth's finite resources to serve an elite minority's interest, regardless of any consequences or long-term repercussions. This unsustainable model is based on a top-down corporate approach (similar to ant colonies) which finally needs to be toppled back into a bottom-up, power-to-the-people model. This kind of change would enable the democratisation of energy where a massive industry can no longer singlehandedly dictate the terms for the rest. The answer would be an ultimate clean and decentralised energy market that bypasses the large fossil fuel industries and power utilities.

Solar hydrogen is a promising and versatile technology that has the potential to enable this type of transition. This is especially true when using the technology for off-grid or distributed applications. In many instances, off-grid power supplies are used when a central grid is not available or not reliable or when grid-dependency is not wished. In some cases, being off-grid is primarily attractive for the fact that it is a lot cleaner, joule-for-joule, than being connected to a central grid: transmission losses are virtually eliminated and the renewable energy technology generates electricity a lot more efficiently than conventional power plants. This is especially true in combined heat and power (CHP) generation, where waste heat is used for heating. Another advantage of the nature of distributed power supplies is that it eliminates the very real and serious threat of massive power outages and blackouts.

Large electricity grids with power lines spanning long distances to connect every dependant consumer to a central system have large losses due to energy lost in the power lines (material conductivity and electrical resistivity). This loss can amount to anywhere from 5% to 20% depending on the distances, the metals used in the power lines and the efficiency of the components [2]. These large centralised grids (wide area synchronous grids) also require the phase (grid frequency) to match and be synchronised with the standard grid frequency in order to operate correctly. This is difficult and expensive, and contributes to the overall energy loss. Decentral and off-grid power supplies practically eliminate electric transmission loss thereby increasing the energy yield by a substantial amount.

This paper attempts to outline the many benefits of locally generating clean electricity and heat from available resources instead of transporting the energy from centralised power plants. It also attempts to identify the most promising methods of generating on-site renewable energy, and how that can increase the consumer's independence from fossil fuels, as well as offering energy security.

Finally, on the philosophical level, it seems that the world is ready for a quantum leap forward towards a future that belongs to clean energy. Will it be hydrogen? This thesis hints at this but does not make it clear, because it is not yet clear. There are, however, cogent arguments herein to back this assumption.

- Physically, because if we manage to use this source in a safe and economical way it would make perfect sense at this moment in time.
- Psychologically, the political changes and events that have occurred to make things better in our world in the past hundred years have all resulted in creating more liberty, equality and autonomy for the ordinary human being. There is work to be done still, and if the sourcing of people's individual energy needs to create a comfortable modern lifestyle can be individualised, then this will go very far to create a more ideal collective life.
- Spiritually, sourcing our energy from the most ubiquitous energy source in the universe seems to be the right thing to do.

I have written my pre-thesis [1] in the field of hydrogen fuel cell technologies and have become increasingly fascinated by the combined use of solar energy coupled with hydrogen technology and have taken up the challenge to explore the true potential of these technologies during the process of writing this thesis. I am also an avid supporter of the use of small and decentralised renewable energy systems to power an independent and transparent energy democracy. Another important motivating aspect of this project is to make this information available to the public in and easily understandable and freely available way.

The first part of this paper provides a description of solar energy as the primary source of energy that can be transformed in different conversion processes for distributed applications. The second part highlights the hydrogen basics and explores the production of clean hydrogen. The chapter outlining the current status of solar hydrogen systems provides system efficiency, costs, service life, and a long term perspective for the technology. It also describes the technical challenges and introduces an implemented solar hydrogen home. Chapter five of this paper highlights some of the newest stand-alone solar hydrogen systems and co-generative solutions presently in development. It also provides a recommended concept for an off-grid solar hydrogen home. Chapter six describes a solar hydrogen proof of concept study model in detail. The final part of this paper consists of an in-depth discussion on solar hydrogen and presents a future development scenario.

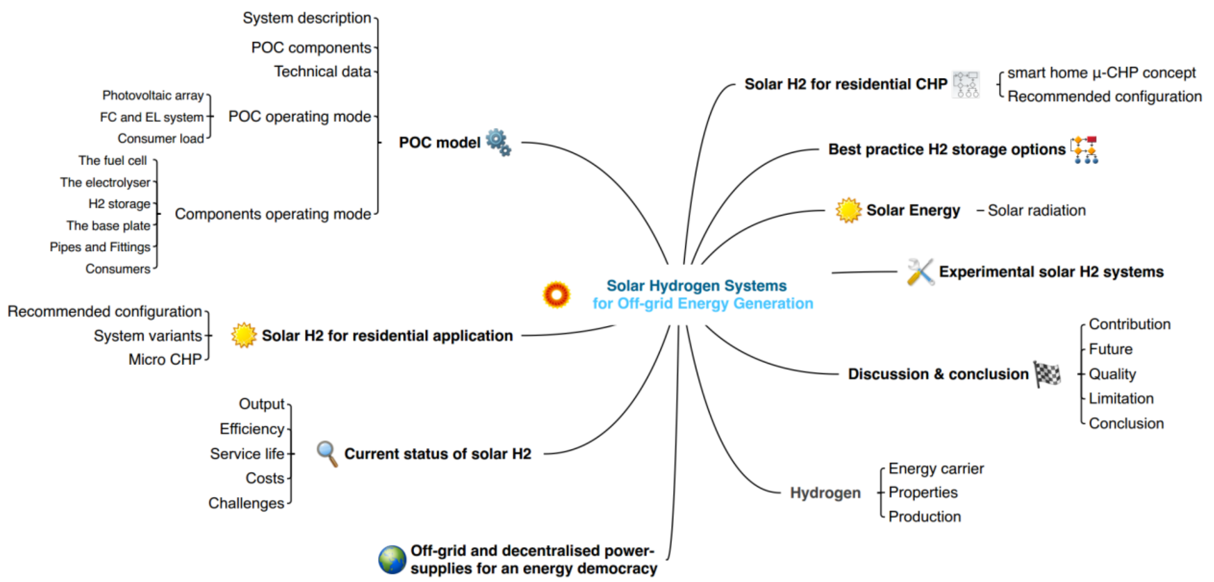
1.1. Project outline

All the data used in this paper has been found through the internet, as well as print copies at the *ETH Grüne Bibliothek* in Zurich. The respective sources have all explicitly been listed in the references section. A solar hydrogen study-model has been assembled for demonstration and learning purposes. The said model will also serve as a proof of concept in the presentation of this thesis, demonstrating the basic principles of a completely functional clean solar hydrogen system for off-grid application.

A mind map (illustrated in figure I) was used to visually organise the key information of each chapter and section of this thesis. It was created around the concept of solar hydrogen systems for off-grid energy generation, to which the associated representations of ideas were added. The major ideas were connected directly to the central concept, and other ideas branched out from those.

1.1.1. Mind map

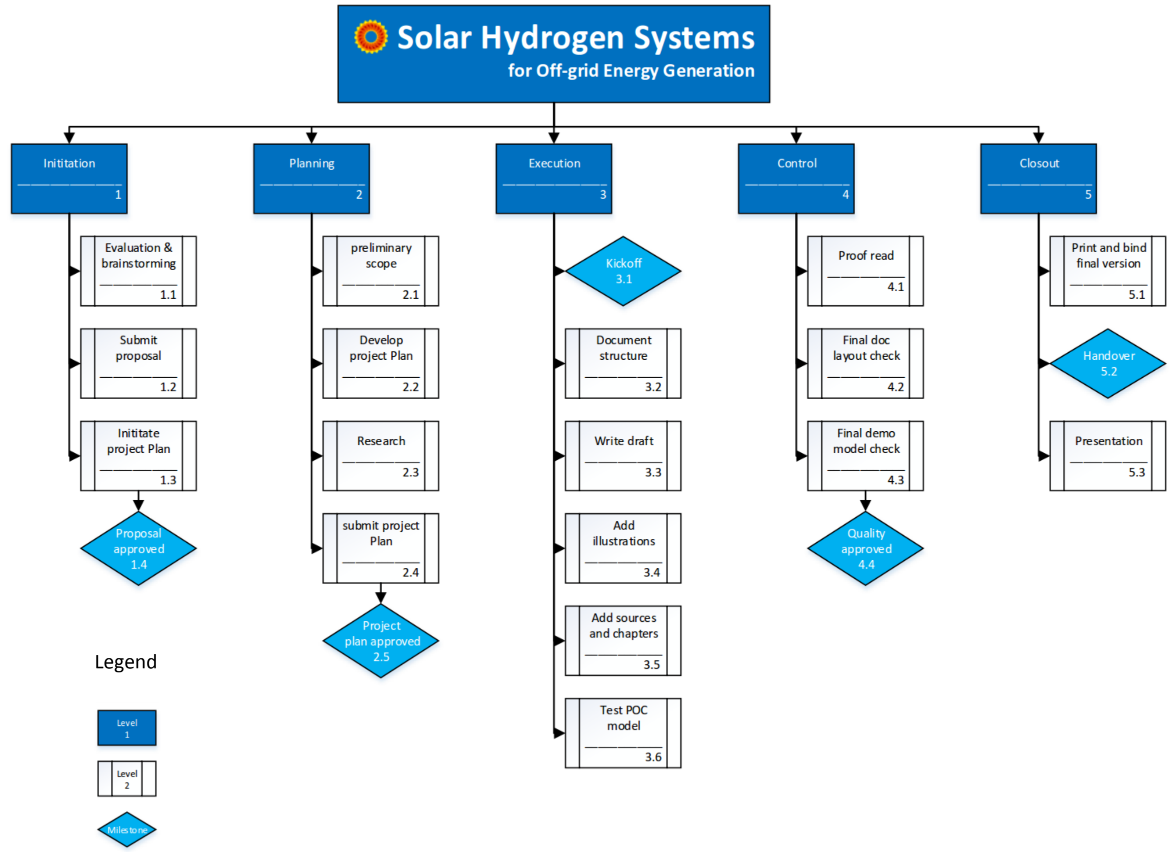
Figure: I: Mind map



With the overview of the project gained from the mind map, the next step was to methodically break down the project into manageable tasks. For this, a work breakdown structure was created. Each separate work packet of the project is depicted in figure II.

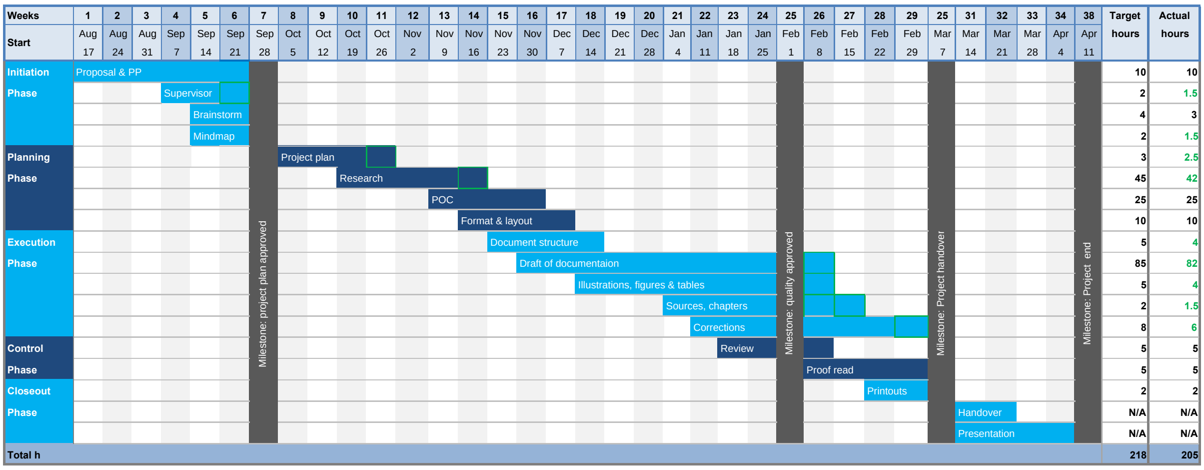
1.1.2. Work breakdown structure

Figure II: WBS



1.1.3. Target/actual performance comparison

Figure III: Project plan



The initial brainstorming and planning of the project did not demand much time, as I already had a good idea and a rather clear picture of how this final thesis project was to be a continuation of my pre-thesis project. The field of regenerative energy technologies presented in this thesis is one that truly fascinates me, and this has rendered the entire process more creative and very valuable. I have therefore been relatively expeditious and productive with the research and during the process of writing the draft. The project's initiation, planning, execution, control and closeout phases, and all the milestones I had set therein, were all accomplished in ample time (as seen in figure III).

1.1.4. Lessons learned

Despite the fact that the entire project amounted to many hours of intensive work, the overall resulting performance and efficiency of the work has proved to be extremely fruitful. As I had learned during the process of the pre-thesis project, breaking down the project into small and manageable work packets has made the entire process for this thesis a lot easier (figures II and III). I stayed true to the initial planning of the project and was able to accomplish all the goals I had set without stress or delay. This highly rewarding experience has fortified my ability to plan and work with increased efficiency, as well as my skills in project- and time-management.

2. Solar Energy

Solar energy in the form of sunlight is the earth's most significant source of energy. It is responsible for most of the primary renewable energy sources that we utilise today. The other important (yet much smaller) source of earth's energy is geothermal energy, which is generated from radioactive decay of materials within the earth's crust.

2.1. Solar radiation

The star at the centre of our solar system, the sun, is the single most important source of energy for life on earth. It continuously emits electromagnetic energy produced by the nuclear fusion processes at its core. In this nuclear process, two hydrogen nuclei combine to form one helium atom, and since the nuclear mass of the helium atom has a smaller mass than the sum of the mass of both hydrogen nuclei, the remnant of the nuclear mass is converted into electromagnetic radiation according to *Albert Einstein's* famous mass-energy equivalence formula:

$$E = mc^2$$

Where ***E*** is the energy in *Joules* [J], ***m*** is the mass in kilograms [kg] and ***c*** is the speed of light (299 792 458) in metres per second [m/s].

Most of the sun's visible radiation is emitted in the yellow-green light spectrum (classification as a *G2V* yellow dwarf) [3]. Its diameter is about 1.39×10^6 kilometres or 109 times that of earth's diameter. Its mass is approximately 330 000 times that of earth's mass and nearly seventy-five percent of it consists of hydrogen. The rest of the sun's mass comprises mostly helium and less than two percent of other elements. The sun, which is essentially a near-perfect sphere of extremely hot plasma, has a surface temperature of about 5 778 K (5 505 °C) [4]. The instantaneous electromagnetic power, which the earth receives from the sun per unit surface is known as solar irradiance, and is expressed in kilowatt per square metre [kW/m^2]. The sun's cumulative electromagnetic power per unit surface is known as solar radiation, and it is expressed in kilowatt-hour per square metre [kWh/m^2] [3].

Figure 1 shows the spectrum of solar energy and the amount available for photovoltaic conversion (illustrated in green). The bands of absorption seen in the spectrum are caused by ozone (O_3), carbon dioxide (CO_2) and water vapour (H_2O) in the earth's atmosphere [4].

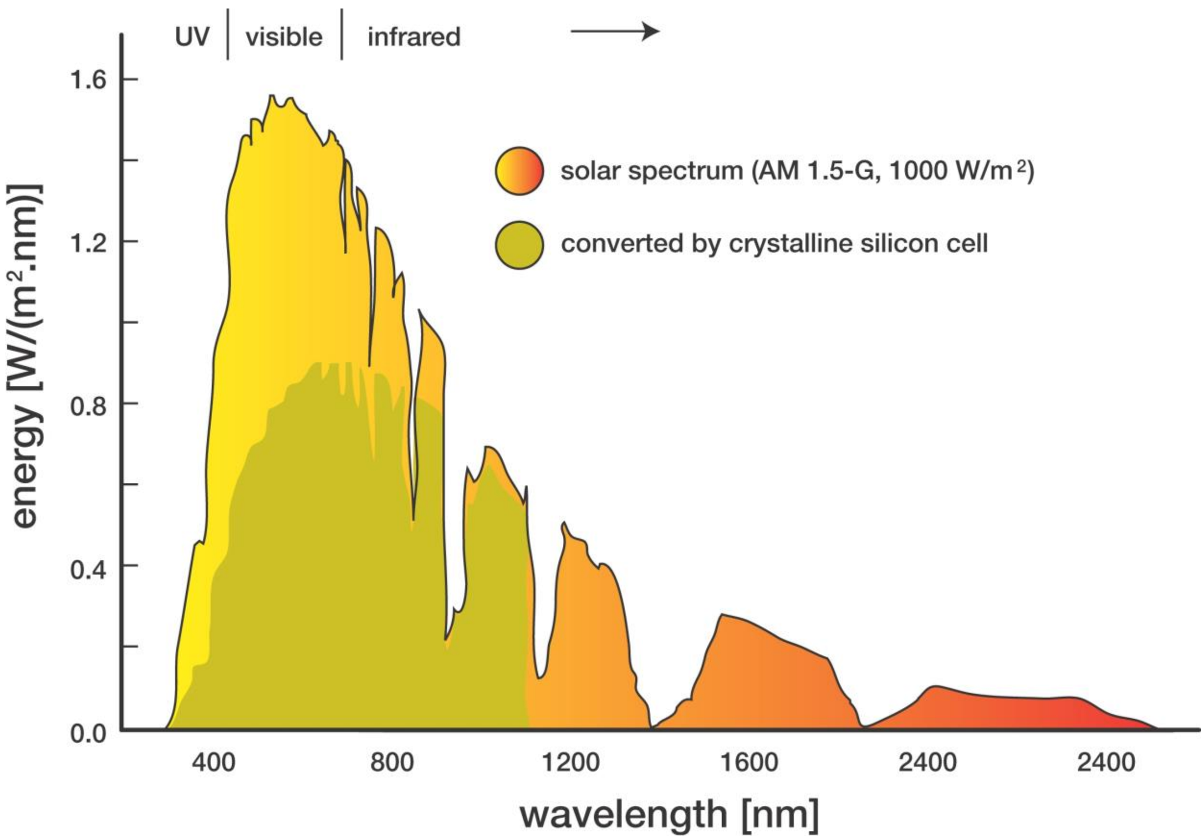


Figure 1: Solar spectrum at sea level as a function of wavelength

The solar constant is the amount of the sun's irradiance that is received on a surface outside of the earth’s atmosphere, which is perpendicular to the rays of light hitting it. The solar constant is made up of all the sun’s electromagnetic radiation and not just the visible light emitted from the sun. This value is around 1.37 kilowatts per square metre [kW/m^2] [5].

