

ÉCOLE POLYTECHNIQUE

MSc&T STEEM

Academic Year 2018-19

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INTERNSHIP REPORT

Support in the conception of a Solar to Hydrogen
research topic



NON CONFIDENTIAL REPORT

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Internship dates: 27/04/2019 -13/09/2019

Declaration of Academic Integrity

Hereby I, Benyamin BIDABAD, confirm that:

1. The results presented in this report are my own work.
2. I am the author of this report.
3. I have not used the work of others without clearly acknowledging it, and quotations and paraphrases from any source are clearly indicated.

Benyamin BIDABAD, 03/09/2019,

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ABSTRACT

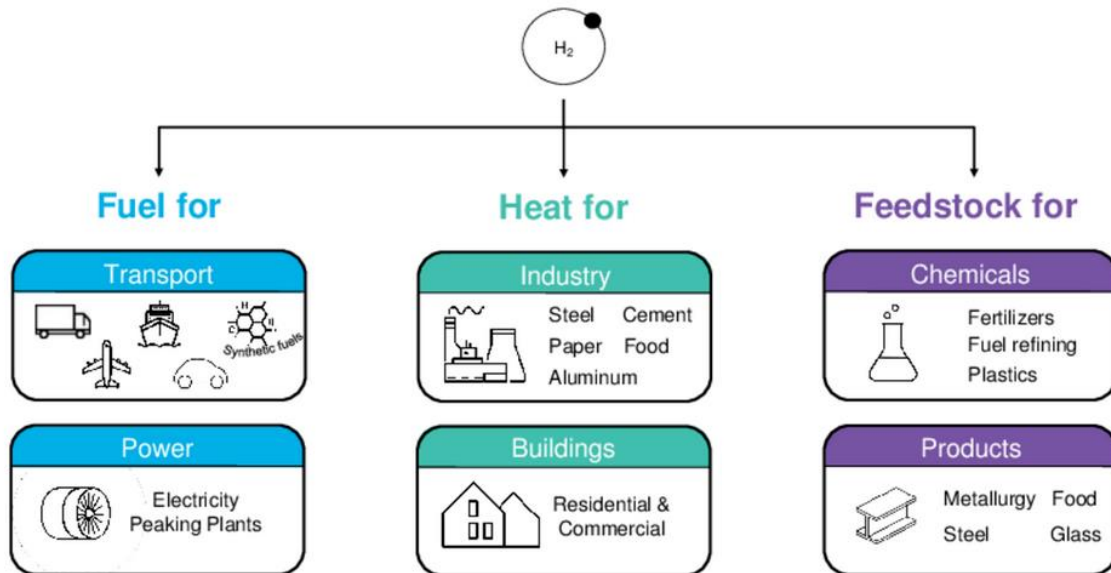
This internship aims to help IPVF define a solar to hydrogen project that would be both of interest to IPVF, and feasible with their lab equipment and experts' knowledge. In this report we are summarizing an overview over solar to hydrogen technologies such as integrated photovoltaics-electrolyzers (PV-E), and photoelectrochemical (PEC) water splitting. After an introduction to the principles of these technologies, their scientific background and their economic aspects will be explained. Steam methane reforming (SMR) being the most common hydrogen production method these days is compared to solar water splitting technologies both from the aspects of economy and carbon emission. The current challenges in the solar to hydrogen field and the potential research pathways that could be of interest are also discussed.

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1. Introduction

Hydrogen is a valuable alternative fuel that could replace commonly used fossil fuels. When burnt, it has no carbon emission and produces only water and heat. It's energy density is higher than other fossil fuels we use nowadays and it can be generated from a wide range of natural resources such as water, hydrocarbons and organic matters. Hydrogen has many different applications as demonstrated in Figure 1.