The amount of solar radiation absorbed by the earth’s surfaces greatly varies according to the sun’s position, the season, the geographical location, the local air mass and the meteorology. When sunrays encounter gases (CO_2, O_3, O_2, H_2O) and particles in the atmosphere, the solar radiation can be reflected back into space, partially absorbed or diffused in every direction. The part of the sun’s radiation, which does go through the atmosphere (after reflection, absorption and diffusion) and hits the surface of the earth is known as direct radiation. The rest of the solar radiation, which diffused in the atmosphere, yet still reaches earth’s surface, is known as diffuse radiation. To define the reduction in solar radiation as it passes through the earth’s atmosphere, the atmosphere thickness needs to be considered as follows:

$$\boldsymbol{AM} = \frac{\boldsymbol{P}}{\boldsymbol{P_0}\,\mathbf{sin}(\Theta)}$$

Where ***AM*** is the air mass index, ***P*** is atmospheric pressure, $\boldsymbol{P_0}$ is the atmospheric pressure at sea level (101325 Pa, 1.01325 bar) and ϴ (*Theta*) is the sun’s angle measured from the horizon. When the sun is perpendicular to the horizon and the altitude is sea level, the air mass index equals one ($AM = 1$) when ($P = P_0$) and ($\Theta = 90°$). AM is equal to two ($AM = 2$) at sea level when the sun is at 30° with the horizon. In Europe, we have a reference value of one and a half ($AM = 1.5$). This reference value is used for standardised tests on photovoltaic cells in laboratory conditions. Outside of the atmosphere where the solar radiation is able to pass unhindered, AM is equal to 0 ($AM = 0$) [3].

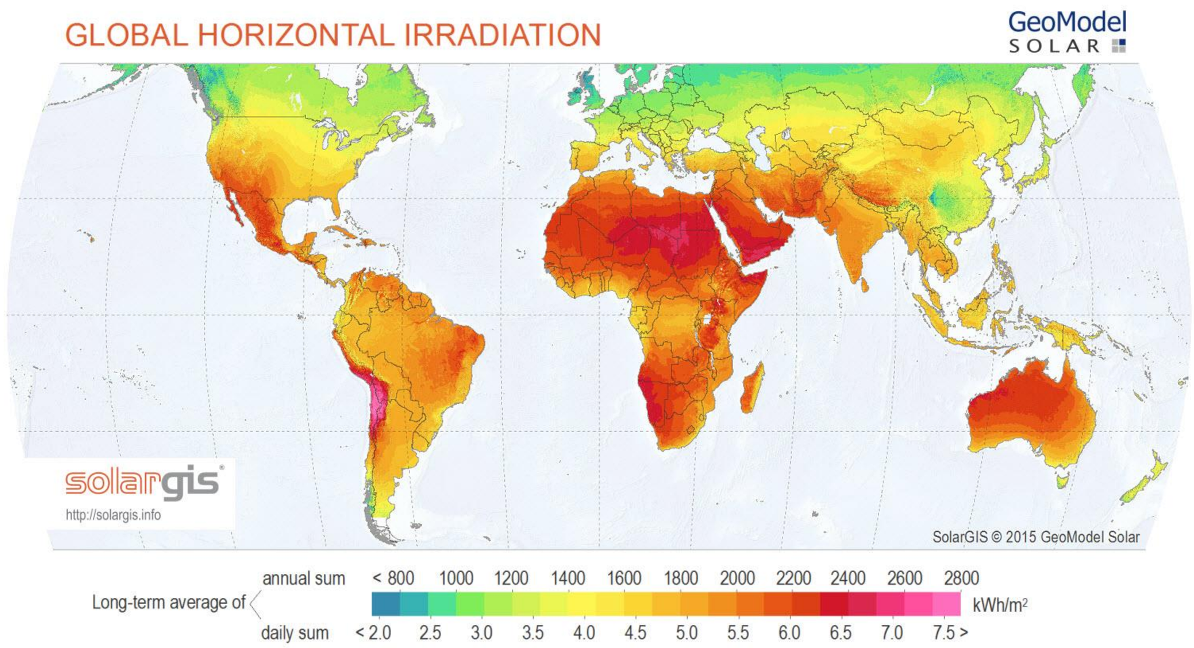


Figure 2: Global Horizontal Irradiation (GHI)

Global horizontal irradiation is the process by which the earth is exposed to horizontal radiation from the sun. The illustration in figure 2 shows the global solar potential of horizontal irradiation. The average annual solar irradiation passing through the earth's atmosphere and reaching the earth is estimated to be 1 kilowatt per square metre (1 kW/m^2) at sea level on a clear and sunny day [4].

2.2. Solar energy adoption

Mankind has come up with many different ways of tapping into the sun's energy. Some very innovative approaches have been made to convert this energy into a more convenient type of energy which is usable by an ever-growing number of applications. Among those are solar-thermal and photovoltaic technology; these are arguably the most feasible clean energy solutions available from an environmental point of view. Photovoltaics is presently experiencing a rapid growth rate and has surpassed all the other renewables [6].Due to the sinking prices of solar modules and solar power inverters, there are ever more solutions for a growing number of applications available on the market at an affordable price. This trend is clearly visible and is responsible for a large portion of the "early birds" in renewable energy adoption.

2.2.1. Solar energy conversion – photovoltaics

Photovoltaic technology collects the solar radiation emitted by the sun and converts the photons to electrons (electric energy) which can then be used to supply an electric load or, when produced in surplus, be stored for later use. Since the solar radiation that reaches the surface of the earth varies intermittently according to the meteorology, the time of day and the seasons, the storage of this energy is the key to render photovoltaic energy more predictable and reliable. The reason we only pull around 100 – 150 Watt out of an average photovoltaic module when we have upwards of 1000 Watts of solar irradiance per square meter is due to the fact that a typical solar cell has a conversion efficiency of around 14 to 20 percent [7]. This low conversion ratio is due to internal quantum efficiency of crystalline silicon wafers[1], the reflectance of the cell itself, the configuration and components of the system, as well as the spectral dependence[2] of the silicon making up the cell.

Figure 3: Solar panels

[1] A wafer is a thin slice of crystalline silicon used in photovoltaics for wafer-based solar cells.
[2] The range in the spectrum of light in which light-absorption of a material is permitted.

2.2.2. Wind energy

The second promising technology that uses the sun's energy to generate electricity is the wind turbine. We now know that when the sun shines, some of its light reaches the earth's surface, warming it up. Some parts warm up more than others and other parts reflect more of the suns energy. For example, dark coloured soil or rock absorbs more energy and heats up more than water or snow (which reflects more of the light). When the sunlight warms up the darker surfaces it heats up the air above creating a temperature difference between two or more surfaces. Moreover, since warm air is lighter and less dense than cold air, this creates a pressure difference too. This basic meteorological phenomenon is responsible for wind; the sun creates temperature differences, which in turn creates the pressure differences that produce wind. The illustration in figure 4 demonstrates this principle with the land and sea breeze.

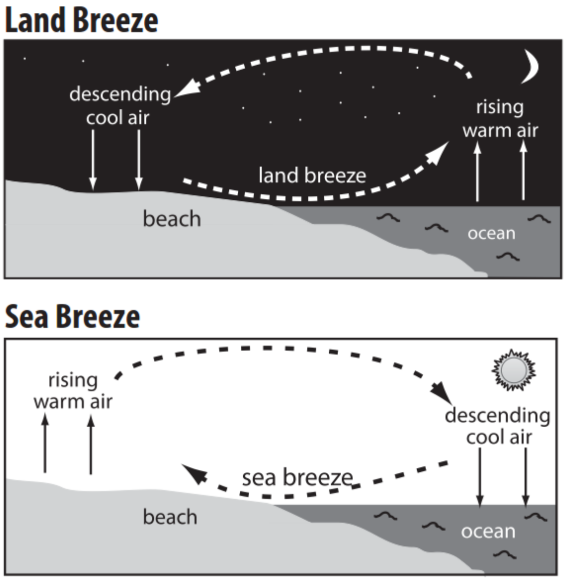


Figure 4: Land and sea breeze principle

Wind turbines have been developed to use this wind energy to produce clean electricity. When the wind blows, it pushes against the wind turbine's blades causing it to turn. This rotary movement is used to turn a generator, which produces electricity -as depicted in figure 6.

As is the case with solar, wind power is also experiencing a rapid growth rate. The global capacity of installed wind turbines has more than doubled every three years since 1995 [6].

Photovoltaic and wind power are on a significant growth path and are becoming a convincing source in today's energy mix. They have unquestionably established themselves in the energy market and are coming out on top as a feasible, clean and sustainable energy solution. In their current growth trajectories, these technologies will become the cheapest and most sensible choice in the near future. They will pave the way for the mitigation of climate change and the replacement of fossil fuels [1].

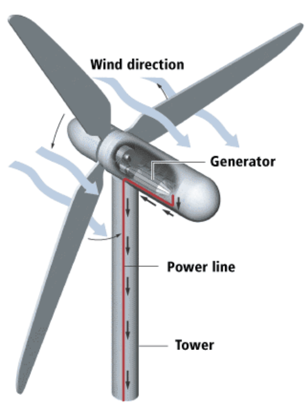
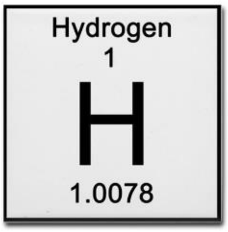


Figure 6:
Illustration of wind turbine, left

Figure 5:
Wind turbines, right

3. Hydrogen



is the first element in the periodic table and has the atomic number 1. In its monatomic state (H) it is the least dense of the elements and by far the most abundant substance in the universe, constituting around 75% of it. At ambient pressure and temperature and in its diatomic molecular state (H_2), hydrogen is a tasteless, odourless, colourless and non-toxic gas. It is also extremely energy-dense and is often described as the most flammable substance known to man. In contrast to most of the fuels in use today, this highly reactive gas is carbon-free, one hundred percent renewable and has all the qualities to be a fuel for a wide range of applications.

Conventional energy sources such as fossil fuels are rapidly being depleted and need to be replaced by clean and renewable alternatives. Hydrogen, despite all the disinformation spread by *Big Oil*, fulfils all the criteria (and more) for a new fuel and it is a perfect candidate for a future energy carrier. The nature of hydrogen does however, come with some challenges. Although it is abundant, it still needs to be extracted, stored and distributed safely before it can be used as an energy carrier. It is therefore critical that these processes be safe and environmentally sound. The obvious choice of energy used for these processes is solar electricity. Solar electricity encompasses all the main renewable energies (i.e. photovoltaic, wind, hydro) for which the sun is responsible.

3.1. Hydrogen as a potential energy carrier

Since our present primary energy sources, such as carbon, crude oil and natural gas will run out in the future, we are beginning to wonder what our future energy supply will look like. In a new energy environment, we would like to be able to avoid the kinds of problems that we face with conventional energy resources. This is why the search is on for renewable energy sources that are CO_2-neutral and do not produce problematic waste during power generation. To meet the demands of the ever-increasing energy consumption, it is clear that renewable energy technology is the answer. The advantage with renewables is that they are safe, regenerative, clean, and readily available. The main disadvantage with them, however, is that most of the renewables are intermittent sources. For example, with solar energy, the intensity of solar radiation is not constant and varies from day to day and throughout the seasons. In the case of wind, there is also no fixed pattern to ensure constant energy production. Therefore, not only do we need a clean and environmentally friendly energy carrier, but also an efficient and reliable storage technology in order to offer a constant and high-availability energy solution.

As mentioned above, one such candidate is hydrogen. It stands out especially because its combustion product is pure water. Hydrogen does not exist in nature as a primary energy medium that is easily tapped, although it is present in many chemical bonds. The most common is water (H_2O). The extraction of hydrogen from water requires electric energy - the generation of which cannot be regarded as clean at present. Therefore, the further development of renewable and emission-free power generation for a future emission-free energy scenario is of critical importance. In this, hydrogen plays the role of an energy carrier and storage medium, which allows, for example, to store solar-generated electricity and retransform it at a later time (for example at night) into electric energy. This is why the development of hydrogen storage options is also very important.

The storage of hydrogen can be achieved in a number of different ways; these are described in my pre-thesis [1]. A low cost alternative that is chosen for the recommended concept in this paper is compressed gas of up to 50 bar in low-pressure metal cylinders. This type of storage matches well with the capabilities of current electrolysers to produce hydrogen under pressure for direct storage without the use of compressors. This option is thus very cost-effective, because the compression achievable by new PEM electrolysers considerably reduce the necessary storage volumes. Using this method, the additional costs, as well as the reduction in overall system efficiency by the compressor are avoided. These auxiliaries significantly lower the net energy production of a given hydrogen system, and therefore, designing small-scale solar hydrogen systems without these auxiliaries improves performance and efficiency [8].

The international scientific community has already made big advances in hydrogen technology, and has thus laid down the foundation for a future hydrogen economy. The main factors for a global adoption of this technology are its cost and the efficiency of hydrogen production, storage and distribution. As soon as these costs drop lower than the costs of fossil fuel production, *Big Oil* will lose its advantage and control on the energy markets. As with any technology, free market demand and competition dictates the price. Solar hydrogen is no exception to this rule; it is a technology and not a fuel and it will therefore become cheaper and more efficient with time. The progressive shift of this disruptive technology would unleash the true potential and the massive adoption of hydrogen as an energy carrier.

3.2. Hydrogen properties

Hydrogen is about fourteen times lighter than air, making it the lightest of the elements in the periodic table. Hydrogen undergoes a phase change from its gaseous state to its liquid state at a temperature of 20.26 K (-252.8 °C). It is an extremely buoyant gas, which is highly diffusive in the ambient air resulting in a rapid dispersion when released into the atmosphere. These properties of hydrogen gas pose some challenges for safe and economic storage.

The nontoxic, colourless, tasteless and odourless gas has a lower energy density per unit volume than fossil fuels (in both compressed and liquid state), but its energy density per unit mass is greater than any other conventional fuel. It has a specific energy of 142 MJ/kg, which is about three times greater than that of diesel and petrol. Hydrogen readily ignites across a wide range of hydrogen-to-air-ratios of about 0.04 to 0.74. The energy released during the combustion of hydrogen and the properties thereof make it well suited as an energy carrier.

The combustion, as well as the electrochemical reaction (cold combustion) of hydrogen in combination with oxygen, both produce energy. The by-product of these energy-releasing reactions is water vapour. Due to the highly reactive characteristics of hydrogen gas, safety measures against leakages resulting in combustion or asphyxiation need to be taken. In the presence of oxygen, hydrogen will immediately ignite when coming in contact with heat sources, sparks and flames. A stoichiometric hydrogen-to-air mixture, where all the hydrogen is consumed upon reaction and where the maximum combustion energy is achieved, contains 29.5 volume-percent of hydrogen. This proportion of hydrogen-to-air makes the flame practically invisible and thus requires the use of hydrogen flame detectors for safety. The oxygen-hydrogen combustion in the main engine of a space shuttle seen in figure 7 produces a practically invisible bluish flame. In comparison, a space shuttle's solid rocket booster engine produces a highly visible flame with a large trailing plume of smoke and water vapour.

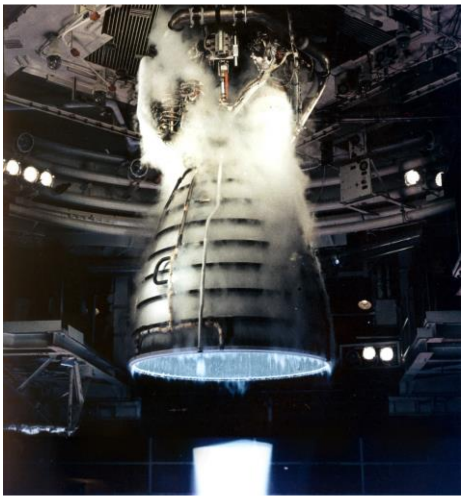


Figure 7: Oxygen-hydrogen combustion in the main engine of a space shuttle.

Below are some of the main properties of hydrogen [9]:

H_2 properties	Value
Name	Hydrogen
Symbol	H
Atomic number	1
Period	1
Element category	Diatomic non-metal
Colour	colourless
Phase	gas
Thermal conductivity	0.1805 W/(m·K)
Density (gas) at stp (0 °C and 101.325 kPa)	0.0899 kg/m^3
Density (fluid) (-252.8 °C)	70,9 kg/ m^3
Melting point	- 259.2 °C
Boiling point	- 252.8 °C
Gas constant	4,127 Ws/kgK
Low heating value	3.00 kWh/Nm^3
High heating value	3.54 kWh/Nm^3

3.3. Hydrogen production

Hydrogen is a promising and potential solution for a clean and sustainable energy society and the production method of hydrogen gas plays a crucial role in proving how it fulfils the requirements of being clean, renewable and environmentally friendly. The low-density gas can be produced using various molecules or compounds containing hydrogen atoms (i.e. water, biomass, hydrocarbons), to be used as an energy carrier with virtually no polluting emissions. Since it is not found in its pure element-form, it is necessary to separate it from the above-mentioned sources. This energy-consuming separation process is classified in the following categories: bio-chemical, photonic, thermal and electrical energy processes. If the energy source used for these processes is generated with clean and renewable energy technologies, then it is a carbon-neutral and sustainable energy path.

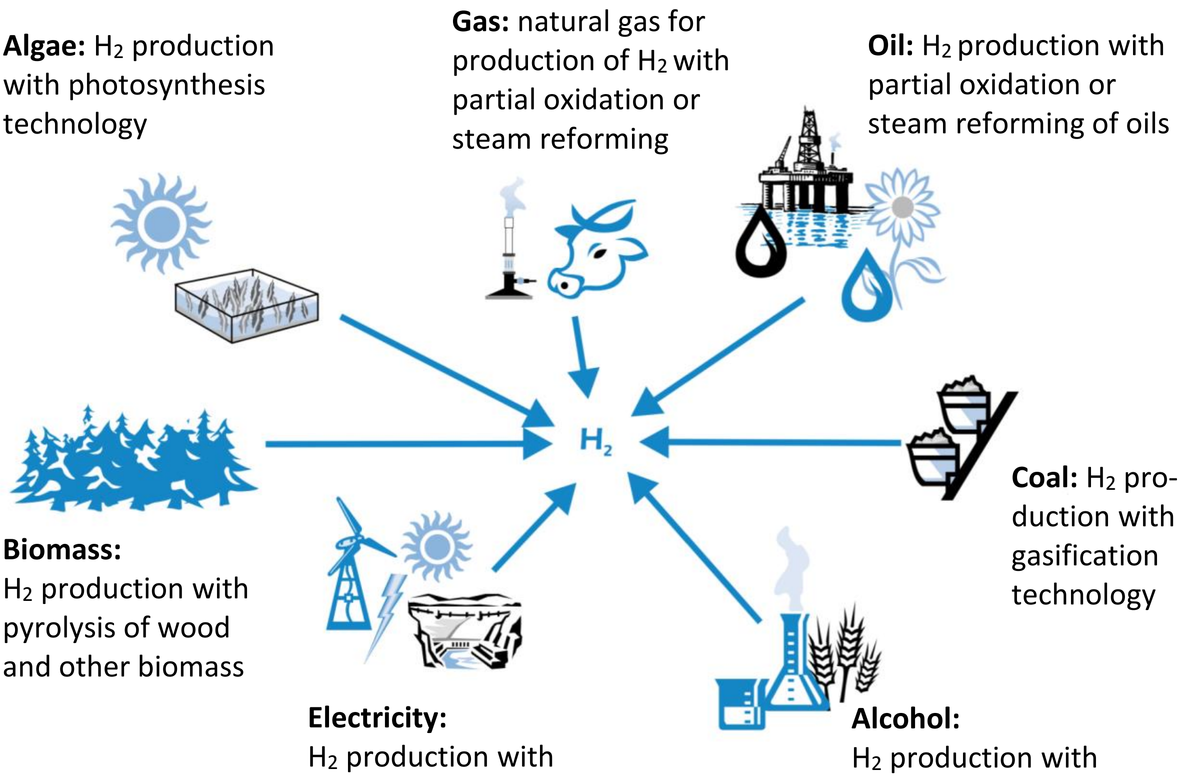


Figure 8: Hydrogen production methods

Practically any source of energy (nuclear, hydrocarbons, as well as renewable energies such as solar, wind, hydro etc.) can be used in the conversion process to produce hydrogen gas. The most common sources of hydrogen are water, fossil fuels and biomass – figure 8 illustrates all the methods available. Water and biomass are clean and carbon neutral while hydrocarbons are more efficiently extracted, but all of these sources can be utilised to produce the ultimate energy carrier - hydrogen. Today most of the hydrogen gas is produced by catalytic steam reforming fossil fuels, this equates to about forty-eight percent of the global hydrogen production. This is the most financially economical process to date in the short run, but unfortunately, it has a negative impact on our atmosphere in the long run and is dependent on finite resources.

3.3.1. Water electrolysis

The following is an excerpt from *Hydrogen Fuel Cells: A Feasible Regenerative Energy Technology* wherein the topic of water electrolysis is covered in more detail.

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

Electrolysis is the process of splitting water molecules (H_2O) into its constituents; hydrogen (H_2) and oxygen (O_2) using an electric current. 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 utilises a PEM electrolyser, which is basically a reverse PEM fuel cell (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 hydrogen production. Storing the excess solar energy from wind turbines or photovoltaic arrays in the form of hydrogen - or *bottled sunshine*, can greatly improve the overall efficiency of a smart energy production, storage and distribution system. Hydrogen gas makes it possible to store the energy for long periods with virtually no loss, and it can directly be used for a wide array of applications, not just for electricity production. [1].

3.3.2. Solar-driven hydrogen production

As we have seen, hydrogen can be separated from its bonds with other elements in various ways. The common manufacturing method however, imposes concerns due to the decline in fossil fuels as well as the high CO_2 outputs and the impact that this has on the environment. Therefore, all industrial uses of hydrogen produced with fossil fuels involve the above-mentioned problems. Hydrogen production technologies without greenhouse gas emissions are therefore the optimal solution, which is possible when using biomass gasification or renewable power sources such as geothermal, wind and photovoltaics to produce hydrogen through water electrolysis. Biomass gasification used to obtain hydrogen may even be referred to as having a net zero carbon footprint when calculating the carbon dioxide absorbed during the photosynthesis phase. The second and most promising method to create clean hydrogen is the use of water electrolysis using regenerative energy such as solar and wind.

Solar energy has been shown to be the most economical and more importantly sustainable way to produce H_2 this way [10]. A big potential is also seen in the photo-catalytic water splitting technology, which splits water into hydrogen and oxygen directly with the use of sunlight. This is an attractive solution for generating energy while releasing no harmful gases into the environment, however, the cost of production still needs to be overcome. Research is now focussing on increasing the efficiency and stability of the photoactive materials in order for it to be generated on a big scale [11].

4. Current status of solar hydrogen systems

There have been few experiments with off-grid solar hydrogen systems in the past, and today the number of fully autonomous solar hydrogen homes can be counted on the fingers of one hand. These systems all have a few fundamental components in common to convert the sun's energy into electricity and heat, and to store and distribute this energy when needed. These components are photovoltaics and/or wind turbines to produce electricity, batteries to buffer the electricity flow, an electrolyser to produce hydrogen with the surplus electricity, a tank to store the hydrogen and fuel cells to convert the hydrogen into electricity when required. These components can be integrated and controlled in different ways depending on the requirements of the system.

An off-grid solar hydrogen system is considered to have energy-autarky when: The sun is the only external source of energy. The system has no connection to the central grid. The residents only use the energy that is generated year-round and stored by the system for household and mobility needs.

Every system is designed for a specific purpose and gives priority to either system efficiency, service life or power output. Therefore, any such system is always a compromise between these three aspects, and where a particular system is found in this triangle depends on the system requirements. Figure 9 shows these three aspects with their corresponding applications: i.e. a hydrogen fuel cell system for mobile (automotive) application would require a high energy density (power-to-weight ratio) and high power output, which would inevitably result in a relatively lower efficiency and service life.

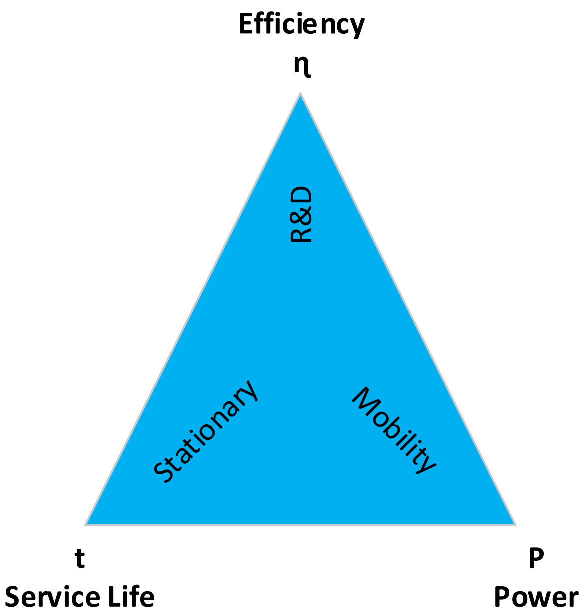


Figure 9: Performance-efficiency-service life-triangle

Since very little reliable data exists on current solar hydrogen systems, it remains to be seen how well these systems perform. However, one thing is certain: this technology has a myriad of advantages for off-grid applications, and it is just beginning to catch on.

4.1. System efficiency

The efficiency of a solar hydrogen CHP system can approach 98 % when the waste heat generated by the fuel cells and electrolyser is recuperated and used for room heating. The Sankey diagram below (figure 10) shows the flow of energy through the different system components and the respective efficiencies of a small-scale, low-pressure solar hydrogen system. These values vary according to system size, materials used and setup [12] [13].

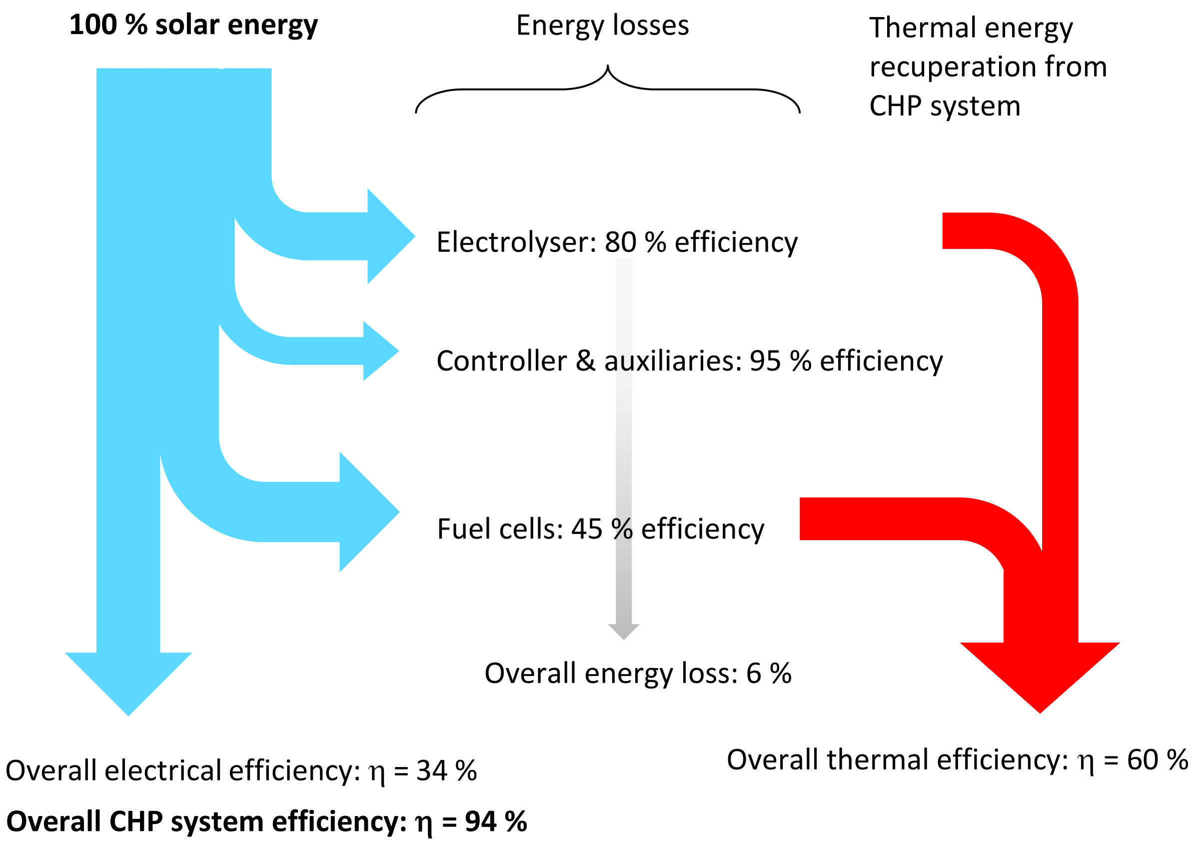


Figure 10: CHP system efficiency Sankey diagram

The Sankey diagram represents the small-scale, off-grid solar hydrogen residential heat and power system described in figures 17 and 18 where state of the art components are used. Each system is unique and will perform differently according to numerous parameters, so a generalised efficiency estimation is therefore unrealistic and inconclusive.

4.2. Service life

Due to the fact that these types of systems are very rare and that the existing ones are still too young to be able to give us any usable data, only rough estimates can be made to determine the service life. By looking at the individual durability of the system's components, we can get a good idea of the overall lifetime:

Most manufacturers of solar panels offer a 25-year warranty, guaranteeing that power output will not be less than 80 % of the rated power after 25 years. That is the guaranteed minimum, and most quality monocrystalline panels will have no problem exceeding 30-40 years without a huge loss in power output.

Batteries and inverters typically need to be replaced every 5-10 years [14]. This is an important factor to consider when planning a PV-only system, as these components are very expensive and need to be replaced relatively frequently. This drawback can partially be solved by opting for an off-grid DC, instead of an AC solar hydrogen hybrid system.

PEM electrolysers and fuels cells for stationary use are able to run for approximately 40 000 - 60 000 h with a degradation of below 20 %. As an example; a PEM fuel cell or electrolyser running 24 h a day would theoretically last around 7 years before it would drop below 80 % of its rated output. In a real life solar hydrogen application however, an electrolyser would only need to run for an average of about 4-5 h per day (Switzerland). The fuel cells in such a system would on average need to run for about 6-10 h per day.

4.3. System costs

Because the cost of a fully autonomous solar hydrogen system is highly system-specific and because very little data on such systems exist, a cost effectiveness study cannot reliably be calculated. As with photovoltaics, fuel cell technology has been around for a long time and has only recently experienced new interest and research and development (R&D) efforts. For photovoltaics this process is already well underway, however, commercial fuel cell technology adoption is still in its infancy and the technology is therefore still overpriced. As soon as the true potential for this technology is recognised, we will also see a huge decrease in production costs resulting from the mass production of fuel cells and electrolysers in China. Until then it is fair to say that considering the present low fossil fuel prices, solar hydrogen systems are less commercially viable than conventional grid-connected fossil fuel solutions. This means that interest in these systems are presently mostly coming from environmentally-conscious and off-grid homesteaders whose primary interest is not a purely financial-profitability one. Hydrogen system costs are further described in the discussion section.

4.4. Technical challenges

Many of the challenges of hydrogen technology have already been solved and the technology is available and ready to use. The material challenges and safety concerns of hydrogen fuel cells and electrolysers pose no threat to future adoption. The challenges are mostly systems-integration and cost-related ones. All the necessary components needed to build complete hydrogen systems already exist for specialised and isolated applications, but there is a lack of compatibility between system components. In order to seamlessly integrate the available technology for cost-effective use in solar hydrogen systems we still need to see manufacturers agree on norms and standards for interoperability and easy system-integration. This will only happen once large-scale production is available at lower costs. As soon as this happens, we will also see the free market forces do their work, offering more efficient systems at lower prices.

4.5. The long term perspective of solar hydrogen

The growth rate over time of hydrogen technology is represented in figure 11. This is qualitative forecast of how market growth for this technology may unfold in the near future.

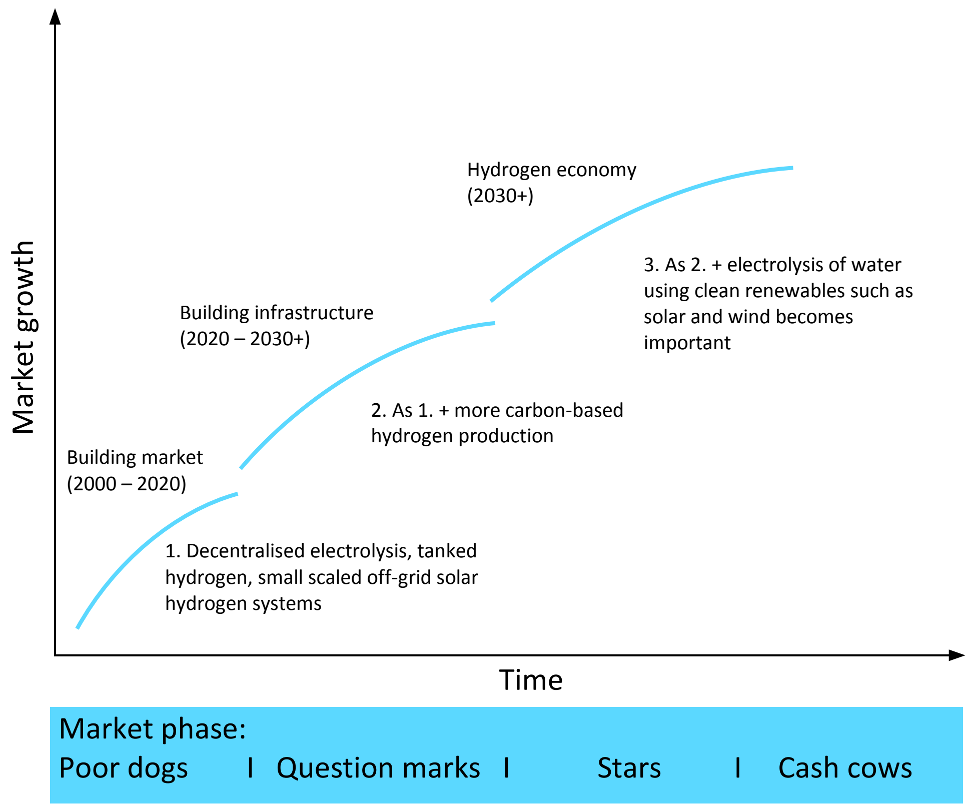


Figure 11: Hydrogen market growth matrix

This type of forecast is not, however, all-inclusive, and cannot be used for an accurate quantitative prediction, but can serve as a simple tool to view the hydrogen technology market future at a glance, and may even serve as a starting point to discuss the allocation of resources among strategic players. For a more detailed analysis of the hydrogen market and R&D needs, recent specialised papers discussing each technology in greater details should be sought.

The year 2015 has been a milestone in the hydrogen timeline; several large automobile manufacturers have announced plans to build state-of-the-art fuel cell vehicles (FCVs) and some have already started mass production. Some leading European manufacturers of heating, ventilation and refrigeration systems have also developed cost-effective fuel cell CHP solutions for residential application. The recent introduction of plug and play hydrogen solutions into the niche market is a big step forward for the widespread adoption of the technology. The next few years will certainly be very revealing and will determine the future of hydrogen.

4.6. Example of an implemented solar hydrogen home

A new development in solar hydrogen is the *Phi Suea House* project in Chiang Mai, Thailand, which generates photovoltaic electricity and stores the energy as hydrogen for later use with fuel cells. The project consists of four houses as well as some purpose-built buildings. When fully up and running, the system will have 114 kW of photovoltaics producing around 441 kWh per day. Part of the surplus energy will be stored in 2 000 Ah batteries, and the rest will be converted into hydrogen gas by electrolysers. The gas will be stored until needed, i.e. during the night-time, at which point it will be converted by fuel cells into electrical energy.

Figure 12: The Phi Suea House project in Chiang Mai, Thailand

The system will reportedly be capable of producing hydrogen at a rate of 2 000 l per hour and will be able to store 90 000 l in the hydrogen tanks seen in figure 13.

Figure 13: Hydrogen production and storage at the Phi Suea House project

In order to improve the efficiency of the houses, solar-thermal panels will be used to produce hot water, eliminating the need to electrically heat water. The passive house[3] will have thickly insulated walls, double-glazing on the windows, natural ventilation with energy-efficient fans to decrease the use of air conditioning, as well as large windows for natural lighting and efficient LED electric lights [15].

While hydrogen technology has plenty of critics due to pricing, system efficiency and safety concerns, the project has been built with focus on safety, and has proven to operate more efficiently than similar setups using batteries only. This project was inspired by remote sites designed by the communications industry running similar systems. With the success of the project, it has become a model, especially for houses located in remote regions.

The system is built entirely with existing technologies and there is a 15-year return on investment on these technologies. The aim of the project is to show that the solar technology that exists right now, really works.

The solar hydrogen system is currently undergoing testing with reduced loads, and should be operational and up and running for normal use shortly [15].

[3] Passive house (from Passivhaus in German) refers to a rigorous standard for energy efficient buildings, which greatly reduces their ecological footprint.

5. Solar hydrogen system variations for residential application

We are only since very recently beginning to see stand-alone plug and play hydrogen systems for residential applications in the market. Most of these are still in the development phase and some have recently been introduced to the market. These types of user-friendly, finished products are just what is needed to make solar hydrogen more commercially viable and more widespread. The following systems briefly described here are a first step for this type of technology, however, they already offer a very feasible alternative to the conventional systems and seem attractive enough for large-scale production in the near future.

5.1. Simple photovoltaic hydrogen system

The *Solar Hydrogen Trainer* seen in figure 14 is a simple stand-alone 400 Wp off-grid PV system coupled with an electrolyser, battery and fuel cell to produce and store surplus energy as needed.

The system includes a smart monitoring system, which enables complete balancing of the solar hydrogen production. Performance and generation information of the photovoltaics, electrolyser, electronics and battery are displayed in an included software and can be logged for optimising and troubleshooting. Energy flow between components can be visualised and monitored. The mobile PV modules have an adjustable inclination angle and optional solar sensors allowing for optimised solar power generation [16].

Figure 14: Solar Hydrogen Trainer from Heliocentris

The lightweight and modular system can cover AC loads up to 700 W and is easily extendable. Remote monitoring via network makes this type of system truly versatile and is well suited for small off-grid homes and remote service areas where backup power is needed.

5.2. Combined heat and power hydrogen fuel cell systems

At present, domestic stand-alone CHP fuel cell systems are still in development stages, so not much data is available. *Viessmann* plans to be the first manufacturer to launch a commercially viable fuel cell heating device in Europe. The company claims that the unit will offer electrical efficiency that is double that of current CHP solutions.