Source: BloombergNEF

Figure 1- Hydrogen Applications

So far the most common way of producing hydrogen is by using Steam Methane Reformers (SMR). A method in which methane is put into interaction with high pressure and temperature water in a reformer, which then causes it to split into CO_2 and H_2 . However, this method emits lots of CO_2 emissions. CO_2 as a greenhouse gas can overload in the atmosphere when we burn fossil fuels and cause a heat-trapping effect. CO_2 remains in the atmosphere longer than the other major heat-trapping gases emitted as a result of human activities. It takes about a decade for methane (CH_4) emissions to leave the atmosphere (it converts into CO_2) and about a century for nitrous oxide (N_2O). After a pulse of CO_2 is emitted into the atmosphere, 40% will remain in the atmosphere for 100 years and 20% will reside for 1000 years, while the final 10% will take 10,000 years to turn over [1].

Urgent need to decrease CO2 emissions to reduce global warming

Efforts to decarbonise are not yet strong enough to overcome growing global energy needs

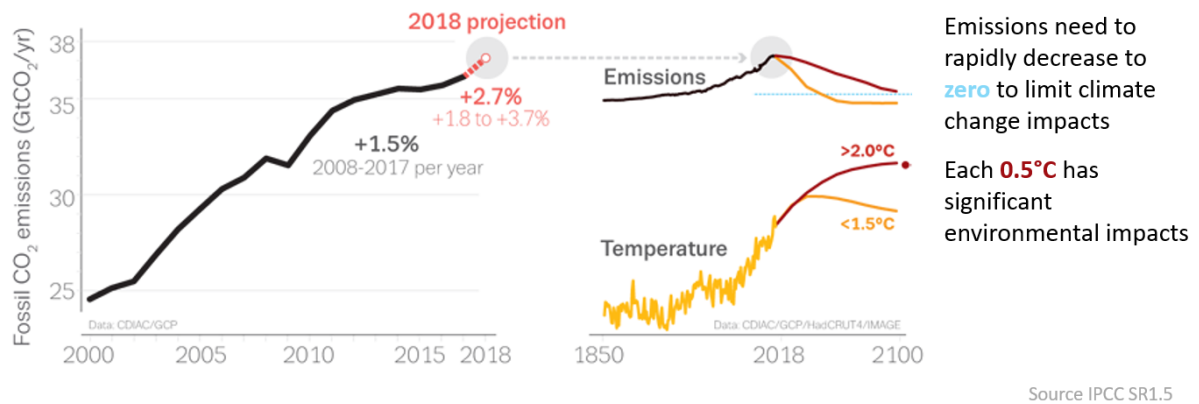


Figure 2 - Urgent need to decrease CO2 emissions to reduce global warming

Alternate methods are to be considered for a cleaner and renewable hydrogen production. A cleaner, yet not so commercial way of producing hydrogen is using the sun, which then is considered a solar fuel. With the sun being an abundant source of energy incident on the planet, researchers are always wondering how to profit the most out of this energy. The use of photovoltaic cells has taken us to a great extent in utilizing the solar energy for electricity production but has been limited mostly by the high cost and challenges of energy storage. Batteries are a common solution to energy storage, but their limited life time and high cost doesn't allow large scale use. Alternative storage methods, such as solar fuels, are expected to make energy storage more convenient. The excess electricity that needs to be stored can be converted into hydrogen and kept as fuel. Later, in time of need, a fuel cell can be used to convert the hydrogen back to electricity, or simply burn it as a combustive fuel.

The focus of this report is on hydrogen production from the sun. One way to do so would be to use carrier separation in semiconductors to split water into hydrogen and oxygen, otherwise known as a photoelectrochemical (PEC) reaction. The other way would be to use an electrolyser powered by photovoltaic panels for water splitting, also known as PV+E. In this report, we will start by explaining the principles of water splitting and electrolysis. We will then present the different solar to hydrogen technologies and their corresponding state-of-the-art advancements and efficiencies. We will conclude by an economic analysis of these systems. The goal of this report is to help IPVF understand the challenges and future directions of solar to hydrogen technologies and also help them define a proper project suitable to their competences and facilities.