The *Vitovalor 300-P* shown in figure 15 is still under development by *Viessmann* and *Panasonic*. It is a fuel cell based micro CHP unit for the generation of electricity and heat. The PEM fuel cell runs on hydrogen and air, where the hydrogen is either directly supplied by an electrolyser, or is derived from natural gas (biogas) using an integrated reformer.

The stand-alone unit delivers 19 kW, which is sufficient thermal output to cover the heat demand of an off-grid home all year round. 15 kWh electricity covers the base power demand in an average household. The integrated gas boiler starts up automatically when the waste heat from the fuel cell stack is insufficient, i.e. at peak times or when lots of hot water is needed at once [17].

Figure 15: Vitovalor 300-P stand-alone CHP system

Specification	Values
Fuel cell module electrical output	750 W
Fuel cell module thermal output	1000 W
Peak load boiler thermal output (gas)	19 kW
Electrical efficiency of FC	37 %
Overall system efficiency	90 %
Fuel cell type	PEM

Another new CHP fuel cell system in development is the *Galileo 1000 N* from *Hexis* seen in figure 16. It is designed to meet all the heating and basic electricity needs of a single family home. The solid oxide fuel cell stack runs on natural gas generating an electrical output of 1 kW and a thermal output of about 2 kW, which is recuperated from the waste heat of the fuel cell. When the heat requirement surpasses this value, an integrated gas burner supplies up to 20 kW of additional thermal energy. This type of system is ideal for off-grid homes or farms with a biogas setup [12].

Specification	Values
Fuel cell module electrical output	1000 W
Fuel cell module thermal output	1800 W
Peak load boiler thermal output (gas)	20 kW
Electrical efficiency of FC	35 %
Thermal efficiency of FC	60 %
Overall system efficiency	95 %
Fuel cell type	SOFC

Figure 16: Galileo 1000 N CHP system from Hexis

5.3. Solar hydrogen µ-CHP concept

Arguably, the most advantageous solar hydrogen concept is the use of distributed and off-grid µ-CHP hydrogen smart homes that are fully autonomous, but can also join a decentralised micro-grid and be part of a democratic energy market. In this type of concept, every home can become its own power station, and each home can be interconnected in micro grids that are able to send power to any prosumer[4] in the energy network. They are not only able to just generate their own electricity; they can also join a network and pool in the surplus energy to form virtual power stations.

This principle is contrary to the industrial revolution that made us increasingly dependent on a small number of large companies. Now, after a communication revolution (the internet), we will have an energy revolution where we can locally generate our own power and supply it to each other as we choose. This type of setup makes it possible to form an ultimate decentralised energy market, enabling us to bypass the large dirty power utilities.

In the solar hydrogen µ-CHP concept presented in the paper, the energy from the sun is collected by PV arrays on the roof as well as a wind turbine, and is fed to a small battery bank. The batteries act as a short-term buffer and supply electricity to the home's consumers as needed when the sun is shining and/or the wind is blowing. The system is slightly over-dimensioned and generates a surplus of energy, which is used to produce hydrogen with a PEM electrolyser. The hydrogen is stored at low pressure (20-50 bar) in cylinders; this method eliminates the need to compress the hydrogen. At night, or when the weather does not permit for sufficient energy production, the stored hydrogen is routed to fuel cells that produce electricity on demand.

Instead of using a single large fuel cell CHP system to power the whole house, a small peripheral fuel cell is situated in each heated room producing the required electricity, and the waste heat is directly used for room heating at the point of generation. This is the most efficient concept possible as it keeps the system simple and offers the highest waste heat thermal output. A solar-thermal array provides hot water, and when demand is high, a backup electric heater can additionally be operated.

The stored hydrogen is also available for cooking with a hydrogen gas cooker, running an H_2 absorption refrigerator in the kitchen as well as for use with an FCV for transportation. All the different systems are integrated in a network using open source *Raspberry Pi*[5] home automation. All systems can be monitored and controlled remotely via the network, making it a truly smart and versatile smart home setup. Since all components in the system are modular, it is very easy to extend and increase the power output according to future energy demands. This allows for easy planning and configuration as well as lowering costs by virtually eliminating the need for expensive system upgrades of non-modular systems. The basic configuration for this type of system is illustrated in figure 17 on the following page. The function of the system is described in figure 18.

[4] A prosumer is both a consumer and producer of electricity.
[5] An ultra-low-cost credit-card sized open source *Linux* computer developed by the *Raspberry Pi Foundation*.

5.4. Recommended configuration for an off-grid solar hydrogen μ-CHP home

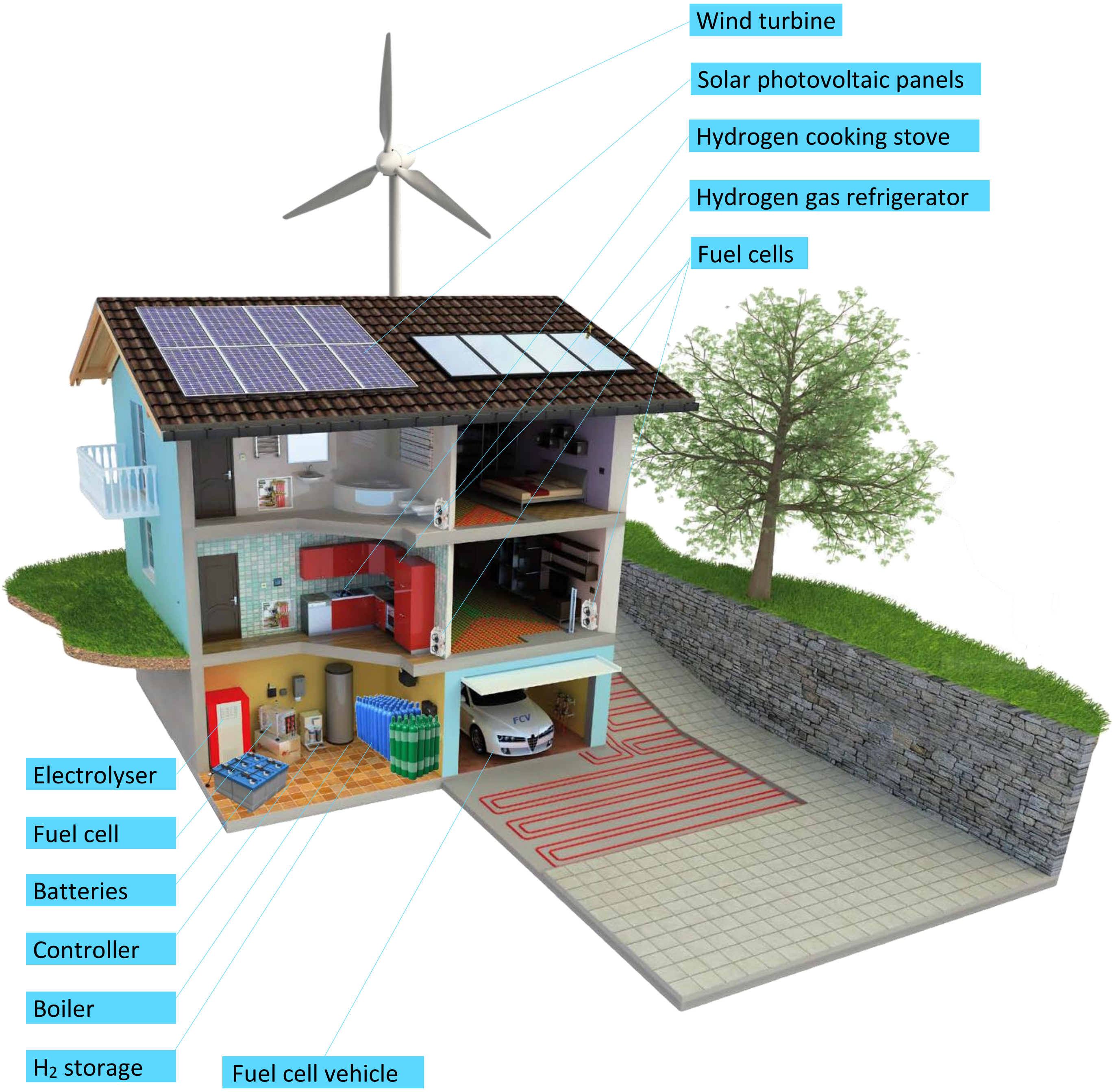
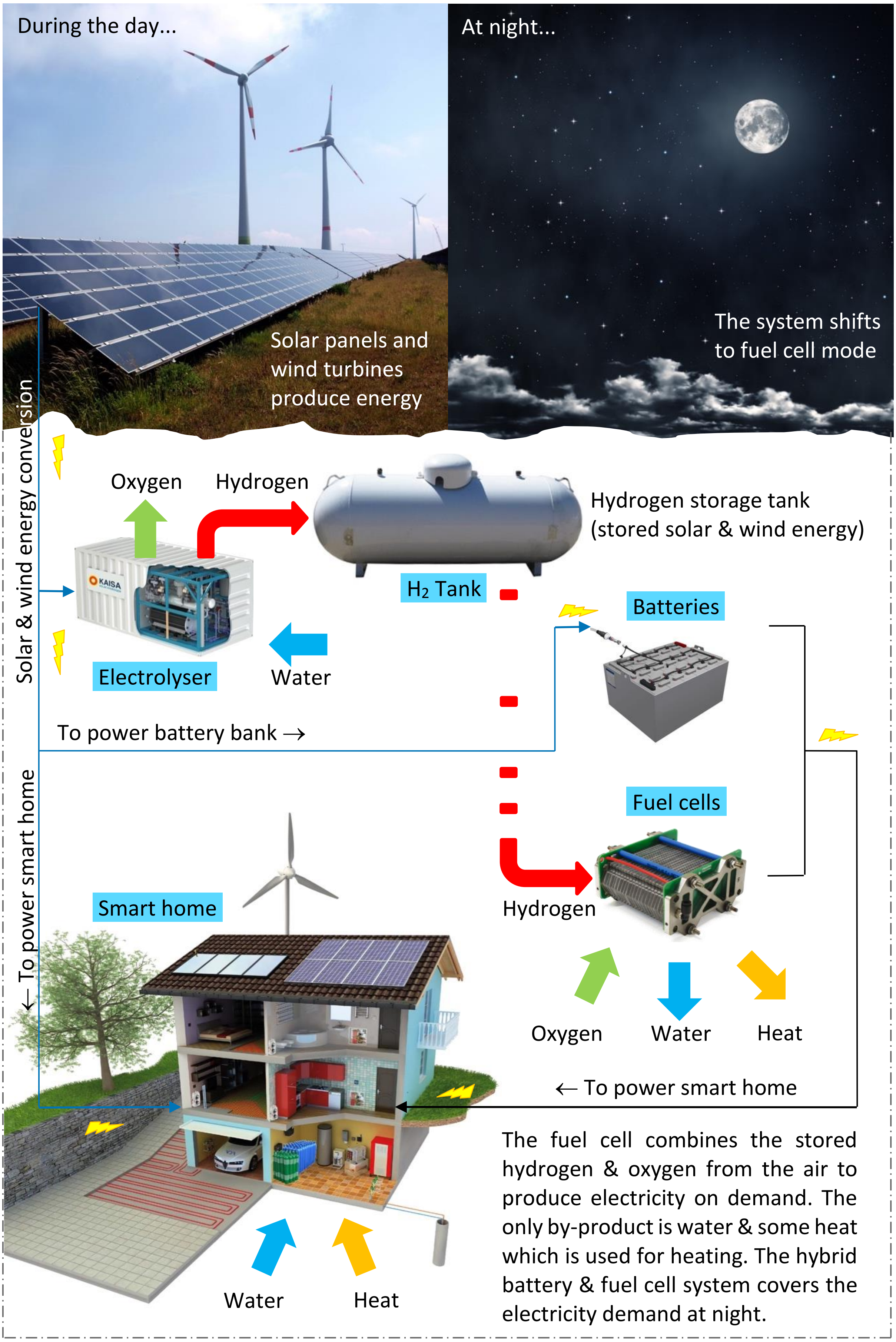


Figure 17: A smart hydrogen home concept

Figure 18: Function of the smart hydrogen home concept during the day and at night



This paper has presented the main options for the production, storage and supply of hydrogen for decentralised and off-grid applications. Below is a summary of the main findings with respect to present technology status, most viable options, and the main R&D problems that still need to be addressed:

Electricity source:
(Photovoltaics)
Status: commercially available at moderate costs
Best option: Monocrystalline rooftop modules
R&D challenges: efficiency, heat management, production cost, service life
(Wind turbines)
Status: commercially available at moderate costs (small-scale turbines)
Best option: micro wind turbines for off-grid residential application
R&D challenges: Noise reduction, production & installation costs, service life

Electrolyser:
Status: commercially available at high cost
Best option: PEM hydrogen generators (no-compressor-type)
R&D challenges: efficiency, material properties, production cost, service life

Hydrogen storage:
Status: commercially available at moderate cost
Best options: low-pressure metal cylinders (20-50 bar) for small-scale, off-grid, stationary, no-compressor systems. Carbon fibre composite tank (350-800 bar) for mobile applications.
R&D challenges: fracture-resistance, safety, energy density, volume reduction

Battery:
Status: commercially available at high cost
Best option: high-performance lithium-ion or lithium-iron-phosphate batteries
R&D challenges: energy loss, service life, manufacturing costs, material properties

Fuel cell:
Status: commercially available at high cost
Best option: proton exchange membrane fuel cells
R&D challenges: material properties, production cost, service life, efficiency

System integration and control:
Status: Highly innovative open source computing at extremely low cost
Best option: *Raspberry Pi*, *Arduino*
R&D challenges: System stability and compatibility, energy consumption, performance

These finding are not all-inclusive, and detailed descriptions of the technology and R&D needs should be sought in specialised scientific papers discussing each technology in greater detail.

6. Proof of concept model

The scaled-down solar hydrogen system presented with this thesis offers a miniaturised system concept that has been assembled for educational and demonstration purpose. The proof of concept model is an emission-free solar hydrogen energy supply system arranged in a chain of the following order:

Solar energy (PV module) → energy buffer (battery) → hydrogen (electrolyser) → storage (volume storage tank) → electric energy conversion (fuel cell) → external load (DC motor with propeller).

The proof of concept (POC) hydrogen system seen in figure 19 has been assembled using components from *h2-interpower GmbH* and *Power Avenue Corporation.* These start-up companies based in Bayern, Munich produced high quality small-scale fuel cells and electrolysers. These components are no longer available due to the high cost of small scale and custom-built manufacturing.

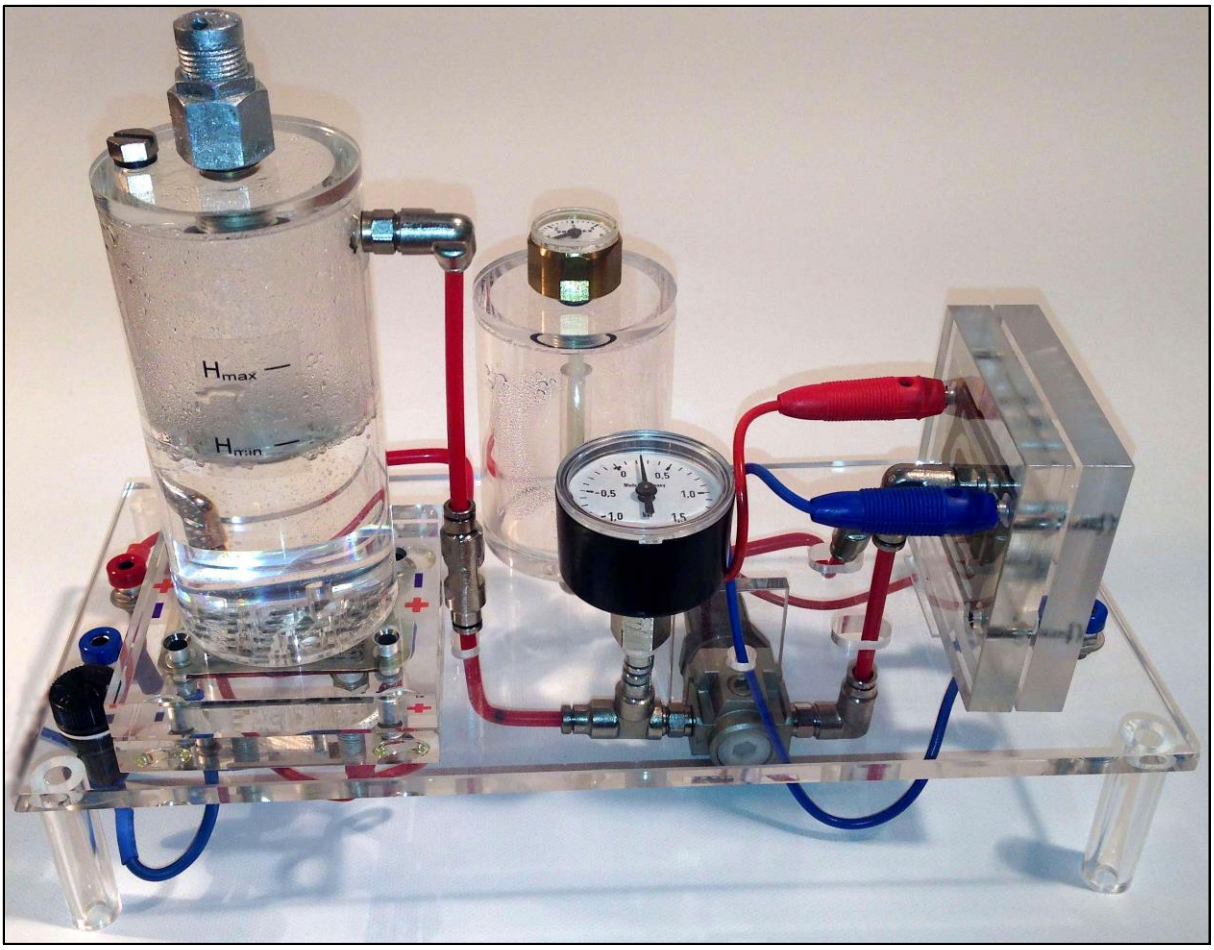


Figure 19: POC hydrogen system

The PEM fuel cells seen in figures 20 and 21 are proton exchange membrane type fuel cells housed in an acrylic casing for protection. Each cell produces a no-load voltage of about 0.9 V and a recommended load of 0.7 V with a short circuit current of 3 A and a nominal power of 1 W. These cells can be stacked together in parallel to increase the current or connected in series to up the voltage in order to meet an application's requirements accordingly.