1.1. About IPVF and the Internship

My internship takes place at the Photovoltaic Institute of Ile de France (IPVF) a research center supported by the French State within the "Investissements d'Avenir" (Investments for the Future) program, working mainly on the advancement of photovoltaic technologies. It has also been granted the title of "Institute for energetic transition" which provides it with many financial benefits from the Investments for the Future program.



Figure 3 - The IPVF building

IPVF is a research institute building, a bridge between academic and industrial researchers. Total, EDF, Air Liquide, CNRS, Ecole Polytechnique, and 2 French SME are working together to make IPVF one of the world's leading research, innovation and training centers in the field of photovoltaic solar energy. IPVF intends to enhance the performances and competitiveness of photovoltaic cells and to develop new breakthrough technologies.

IPVF is divided into 11 projects, each identified by a letter of the alphabet. There are five categories of project. The first three are dealing with PV technologies: silicon (I), thin films (II) and new concepts (III). The two others have cross-cutting objectives: characterization-theory-modelling (IV) and economic and social aspects (V).

The project I was enrolled in is named Project K, and lies into the last category. The goal of project K is to study the techno-economical aspects of the photovoltaic technologies, provide TRL (technology readiness level) evaluation, and support other projects in their economical assessments. The Project K team consists of researchers from EDF, Total and IPVF itself.

The goal of the internship is to perform a background study on the scientific and techno economical advancements of solar hydrogen technologies and help IPVF define a proper project in solar hydrogen. The potential project must be one that could take advantage of the expertise and lab equipment of IPVF. Also, IPVF could enroll in ongoing projects conducted by the partners such as EDF, CNRS, Air Liquide, CEA, Chimie ParisTech and etc to avoid starting from scratch. Project K is to identify these potential partners and their projects in the solar fuel field and organize brainstorming sessions with them to find out about the state of the art challenges and opportunities in the solar fuel field. One other goal of Project K is to perform literature review on current solar fuel technologies and prepare a scientific background to identify potential subjects that would be feasible and interesting to work on in IPVF.

1.2. Solar Fuels

Solar fuels are any kind of synthetic fuel produced from solar energy. These fuels can then be stored with a lower maintenance cost and then be converted into energy whenever needed. There are several methods to produce solar fuels:

- Photochemical/Photobiological processes, for instance artificial photosynthesis is a chemical process that biomimics the natural process of photosynthesis to convert sunlight, water, and carbon dioxide into carbohydrates and oxygen.
- Thermochemical processes by concentrating solar thermal energy to drive a chemical reaction.
- Electrochemical Reactions which uses photons to break water into hydrogen and water

The most widely researched solar fuels are hydrogen and products of carbon dioxide reduction, commonly observed products include formate, formic acid, carbon monoxide, and methanol.

2. Different sources and hydrogen production methods

There are many ways to produce hydrogen one of the most common ones nowadays is by using steam methane reforming (SMR). Other ways of production fall into 3 categories: the thermal processes, the electrolytic processes and the photolytic processes. In the first category, we found the SMR, the coal and biomass gasification, and also the thermochemical water splitting. In this study, we are going to focus on the electrolytic and photolytic processes, based on the dissociation of water molecules by electrons or photons. These two solutions have the lowest environmental impact. Biological processes, using algae to split the water, mimicking photosynthesis, is also regarded as a sustainable production for hydrogen but this is out of the scope of IPVF researches. SMR of natural gas ends up being the cheapest solution according to the IEA 2019 hydrogen report [2], but although it has lower carbon emission compared to oil and coal, it still has a very high amount of carbon emission compared to other renewable solutions (Figure 4).