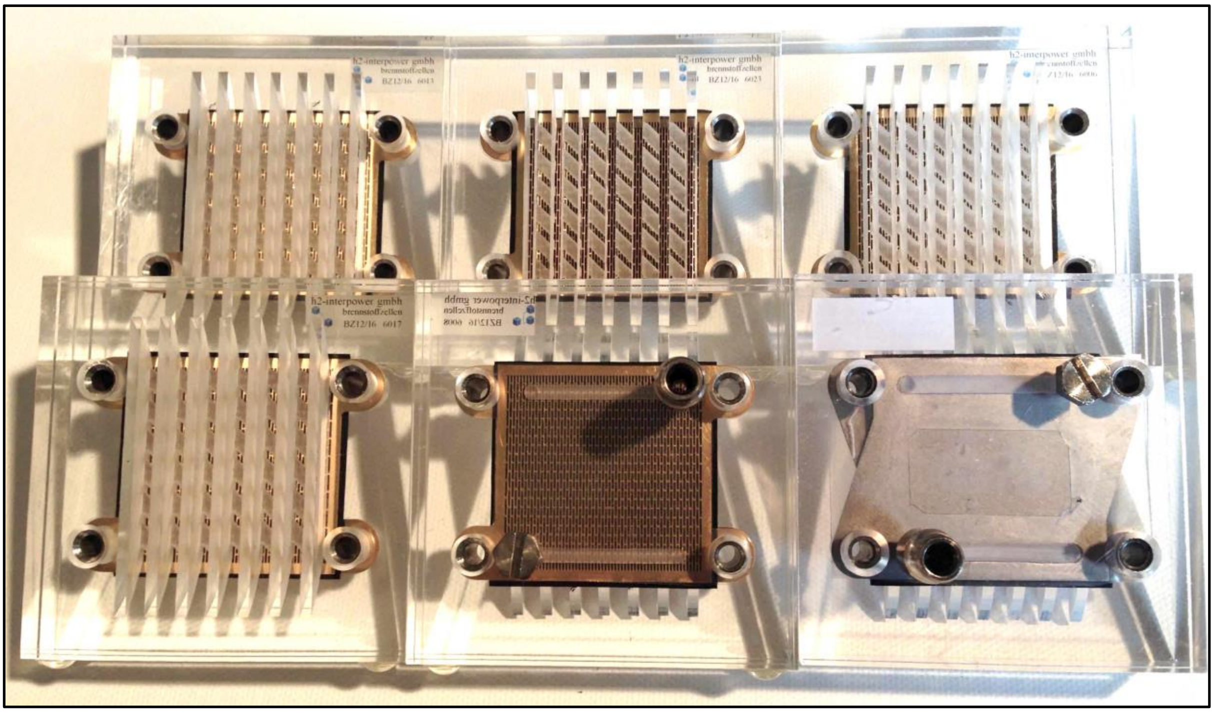


Figure 20: PEM fuel cells

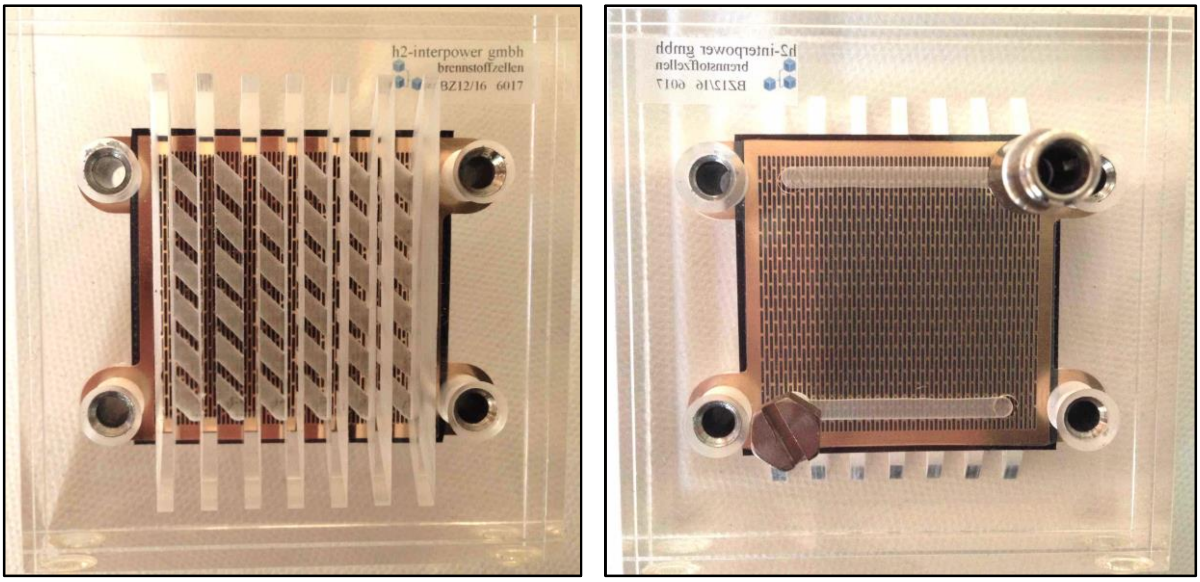


Figure 21: Oxygen-side and hydrogen-side of fuel cell

Figure 21 shows the atmospheric air-vent side of the PEM fuel cell on the left. On the right is the flip side with hydrogen gas inlet and outlet ports. Both sides have electric connectors.

The power unit seen in figure 22 is a portable solar charger purchased from *Powertraveller* – an outdoor electronic device manufacturer that produces rugged outdoor devices for extreme environments.

Figure 22: The Solarmonkey adventurer solar charger

The unit's integrated battery with charge controller makes it possible to use a small-dimensioned fuel cell, resulting in improved overall system efficiency and cost-effectivity. The battery/fuel cell hybrid system offers advantages over a fuel cell-only system. These advantages include energy storage and buffering, high current output for short periods, less dynamic energy demand and load on the fuel cell, all resulting in optimal performance.

The solar cells of the solar panel generate a no-load voltage of about 5 V and so are able to act as power supply for the electrolyser as long as there is sufficient light. The best light source for the solar hydrogen module is obviously natural sunlight. If the POC model is to operate where no sunlight is available, an electric light source can be used as a substitute. However, because the energy absorption of photovoltaic cells relies on the broader spectrum of sunlight, electrical lighting is less efficient than sunlight. When using electrical lighting, a sufficient distance between the light source and the solar panel must be assured in order not to damage it. The use of a 500 Watt halogen bulb, for example, requires a distance of at least 0.5 metres. In addition, the light should be directed onto the panel evenly and as close to perpendicular (90° to the panel) as possible. Figure 25 shows the different characteristics of the solar module under different light sources.

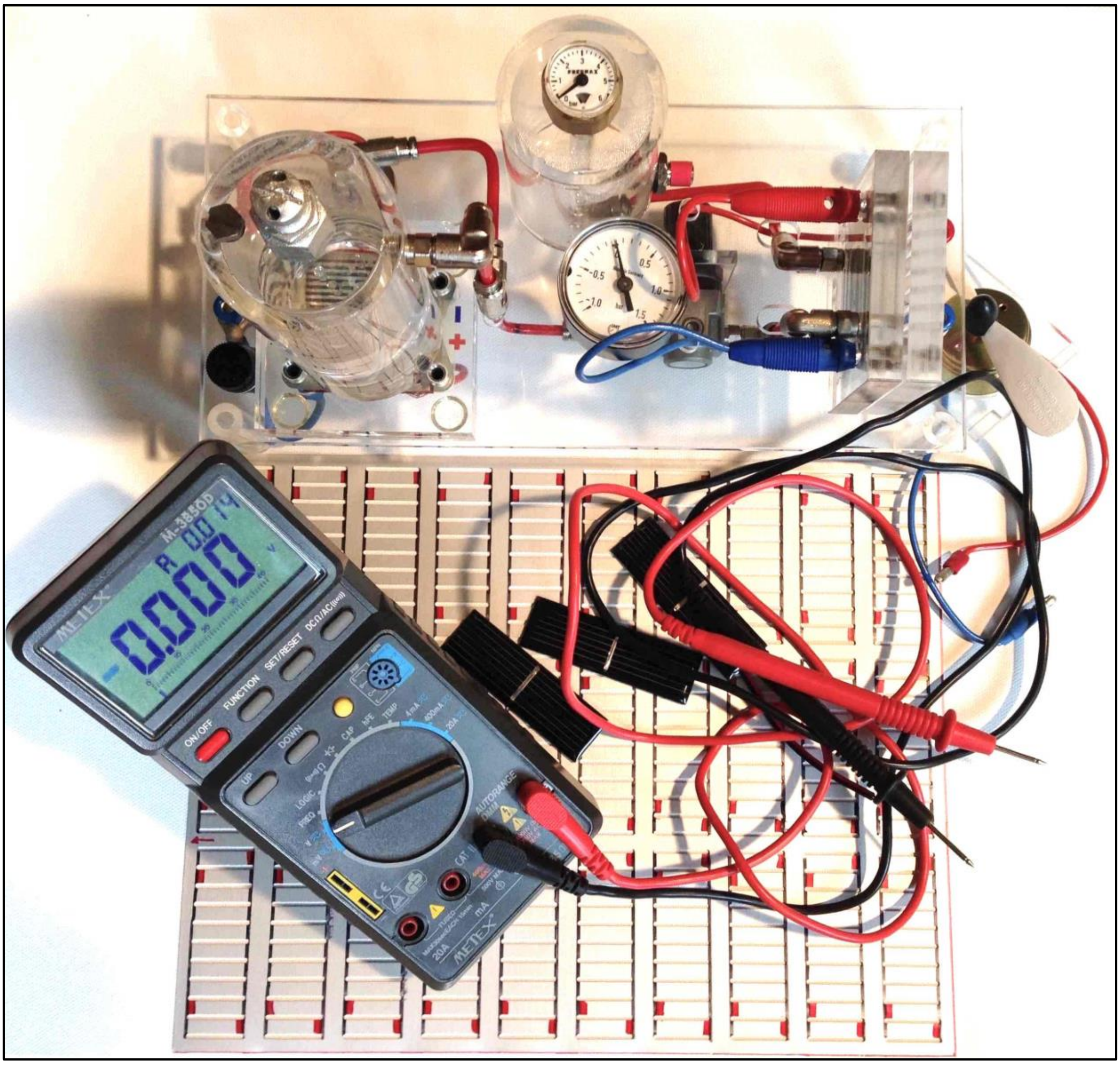


Figure 23: Testing and calibrating the POC system

The pipes and instruments of the system are connected in an easily accessible manner so as to enable user-friendly access and maintenance. The pressure reduction valve and gauge are calibrated and adjusted with a high safety margin, but perform well enough to supply enough hydrogen gas for the system to run approximately 8 hours[6] with no sunshine. After a period of about 8 hours with no sunshine (when the hydrogen is spent), the energy stored in the battery can be used as a backup if needed. This is sufficient for approximately 4 hours with the system powering a small DC motor with propeller. Increasing the load on the battery will proportionally decrease the running time.

[6] An 8-hour runtime is the average operation time of the system before it starts to slow down due to low hydrogen pressure. The system is then switched off in order to prevent all the hydrogen being "leached" out of the tank and thereby creating a negative pressure resulting in atmospheric air entering the tank.

6.1. POC model – P&ID

The piping and instrumentation diagram (P&ID) of the solar hydrogen system with all its components is illustrated in figure 24.

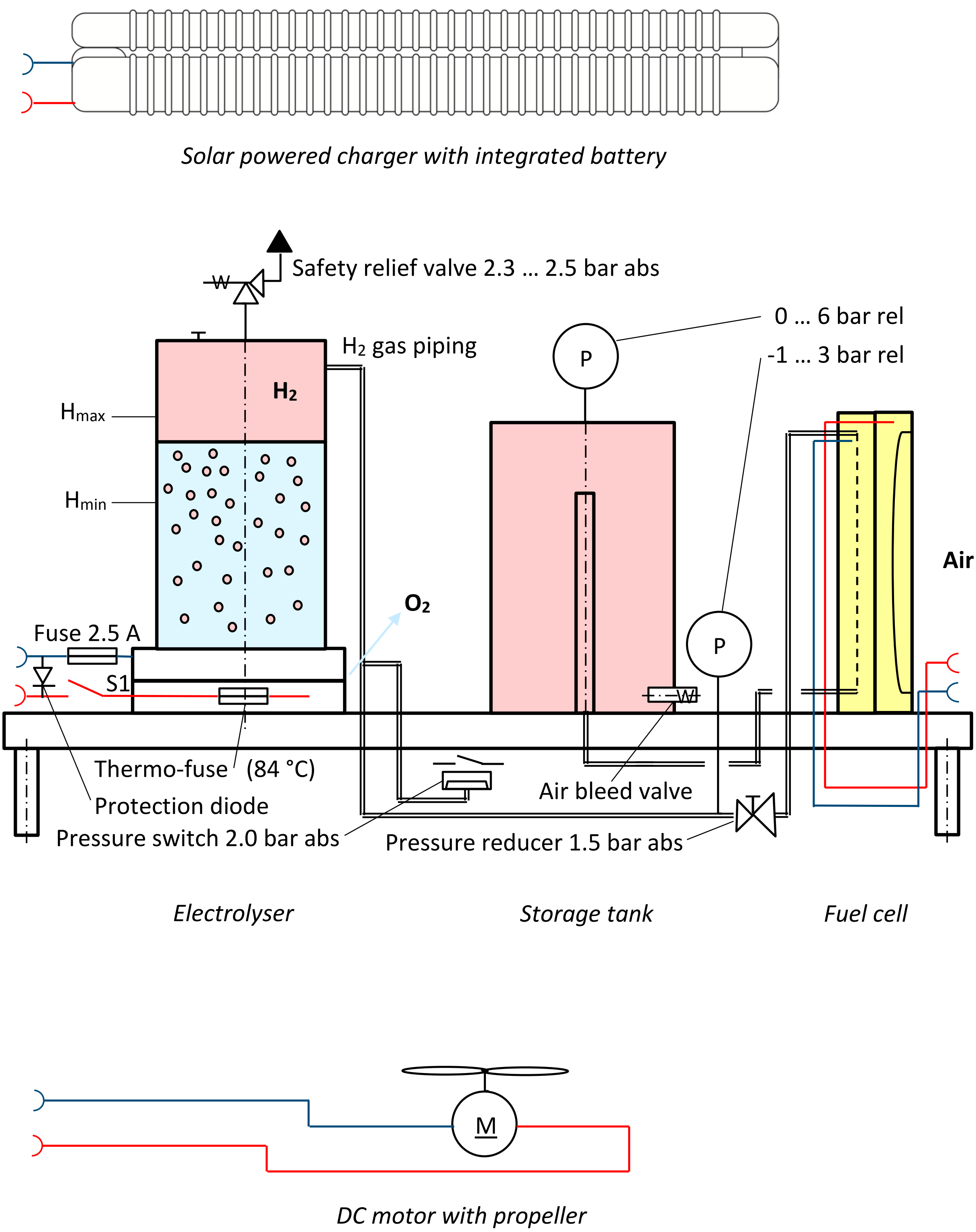
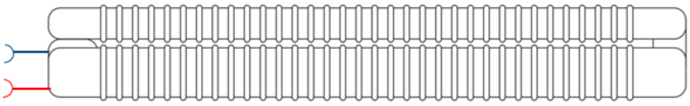


Figure 24: P&ID - scheme of POC system (not true to scale) [18]

6.2. POC model - list of the main components

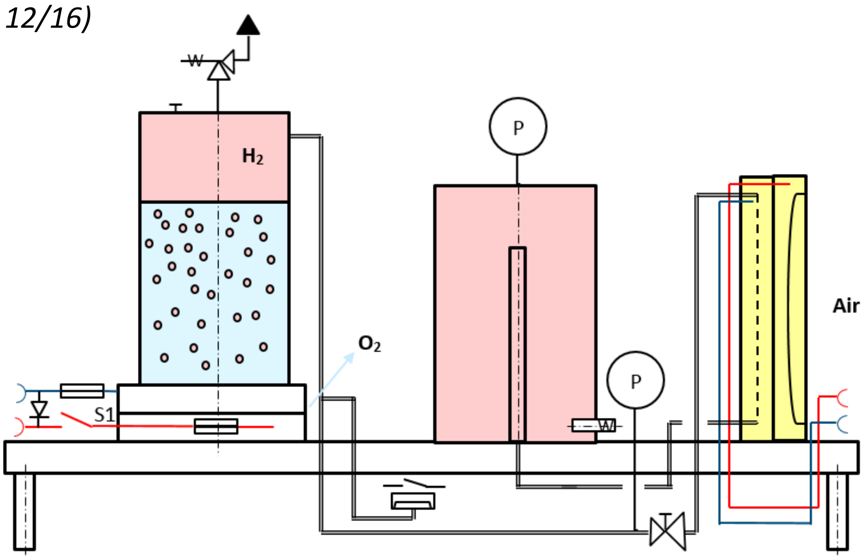
6.2.1. Solar panel with internal battery

1 *Solarmonkey adventurer* solar powered charger with integrated Lithium-ion Polymer battery



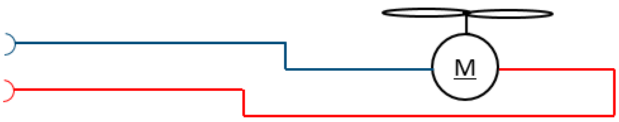
6.2.2. Hydrogen fuel cell and electrolyser model

1 electrolyser *EL 12T* with thermo-fuse and safety relief valve
1 fuel cell FC *12/16 (BZ 12/16)*
2 pressure gauges
1 pressure reducer
1 touch switch
1 protection diode
1 storage tank
1 air bleed valve
1 base plate with parts
Pipes and fittings
Electric connections
Fuse box (2.5A)
Syringe (20ml)
Adapter



6.2.3. Consumer load

1 DC motor with propeller



6.3. POC model - characteristics

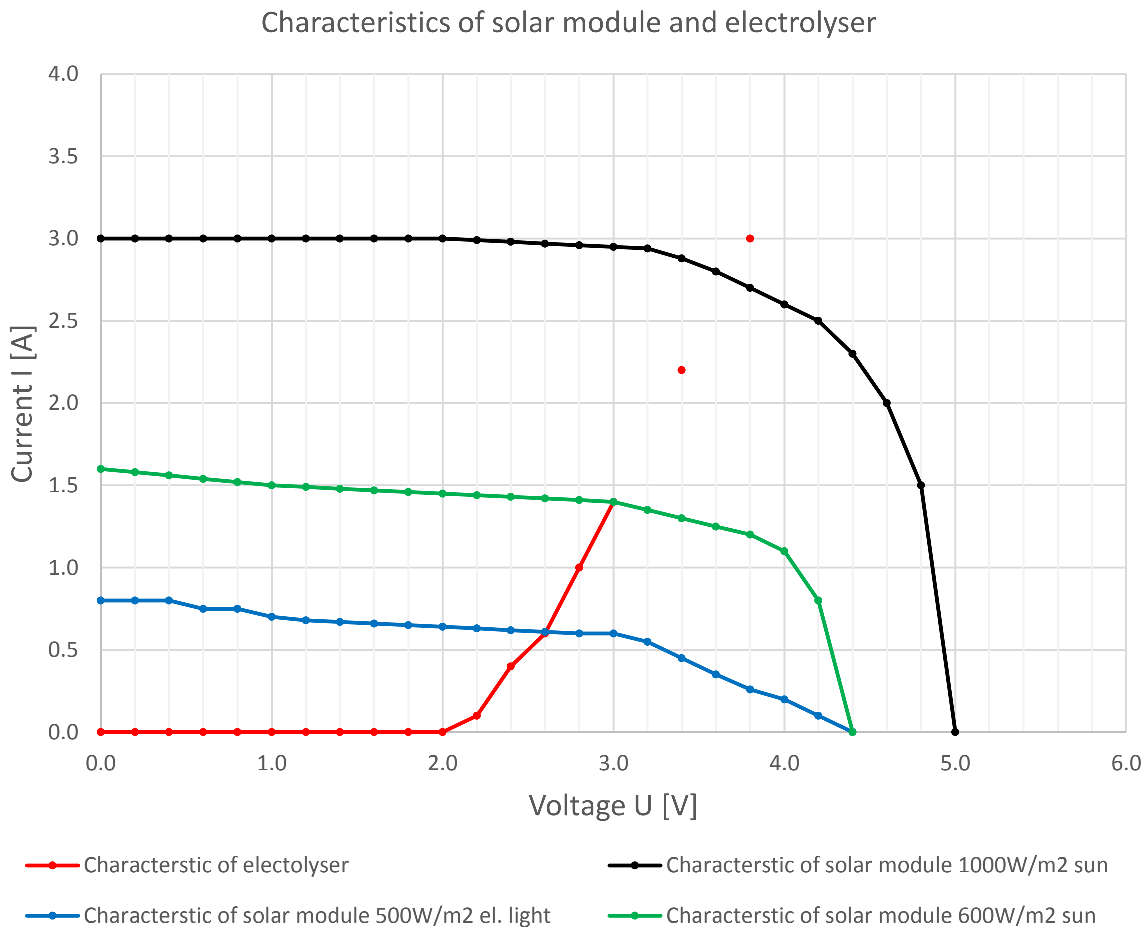


Figure 25: Characteristics of solar module and electrolyser

The varying characteristics of the solar module and the electrolyser measured using different light sources are depicted in Figure 25. Since the electrolyser runs at a maximum of 3 V and 2 A, it performs well even with the solar module operating under inferior electric light sources of 500 W/m^2.

The reading of current and voltage values for specific load resistances can be measured with the help of a multimeter[7] and a potentiometer[8]. The voltage-to-current characteristic curve (the U-I curve) seen in figure 26, shows the performance of the fuel cell under a load. To arrive at the U-I curve, the resistance needs to be varied and the relevant value pairs for current and voltage is read. The measurements are then entered in the diagram. The current meter is connected in series and the voltage meter is connected in parallel [18].

[7] An instrument to measure electric current, voltage, and resistance over several ranges of value.
[8] An adjustable resistor with a sliding or rotating contact (can form an adjustable voltage divider).

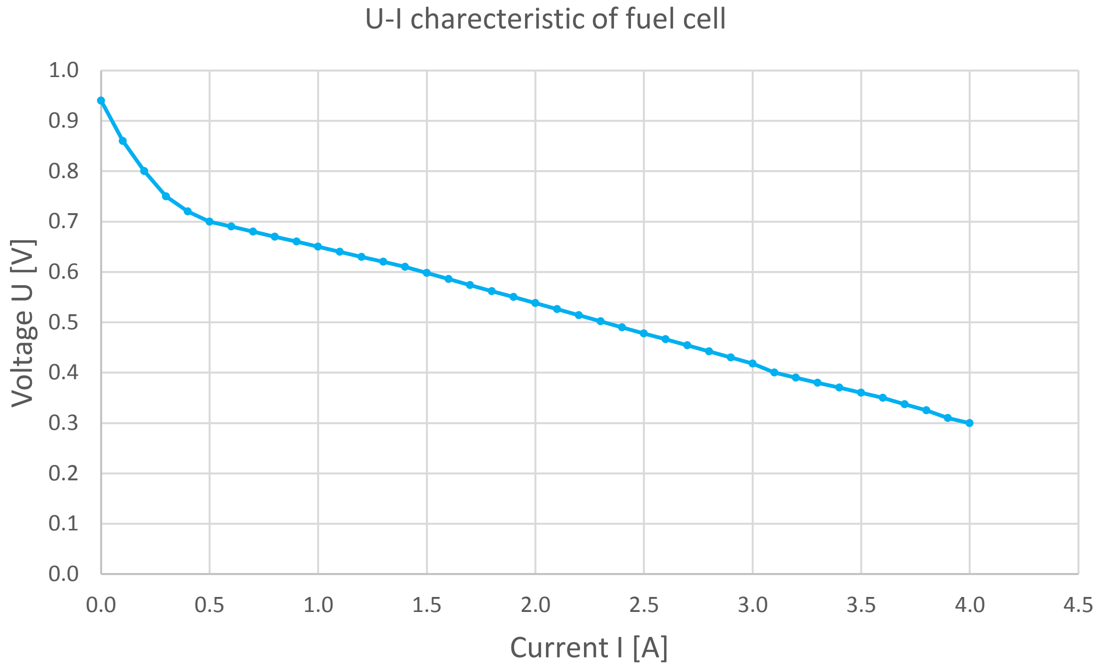


Figure 26: U-I characteristic of fuel cell

The electrical power *P* is calculated as $P = U * I$ illustrated in figure 27. At P_{max} the load resistance is identical with the internal resistance of the fuel cell. The optimal operational voltage of the fuel cell lies between 0.6 and 0.7 V [18].

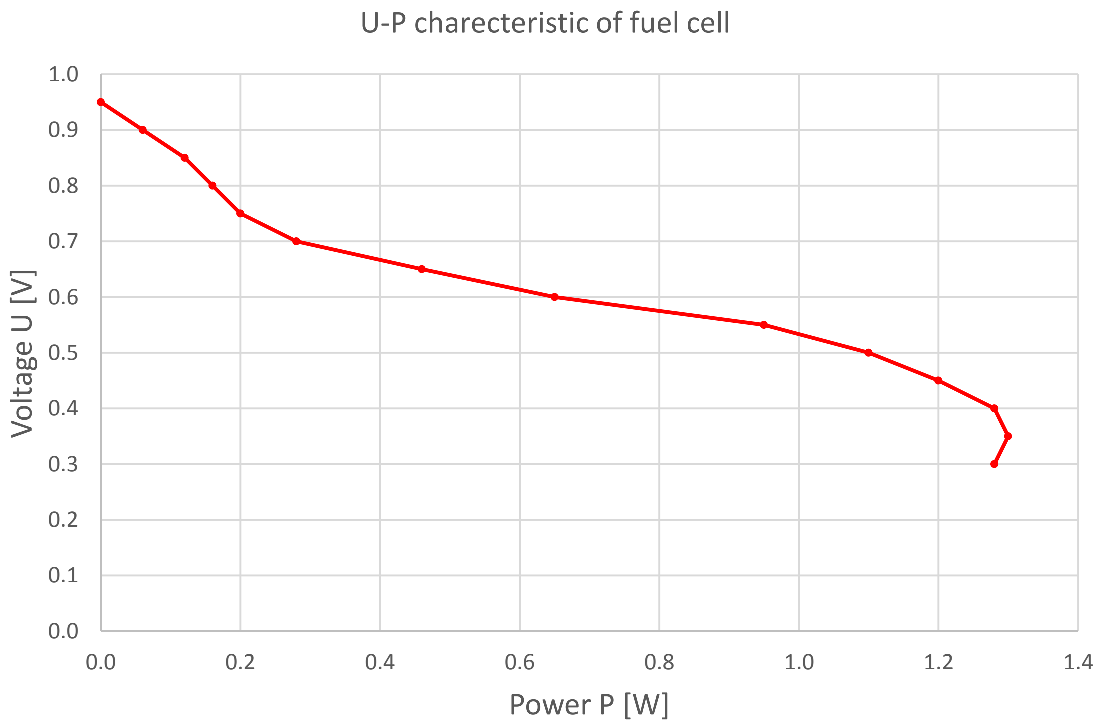


Figure 27: U-P characteristic of fuel cell

6.4. System specifications

Electrolyser & fuel cell model	Value
Dimensions:	260 x 120 x 205 mm
Weight:	1050 g

Electrolyser	Value
Dimensions:	68 x 68 x 165 mm
Weight:	250 g
H_2O storage:	100 cm^2 distilled water
Active cell area:	12 cm^2
Nominal voltage:	3 – 4 V
Max current:	2 – 3 A
Max temperature:	60 °C
Membrane type:	PEM (proton exchange membrane)
Fuse:	2.5 A
Thermo-fuse:	85 °C

Fuel Cell	Value
Dimensions:	68 x 68 x 21 mm
Weight:	106 g
No-load voltage:	0.95 V
Short circuit current:	>3 A
Nominal power:	>1 W
Active cell area:	12 cm^2
Operation:	air, convection
Membrane type:	PEM (proton exchange membrane)

PV panel with battery	Value
Dimensions:	170 x 96 x 22.75 mm (folded)
Weight:	265 g
Solar panel type:	3 W polycrystalline
Input (Solar and DC):	5 V 600 mA
Output (USB port):	5 V 700 mA
Energy	9.2 Wh
Internal battery:	2500 mAh lithium-ion polymer
Protection:	short circuit, overload, low voltage

6.5. Operating mode of the solar hydrogen POC model

The solar module with integrated battery generates the energy needed to operate the electrolyser. The electrolyser splits the distilled water into hydrogen and oxygen by electrolysis of water. The oxygen is released into the atmosphere, and the hydrogen rises to the surface of the water in the electrolyser where it is conducted to the fuel cell via a pipe with a pressure gauge (manometer). Before entering the fuel cell, the hydrogen pressure between the pressure gauge and the fuel cell is reduced to 0.5 bar (1.5 bar absolute) by means of a pressure reducer. Inside the fuel cell, part of the hydrogen, together with oxygen from the air, is transformed into electricity, water and heat. The surplus hydrogen goes to a storage tank where it is stored for future use.

When more hydrogen is generated by the electrolyser than is needed by the fuel cell, the hydrogen pressure rises. At 1 bar pressure (2 bar absolute) the pressure switch electrically disconnects the electrolyser. At 1.5 bar pressure (2.5 bar absolute), the safety valve of the electrolyser starts to release pressure. After the electrolyser has been switched off, the fuel cell continues to operate as long as it is able feed on the remaining hydrogen in the system [18].

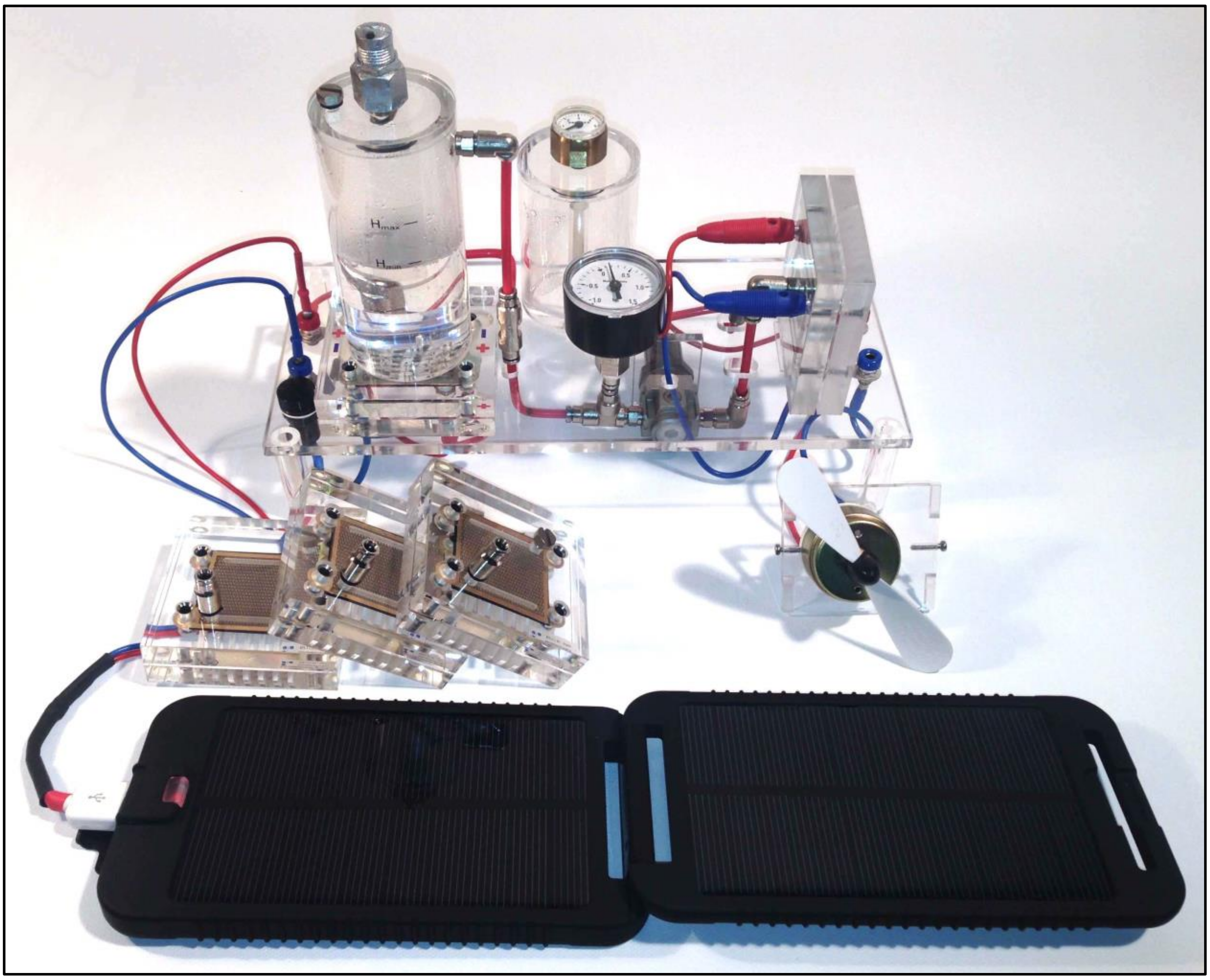


Figure 28: POC system with all components running from electric lighting

6.6. Operating mode of the individual components

6.6.1. The photovoltaic module with integrated battery

The *Solarmonkey adventurer* is a portable solar charger with two solar modules and an integrated lithium-ion polymer battery. The polycrystalline photovoltaic modules generate a maximum output of 3 watts at 17% efficiency. The unit uses maximum power point tracking (MPPT) to efficiently uses each cell in the solar modules to charge the internal 2500 mAh lithium polymer battery even in low light or partial shadows. A system without battery is also possible, however; a battery improves the availability and efficiency of the system. It is dimensioned such that it can be used as an energy buffer when the sun is not shining or when the electrolyser has a high demand. The battery can be fully charged within eight hours of sunshine.

A photovoltaic cell consists of two or more layers of semiconducting materials such as silicon. A positive layer (p-layer) and a negative layer (n-layer). The negative layer contains an abundance of electrons which are able to move freely. When photons in solar radiation come in contact with the photovoltaic cell, some of the photons are absorbed by the negative layer of the semiconductor and thus some of the electrons are freed. When the n-layer and the p-layer are connected to an external load, the free electrons are able to move through the circuit producing an electrical current. Each photovoltaic cell produces a small amount of power. To increase the output power, the cells are combined in a transparent protective casing called a solar module. The modules can then be wired to each other in series and/or parallel to form an array in order to obtain the desired voltage and amperage for a given project [18].

The lithium-ion battery is a rechargeable battery with high energy density and a relatively low charge-loss when not in use. It consists of a negative (anode) and a positive (cathode) electrode. The anode is made of graphite and the cathode is made of lithium oxide and in between the two electrodes is an electrolyte that enables ionic movement. This movement of ions is responsible for the charging and the discharging of the galvanic cell. The single Li-ion cells can be stacked or combined together to increase voltage and current requirements of the complete Li-ion battery.

6.6.2. The electrolyser

The construction of the electrolyser is similar to that of the fuel cell, comprising two end plates with two electrodes, one proton exchange membrane and one diffusion layer. There are four electrical connection sockets for 4 mm plugs. The necessary water supply is stored in a transparent cylinder above the electrolyser. The water tank is equipped with a filling screw, a hydrogen pressure release valve and a safety valve (opens at high pressure).

Starting from the water storage, the electrolyser receives a small amount of water, which enters the acidic electrolyte membrane. An electrochemical reaction takes place as a result of the external voltage, splitting the water in the membrane into hydrogen and oxygen (electrolysis of water). The hydrogen ions accumulate at the negative electrode (inside the water tank), take up a missing electron and recombine to form a hydrogen molecule, and then rise to the surface in the form of H_2 gas bubbles. The oxygen gathering at the positive electrode is released to the environment after having given up two of its electrons and recombining to form O_2-molecules [18]. A more in-depth description of electrolysers is covered in my pre-thesis [1]

6.6.3. The fuel cell

The PEM fuel cell is constructed of two end plates. In between these plate are two electrodes, one proton exchange membrane and two diffusion layers. The fuel cell is equipped with four electrical sockets and plugs.

The fuel cell is a highly efficient galvanic element. It directly converts the chemical energy of an energy carrier (in this case H_2) to electrical energy in a so called cold combustion. This type of direct energy conversion makes fuel cells excellent energy converters. An energy carrier such as H_2 is a fuel (reactant), which releases its reaction energy with the help of an oxidant (O_2) through oxidation. In a fuel cell this oxidation reaction is referred to as a cold combustion process because the process does not involve thermal combustion, but rather a low temperature electrochemical reaction. A big advantage of fuel cells is that no moving parts are required to generate energy; they are quiet achievers [18]. There are several types of fuel cells that function with different fuels and each has their own advantages and properties. These are described in my pre-thesis [1]

6.6.4. The hydrogen gas storage

The hydrogen storage tank is constructed of a transparent acrylic cylinder. Hydrogen gas is led into the storage tank through a rising pipe. If the electrolyser generates more hydrogen gas than the fuel cell can transform into electricity (dependant on load), the surplus hydrogen is stored in the storage tank. In the long-term, the hydrogen produced by the electrolyser and the hydrogen converted by the fuel cell should balance out. The hydrogen storage tank compensates for short-term imbalances [18]. A full tank of hydrogen stores enough energy to operate the DC motor with propeller for approximately 8 hours.

6.6.5. Base plate of the model

The model's base plate holding all the components in place is constructed of acrylic. The electrolyser, H_2 storage tank, fuse, pressure gauge, pressure reducer, switch, diode and the fuel cell are all mounted on the acrylic base plate. The electrical terminals to power the electrolyser are firmly attached to the base plate on the electrolyser side. Likewise, the terminals to connect the fuel cell to external consumers are on the fuel cell side [18].

6.6.6. Pipes and Fittings

The hydrogen gas is transported through the plastic pipes. These pipes are connected together using screw-and-plug links and T-links. In order to disconnect a hose, the small resistance ring needs to be squeezed in order to pull out the pipe correctly. A pipe is reconnected by gently applying a small amount of pressure on the screw link.

There is a pressure gauge (manometer) between the fuel cell and electrolyser. This allows the H_2 pressure in the system to be monitored in relation to the atmospheric air pressure (0 bar = ambient pressure). There is also a second, smaller pressure gauge indicating the H_2 pressure in the H_2 storage tank [18].

6.6.7. Consumer load (DC motor with propeller)

The electrical connection for a consumer load is provided in the form of two 4 mm electrical sockets on the base plate. Additionally, it is possible to connect external consumers directly to the sockets of the fuel cell itself.

The rule of thumb for determining the polarities of the fuel cell is the following: the negative pole is always situated next to the hydrogen connection. Parallel sockets have opposite polarities and diagonal sockets have the same polarities. Any external consumer load may be connected to the fuel cell as long as its current and voltage characteristics are compatible with those of the fuel cell. Consumers should generally take up less current on the average than the electrolyser in order to ensure automatic operation. [18].

7. Discussion & conclusion

7.1. Contribution to the field

When we ask ourselves the question, what do the children today have to look forward to in the coming years? What answer do we come up with? What we are going to discuss here is that with a clean renewable energy infrastructure, we can all once again have something to look forward to. However, as it stands at the moment there is a lot to be concerned about. We are facing an accumulating effect of multiple problems (i.e. climate crisis, resource wars, economic meltdown, terrorism, oil spills, ecosystem breakdown, greenhouse gases, water shortages, smog) happening simultaneously in the 21st century. All of these problems have something in common; they are the result of a total addiction to fossil fuels -and the first big problem with fossil fuel addiction is the supply. We are slowly but surely running out a cheap oil and the operational word here is “cheap” (end of cheap oil = economic ruin). All fossil fuels are becoming more difficult to find and exploit. The low prices of natural gas and fossil fuels that we are experiencing at present does not reflect their true costs. They are just another commodity whose price is being manipulated for the interest and benefit of the big players. One could even argue that *Big Oil* lobbies are very nervous about the recent shift in financial backing from big organisations who have divested their stake with them and now put their money into more sustainable investments. The recent drop in fossil fuel prices could be the new measures taken by the lobbies to try to make it seem like a worthwhile and a cheaper source of energy compared to its clean and renewable competition. Our fossil fuel addiction is leading us to huge economic problems, and this is true regardless of the new fracking and shale oil boom. Contrary to what many people think, a switch to natural gas will not ameliorate the existing problem [19][20].

There is a second and graver issue raised by our addiction to fossil fuels; global warming and climate change. This is not just an environmental problem, apparently it is a civilizational one (climate change = environmental ruin). According to many scientists, the very existence of modern civilization as we know it and its future are being questioned [21]. Given the above-mentioned problems, there are four basic assumptions to this discussion.

I. Urgency:
The first is to simply recognise the sheer urgency of the situation and the necessity to solve our global dilemmas.

II. Inadequacy:
The second is to admit that despite all the talk about global warming and climate change, the small effort we are actually putting in now is not enough. Not even close. The status quo is simply not working for us and it is time to change this.

III. Paradigm shifts and infrastructure-revolutions are a real possibility:
The third assumption is a more hopeful one; it is that we humans are definitely capable of successfully achieving paradigm shifts, and which means that…

IV. …there is cause for positive optimism and chance taking:

Things can actually change for the better faster than we may realise. So let us get more specific about positive optimism; despite the torrent of bad news covering the climate change problem, there is some promising and significant good news as well, such as the dropping costs of photovoltaic technology.

As *Ronald Bailey* historically said, *"The stone age didn't end because humanity ran out of stones".* It was innovation and the need to evolve in order to survive. We would be well advised to learn from this lesson in change management and to do the same.

This leads to the five most important reasons why we need to build up hydrogen technology for the future generations.

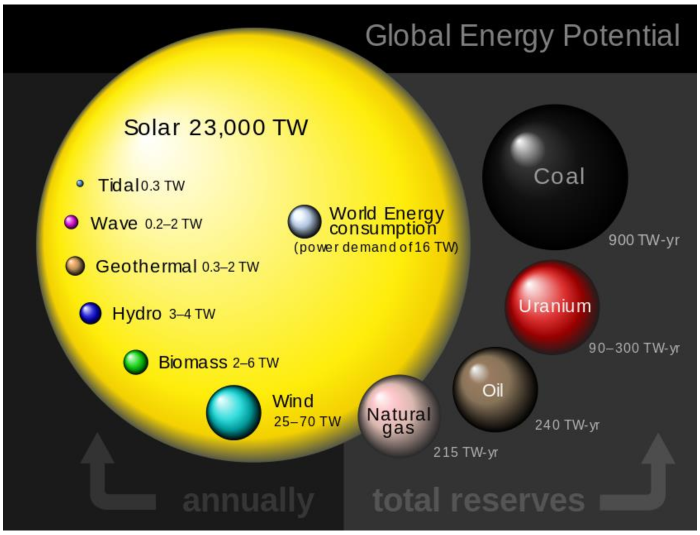
I. Climate change is a real problem and it is a man-made one with critical long-term, as well as immediate repercussions.

II. This means that our fossil fuel addiction needs to be remedied with real urgency. Not in the next politician's term of office[9] or in twenty, thirty, or forty years from now. Due to the real urgency of this situation, we do not have the choice and need to act now.

III. Nuclear technology will not mitigate the problem; it is unsafe, carries too many long-term disadvantages with it and is not a feasible alternative to fossil fuels.

IV. At the moment wind and solar energy are the only viable options for our prevalent source of energy. Solar and wind do not however, provide a continuous supply of energy, they are intermittent sources, and this means:

V. A new effective and efficient way to store energy is needed. Conventional batteries alone do not meet the demands, and our present power grid is definitely not capable or intelligent enough to handle this. Given all the advantageous properties of hydrogen, it has potential to fulfil these demands and is therefore the best candidate.



When we consider solar energy for our primary source of energy, there is one phrase that stands out above all; a maximum normal surface irradiance of approximately 1000 watts per square metre. As we have learned, that is on average how much of the sun's energy we receive at mean sea level on a clear day.

Figure 29: Global energy potential

[9] The length of time a politician serves in a particular office (which conveniently frees them of all responsibilities once served).

When we compare the potential for solar energy seen here in figure 29 with other energy sources, this is what it looks like; we see an outstanding solar potential, which dwarfs all other energy sources. The potential solar energy yield will only grow as the efficiency of solar technologies are improved. When we consider that Germany, by far the world leader in solar energy, has only a relatively low horizontal radiation from the sun (refer back to illustration of global horizontal irradiation in figure 2), we can safely conclude that locations that are exposed to much higher solar irradiation have great potential for future solar energy yield.

Figure 30 is a map showing global mean wind speed where the wind energy potential can be derived.

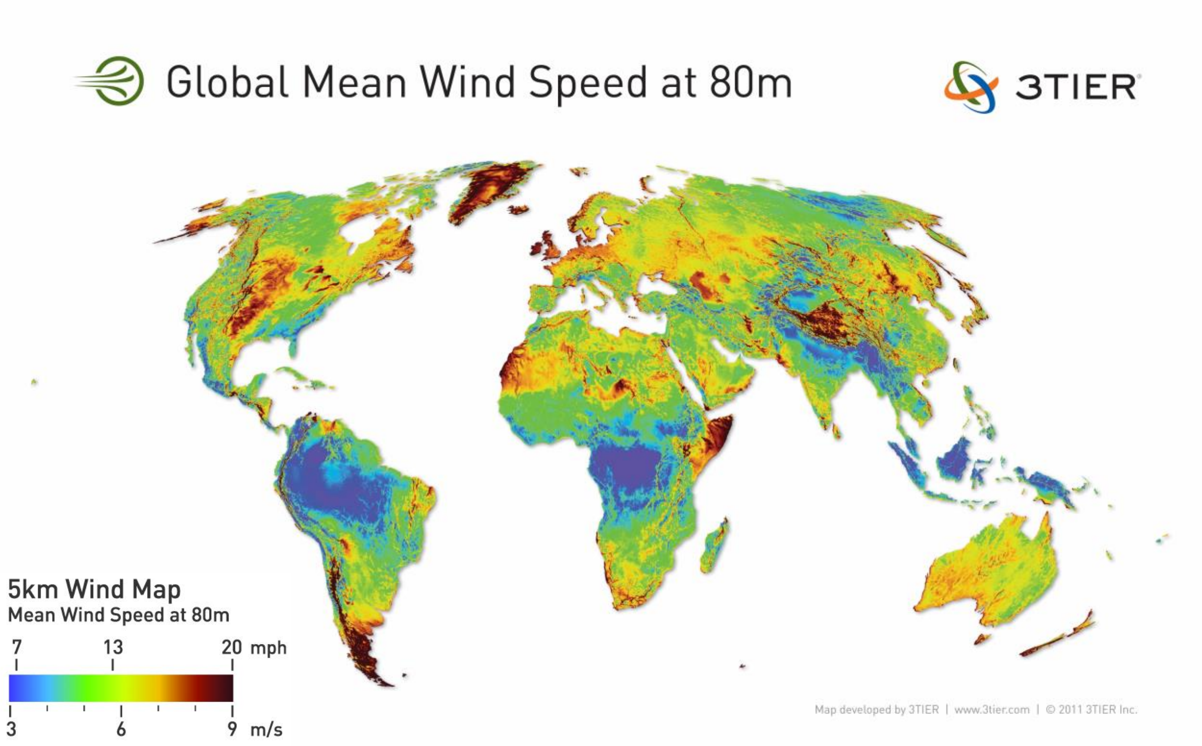


Figure 30: Global average wind speed

When we overlay this map with the map showing the global solar irradiation, the lesson here is that in many places where it is not very sunny it is usually windy, and is therefore more suitable for wind power production instead of just solar.

There are several misconceptions about solar energy. The most common of these is that solar technology is still too expensive. This is not the case anymore; the price for solar energy is steadily going down. The average cost for solar energy today is about 1% of what it was in 1970. The large initial investment costs of switching to solar are no longer a barrier. Businesses and homeowners can now also lease solar panels instead of buying them, or they can rent their roof space for a solar installation. Apart from that, the purchasing price of solar panels has decreased so much that it is now common practice to receive a bank loan for a solar installation.

Another misconception about photovoltaic is that it requires too much space that is otherwise used for other things. However, if rooftops and buildings are designed for this technology, there is potentially sufficient rooftop-space in Europe to supply all the power needs of the people. Decentralised rooftop solar power generation forming virtual power stations means that large centralised power stations of any kind will be redundant.

Figure 32: Green roof with PV panels

Figure 31: Solar rooftops

Rooftop photovoltaic and the greening of our villages, towns and cities is what we need to make happen. As this new type of distributed energy production becomes more widespread it will also become less and less conspicuous. With wider adoption, solar panels will become more incorporated in the innovative architecture and landscape. In many cases, we will not even know it is there.

Figure 34: In-roof photovoltaics

Figure 33: PV tiles and shingles

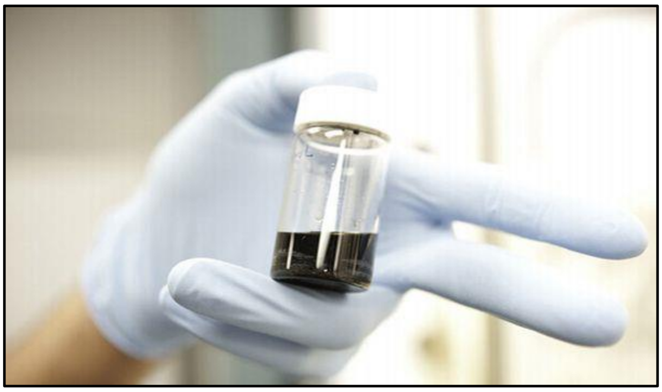


Figure 36: PV paint

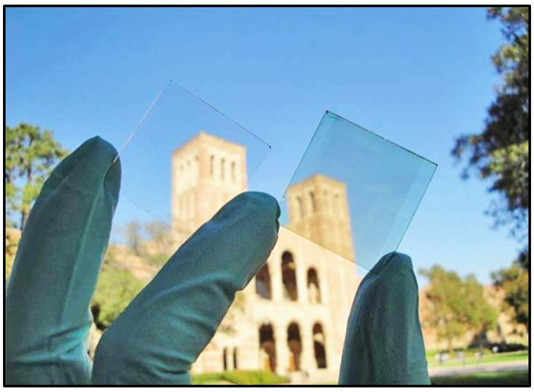


Figure 35: Transparent PV cell

Figure 38: Solar roadways

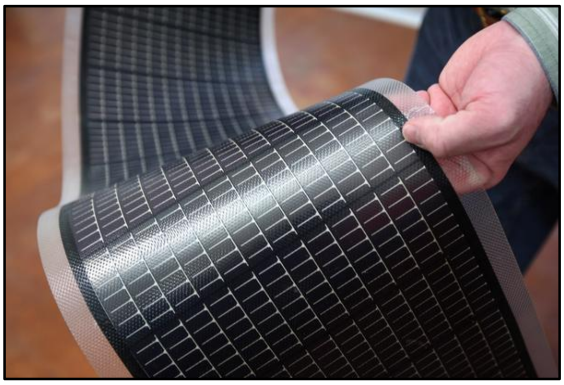


Figure 37: Flexible thin-film PV panel

A solar-power revolution is happening now and it is growing to encompass not only rooftops and stand-alone solar arrays, but also many different aspects of buildings and landscapes. Depicted in figures 32 - 38; these include solar tiles, solar glass and windows, solar shingles and solar paint. Solar paint and thin-film solar technology makes it possible for practically any surface to be used for solar energy production. All these blooming technologies will facilitate distributed solar energy production and render large centralised power stations redundant.

However, all this solar energy is available to us at daytime and when the sun is shining, unobscured by clouds. Where does the energy come from the rest the time? This is where solar hydrogen technology comes in. The advantages of utilising hydrogen to store the solar energy (as well as other renewable energies) are listed below:

Renewable and clean:
No toxic fumes
No greenhouse gases
No pollutants or waste

Readily available and truly abundant:
Can easily be produced by multiple means in virtually any location

Scalable and modular:
Not dependent on a central grid and easily expandable

Flexible and multi-purpose:
Electricity, cooking, heating, oxygen and water production, quick recharge/refuelling (i.e. FCV, portable power unit)

Reliable and high-availability:
Long term hydrogen storage does not decrease or degrade

Even though hydrogen technology offers many benefits, there still are misconceptions and myths that presently need to be addressed. A peer reviewed white paper "*Twenty Hydrogen Myths*" which is written by *Amory B. Lovins* and offers both lay as well as technical readers a primer on the basic hydrogen facts can be found here[10]. Some of these concerns and misconceptions are:

- Safety factor for widespread use
- High cost of hydrogen technology
- Efficiency of hydrogen technology
- Logistical problem: "*chicken or the egg"* causality dilemma

The fact that hydrogen technology has always been obscured by the shadow of *Big Oil* has greatly divided its development path, resulting in numerous independent players working with small budgets in isolation. The first hydrogen automobiles were already developed in the 1960s. This may lead one to the question; what is it that is taking so long? Surely this delay had partly to do with technical challenges that still needed to be worked on. There undoubtedly also has been direct, as well as indirect hindrance from the powers that be, namely *Big Oil*. This is business as usual for today's corporate growth mentality and is to be expected. One could even argue that they conducted psychological operations (PSYOPs) using tactics including false promises at an early stage (which inevitably resulted in a lack of positive results) as well as misinformation campaigns, inertia, media-blackouts and obstructions.

Fortunately, with the rising necessity for clean renewable energy sources and storage technologies, the pieces have now fallen in place. Below is a recap of the basics of hydrogen technology:

Our need for hydrogen systems comes from the fact that wind and solar energy are intermittent and seasonal. When the wind is blowing or when the sun is out the hydrogen storage is not used, the produced electricity is used directly. When there is no wind or sun however, we use the stored energy. An electrolyser converts the electricity generated by the wind turbine and solar array by the process of electrolysis of water, into hydrogen gas. This is achieved by splitting H_2O into H_2 and O_2. The produced hydrogen gas is piped to a storage tank for later use. If there is a demand for electricity the hydrogen is supplied to a fuel cell which converts it back into electrical energy. Figure 39 illustrates the function of a fuel cell:

[10] https://drive.google.com/file/d/0BxLJh12BbrzAX0pXU0xCSkphSTQ/view?usp=sharing

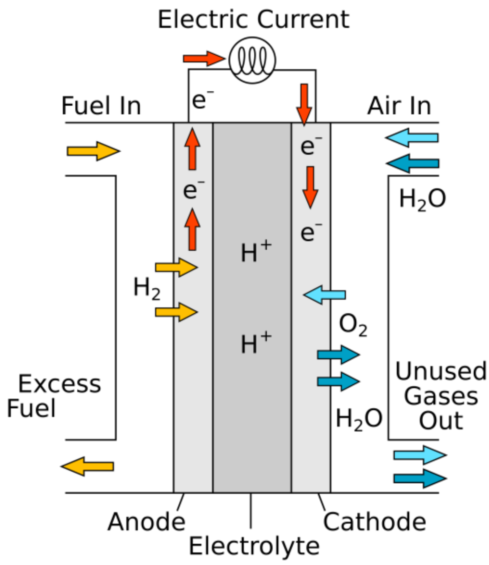


Figure 39: Function of a fuel cell

Inside the fuel cell, the hydrogen gas combines with oxygen from the air to produce electrical energy, some heat and purified water. *Hydrogen Fuel Cells: A Feasible Regenerative Energy Technology* (pre-thesis) [1] describes fuel cells in much more detail.

The hydrogen can also fuel an FCV in a matter of minutes, in contrast to a battery-only EV, which typically requires several hours to recharge. Furthermore, virtually any form of transportation can be made to run on clean, renewable hydrogen. The public transportation sector is an especially promising application for hydrogen, where ships, trains, trams and buses can use hydrogen fuel cells to produce energy on board.

As we have now learnt, there are new methods of generating hydrogen from the sun's energy that are being developed and that do not require the use of an electrolyser. These methods are intensively being researched and further developed at present, but unlike the electrolyser they are not yet ripe for widespread use.

Perhaps one of the biggest advantages of using hydrogen technology that is completely overlooked and ignored is its implications for our fresh water supply. Simply stated, the commercialisation of hydrogen and fuel cell technology would produce significant amounts of pure drinking water specifically in the places where it is most needed. This means that the earth's potable water problems could potentially be solved. Not only would the predominant use of fuel cells offer a new source of clean drinking water, it would also save all the precious fresh water that is currently being utilised in power stations and fossil fuel industries that is being lost or not properly recycled.

So much for the benefits and advantages of solar hydrogen, let us now discuss its concerns. The primary concern is the safety of this technology, and we start with the 3 H's: The hydrogen bomb, *Hindenburg* and *Hollywood* illustrated in figure 40.

Figure 40: Hydrogen bomb, Hindenburg & Hollywood

The above-mentioned three factors play a central role in the mainstream opinion of hydrogen technology. Most people have been taught in school about the *Hindenburg* accident, which occurred in 1937 and how it confirmed the "dangers" of hydrogen. What most people don't know is that recent evidence has shown that the cause of ignition was not hydrogen itself, but static electricity from the paint on the exterior of the *Hindenburg's* fabric [22]. More importantly, we have gained a lot of know-how in handling hydrogen since 1937, and the challenges of containing the gas in a thin fabric have very little to do with the state of modern hydrogen technologies. The impressive safety record of hydrogen since the 1930s speaks for itself.

Almost everyone knows about the *H-bomb*, but it appears many people forget that there is a big difference between a chemical reaction and a nuclear one. A chemical reaction is millions of times weaker than a nuclear reaction. When saying we use hydrogen for the storage of clean solar energy, we are implying only the usage of chemical reactions. Furthermore, the only time when nuclear-fusion reactions (as in hydrogen bombs) can even take place, is in extreme temperatures of around one hundred million Kelvin, which is achieved by the detonation of a typical fission atom bomb, which triggers the reaction. That is to say these weapons derive the majority of their energy from the initial nuclear fission reaction [23].

Then there is the *Hollywood* film industry, which appears to have an agenda against hydrogen and falsely portrays it as being the most dangerous and explosive substance out there. They do this time and time again. For example, a recent *James Bond* film portrays the villain with a covert base in the desert that is powered by hydrogen fuel cells. *007* shoots a single bullet at a hydrogen storage tank causing a massive explosion that destroys the whole complex. This is absurd and very unrealistic, and it conveys a false message that most people take for a fact. In short, *Hollywood* has performed a strong disservice to the alternative energy sector, and would do well to restore its credibility with new films displaying the real promises of hydrogen.

The peer-reviewed paper "*Twenty Hydrogen Myths*" by physicist *Amory B. Lovins*, has stood the test of time and best describes the myths regarding the safety of hydrogen. Many have tried to disprove it, none have managed. One of the myths, which I explain in my pre-thesis *Hydrogen Fuel Cells: A Feasible Regenerative Energy Technology* [1] is that hydrogen is more dangerous than gasoline for use in automobiles.

Figure 41: Time-lapse of hydrogen and gasoline fires

In figure 41, we see time-lapse frames of an experiment conducted where two car fires were simulated, on the left an FCV with a pressurised hydrogen tank, on the right a conventional car with a gasoline tank. The hydrogen in the FCV burns straight up due to its low density, whereas the gasoline in the car spills on the ground and sets off an inferno, which consumes the entire car. To be fair, there are certain situations where hydrogen may pose a greater danger than gasoline, but the consensus among technicians is that hydrogen offers a safer overall alternative than gasoline.

Recent advances in hydrogen technology have solved the related safety risks. Advanced quick-release valves that are corrosion-proof and leak-proof now make refuelling an FCV just as safe, quick and convenient as its gasoline counterpart. Kevlar and carbon-fibre hydrogen tanks that can resist explosions and close-range gunshots practically eliminate the risk of fire or explosion on FCVs. This new hydrogen storage technology has performed remarkably well in recorded FCV collisions, and has proved to be as safe, if not safer, than gasoline cars.

Figure 42: Composite hydrogen tank

Another challenge of hydrogen technology is the relatively high cost of fuel cells. However, when we look at the plummeting fuel cell production costs in the past ten years, we can conclude that similar to solar energy, the fuel cell price parity is expected in the near future. In figure 43, a sinking automotive fuel cell cost by over 50% since 2006 is visible (based on projections of high-volume production of fuel cells by the US department of energy) [24].

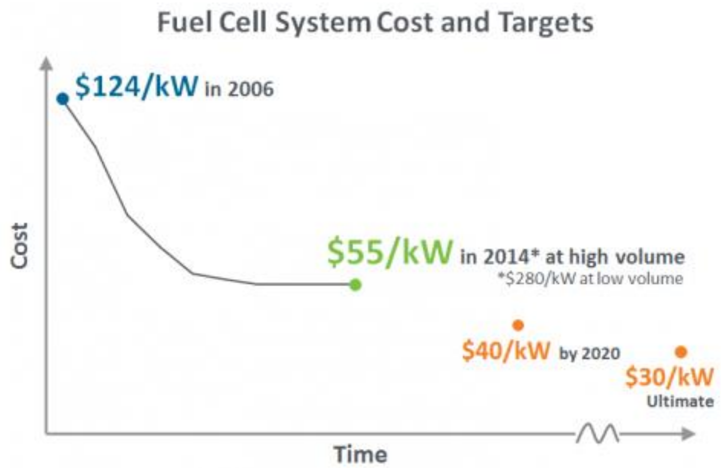


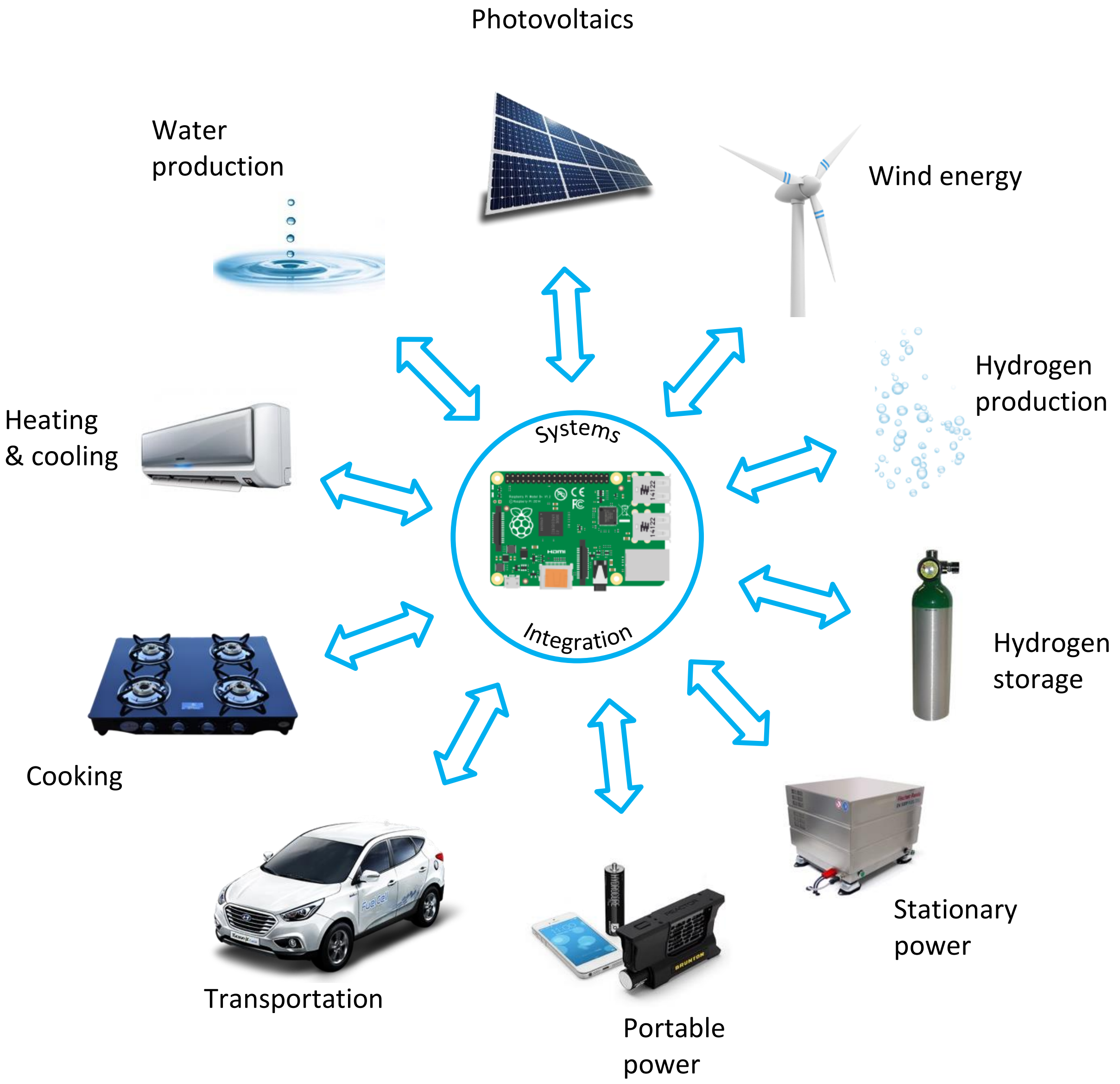
Figure 43: Hydrogen fuel cell system price per kW

When people speak of the efficiency or the cost of a new system or technology, a common mistake is that the whole picture is often overlooked. Case in point; people tend to compare the efficiency of clean technologies such as hydrogen, with that of polluting ones such as fossil fuels, which is pointless and futile. As previously discussed, all uses of polluting sources of energy such as fossil fuels and natural gas, are a cause for the pollution of our atmosphere and are therefore not a responsible solution.

In order to get the true larger picture there are a few rules for measuring the efficiency of a given system as a whole, which need to be kept. These rules are; consider all factors, do not just focus narrowly on system-efficiency, and do not compare apples with oranges. For example, when people compare batteries to hydrogen technology, they conveniently leave out the time and cost factor of charging the batteries, the energy-loss due to battery discharge or the impact on the environment from disposing of massive amounts of old, used batteries.

When we judge and compare hydrogen technology, we need to take the important factor of flexibility into account, because as it stands now there is no other technology to store or carry energy (be it batteries, compressed air, or any other) that offers as many benefits as hydrogen does. This may change in the future, but until then hydrogen technology, with its versatility and numerous benefits is the technology to focus on. Figure 44 illustrates the many different uses of hydrogen that can be integrated smartly and efficiently to power an off-grid home's total energy needs. This type of systems integration may seem overwhelming, but for a curious and tech-savvy individual, low-cost hardware such as *Raspberry Pi* or *Arduino* running free, open-source software to control the various input and output devices are available and make this type of integrated system possible without the need for highly specialised skills.

Figure 44: Hydrogen systems integration



It is often assumed that batteries are in direct competition with hydrogen, but that is not the case, in fact, most optimised hydrogen systems and FCVs use batteries as an energy buffer and thereby they take advantage of the best of both technologies. These highly versatile hybrid systems use the fuel cell to supply a steady baseload, and the batteries to supply rapid peaks of power to compliment the FC system. Case in point; When *Elon Musk*, the co-founder of *Tesla Motors* famously mocked that FCVs are "bullshit", at least one FCV manufacturer took him at his word, pointing out that you could potentially run an FCV on hydrogen gas produced from cow manure [25].

Finally, another common concern about hydrogen is the logistics challenge, or the "*chicken or the egg*" causality dilemma. In other words; who is going to build FCVs on a mass-scale if there are no hydrogen fuelling stations available to refuel them, and who is going to build the refuelling stations if there are no FCVs creating a demand for the hydrogen. Fortunately, solutions have been developed; the first one is that relatively small countries like Japan, Germany and South Korea are already constructing FCVs regardless of what the rest of the world is doing. The second solution is that contrary to what the oil industry makes us believe; with distributed, homemade and locally available hydrogen, we will not be dependent on public gas stations as much. Homemade and distributed hydrogen production circumvents the need for so many fuelling stations.

Of the four important energy-political problems that need to be discussed, the first one is the question of wind and solar energy storage. The question here is whether we want large centralised power utilities to have full control of our energy storage, or whether we prefer to distribute the storage of energy. Until now, the entrenched interests have exercised their desire for large electrical grids and centralised power stations. Hydrogen not only gives us the possibility to have our own home energy storage, but also to have much smaller, locally managed grids or no grid at all. The two real advantages of doing this are:

A) Distributed solar hydrogen offers the possibility for co-generative, namely combined heat and power (CHP) electricity generation, making use of the waste heat of fuel cells for room and water heating. This saves a lot of otherwise wasted energy.

B) The fuel cells can be used to produce 100 percent pure water, which, in arid regions of the world is a feasible solution to the water shortage problems.

A big problem in the energy politics today are the opinions and solutions of the over-specialised experts. Such persons continue dealing with each problem in isolation, with no consideration for the connections and the bigger picture. We need to adopt a whole-systems approach if we want a responsible and sustainable solution. If we seriously want to make a significant change, we will have to attempt something revolutionary -which involves overcoming these three conflicts:

- Centralised control of energy vs. distributed energy (energy democracy)
- Continuation of narrow, over-specialisation vs. holistic outlook approach
- Continuation of small and meaningless incremental changes vs. paradigm shift

Finally, what type of strategy shall we advance with? The conventional top-down corporate policy pathway (waiting for politicians and the government to do something), or shall we recognise and assume our power and form a grassroots movement?

Here are the fundamental characteristics required for changing over to a hydrogen infrastructure:

- Distributed power stations
- Holistic outlook approach
- Paradigm shift forward
- People's grassroots movement

Some things however, are very hard to change. Since solar and hydrogen technologies are disruptive and challenge the status quo, we see many obstructionists and cynics opposing them. It is, for example, intellectually popular to say "there are no such things as magic bullets". It sounds like a sensible thing to say, doesn't it? There is unfortunately a vast amount of misinformation that is being spread by the fossil fuel lobbies and many instances could be named about how, despite the seriousness of the situation, regenerative energy technology is being hindered. This should not surprise us, could these types of clichés be nothing but foolish stall-tactics?

Now, as a case in point, paradigm shifts in innovative technologies can and do happen; history shows us there have been many magic bullet technological developments (single innovative technologies that have solved multiple problems). The wheel, the printing press, the steam engine, the telephone, the airplane, the computer and the internet, just to name a few. Distributed solar hydrogen infrastructure could well be the next magic bullet. In other words, it can become a feasible, clean and holistic energy system alternative to polluting fossil fuels. As of now, solar hydrogen appears to be the single most promising energy strategy with the potential to completely replace the majority of fossil fuel use in the next 20 years.

Unfortunately, we cannot afford to just sit back and wait much longer for lawmakers and market forces alone to support renewable energies. We cannot use the excuse of the cost being too high, and wait for it to come down just a little more. We do not have the time for that.

We might ask; how to begin this change? With all that is going on in the world at the moment, how can we put all the pieces together. Let us consider the possibility of an internet-based, massive movement. The network would consist of a quickly increasing numbers of people who, feeling that they are a part of a worldwide grassroots movement, commit themselves to making immediate and increasingly ambitious changes of lifestyle.

Maybe this is possible, think about it. There are, perhaps, a number of people, who are ready and eager for something like this. All this could start with an internet-powered information and promotion movement for things like rooftop solar, LED lighting, hydrogen production and storage systems for home use, and FCVs. Even if the catalyst for all this is just the human desire to get a good deal and save money.

Consider the case of homeowners purchasing an electrolyser device to produce and store their own hydrogen. Whereas one single electrolyser would cost a lot, with a large order of several thousand units, the cost would drop significantly.

These are the building blocks to build a solar hydrogen future. This would enable us to reach 100 percent clean and renewable energy in the near future, with most homeowners producing all their energy themselves, producing their own hydrogen and fuelling their own FCVs. This shift could happen simply because it needs to happen. Let us utilise the power of the internet to its true potential and create an innovative new clean-energy infrastructure.

If not now, when?
If not us, who?

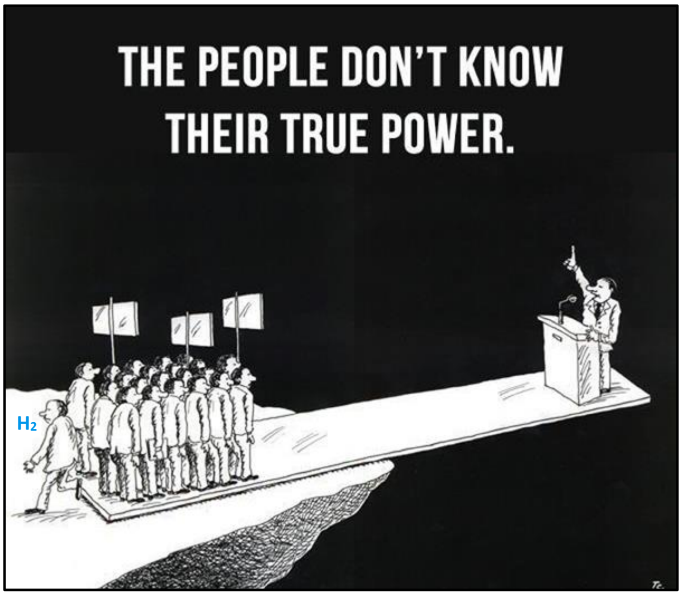


Figure 45: Power of the people

7.2. The future development scenario

The following is the plan proposed in this paper for the next twenty years:

Firstly, we accept to reduce and then discontinue the reckless use of fossil fuels, leaving the majority of the remaining reserves in the ground. In fact, just recently a literally world-changing agreement took place in Paris. Some two hundred of the world's leading nations got together and unanimously agreed to work together to combat climate change in a concerted effort to mitigate climate change effects and to keep the global warming to below 2°C above pre-industrial levels. This is a huge achievement and means that if it goes through, we will have to leave most of the remaining oil in the ground and start producing most of our energy with clean and renewable alternatives.

Secondly, we agree to shut down and put an end to the use of nuclear power plants for good. While this happens, we consequently and methodically take action and cover the costs to rapidly build up distributed solar energy generation everywhere (illustrated in figures 46-47).

We also decide to create "*greentech*" cooperatives and invest in renewable energies, in which people can buy shares instead of putting their money in banks where it only devaluates due to inflation.

Figure 46: Sustainable housing with solar rooftops

The result of the new increase in mass production and demand for this technology will be the plummeting of solar installation costs and widespread availability. As a consequence, we will no longer carry the burden of an addiction to fossil fuels so we shall experience rapid return on investment.

Figure 47: Earthship Biotecture sustainable building with solar and wind power

With the generated electricity from solar, wind and other renewable energies, we shall be able to produce hydrogen gas. The paradigm shift to a hydrogen-powered world will unfold quicker than estimated. After fifteen years, the most difficult part will be achieved. Like the mobile phone, it may start out slowly, but will gather momentum and finally go viral. With this, we will achieve the democratisation not only of energy and information, but also of the economy, and this is the transition of power to the people in a literal sense. People that were consumers will become producers of power and change the system, bottom-up [20].

We must use a strategic methodology for change, which entails everything from plain market force with its lure of new products for the consumer, to non-profit organisations and grassroots information and awareness campaigns. We have to tap into the public's inclination to do the right thing. We then all reap the benefits of clean energy independence.

These are precarious, but also very exciting times that we live in today, and there is a chance for truly great things to happen now.

7.3. Conclusion

Wall Street and corporate lobbies would have us believe that money is the cause for great things and that 5% of a corporation's profit put into research is a big step in the right direction. They would have us believe that billions of dollars spent to "educate" doctors and experts is the answer. However, the truth is that it is not about the money. Scores of PHDs do not come up with great inventions. Most great inventions were made by tinkerers, or a couple curious guys in a garage who could think outside of the box. History has shown us that, and yet our system insists that a thousand more PHDs and billions more in funds are required to come up with a solution to the world's problems. We do not need more consultants and experts. Their jobs are to make simple things complicated. They are specialised in what ***was***. Experts can tell us everything about what ***was*** and whether something is possible or not based on that information. We need to focus on what ***is*** and what ***will be***. If we look to experts and consultants to give us a solution for what ***was***, then we do not stand a chance to be creative and innovative. We need curious and innovative divergent-thinkers and chance-takers with an honest drive to do the right thing and to make the what ***will be*** possible. To "*be the change we wish to see in the world*" [26].

What it asks is doing the right thing and inventing the right thing for a vision that we believe in. Life is too short and precious to do that which does not have a true and positive impact.

Solar Hydrogen Systems

for Off-grid Energy Generation

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