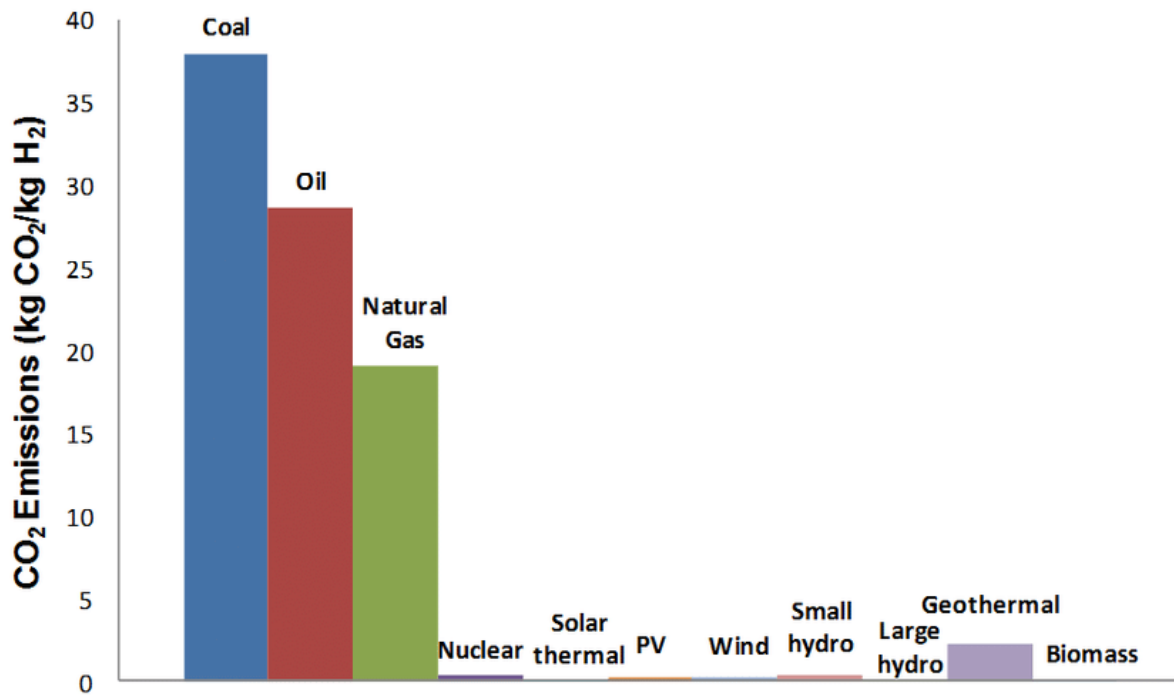


Figure 4 - Carbon emission of hydrogen production [3].

Hydrogen has been classified by the source of its production that differentiates based on the carbon emission level of its production method (Figure 5). Each different production source is defined by a color.

Electrolysis requires only pure water and electricity. The result is hydrogen and oxygen. This process provides CO_2 -neutral energy when the electricity used also comes from renewable sources, such as sun and wind. This type of hydrogen is often called “**green hydrogen**”.

In the Netherlands and the rest of the world, most hydrogen is currently being produced via steam-methane (from natural gas) reforming, which produces hydrogen and CO_2 . As long as we release this CO_2 into the air, we call this product “**grey hydrogen**”. But there is a solution: Carbon Capture, Utilization and Storage (CCUS). If the CO_2 from this process is captured and stored, the hydrogen produced has lower CO_2 emission. This hydrogen is often called “**blue hydrogen**”. Not really green, but certainly not grey.

France’s hydrogen strategy includes indicative targets for greening the current use of grey hydrogen in industry. The French government has set a target of 10% green hydrogen use in industry for 2022 and 20% to 40% for 2027. Further efforts are being made according to the Paris agreement. The Paris Agreement central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Reducing carbon emissions will contribute notably to this cause.

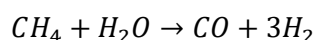
Black	Grey	Brown	Blue	Green	Not associated
•Coal	•Natural Gas	•Lignite	•CO2 reduced by CCUS	•Renewable electricity	•Biomass, nuclear, etc.

Figure 5 - Hydrogen classification by color based on the source of its production

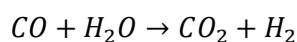
After a quick review on how SMR works, we will further discuss electrolytic and photolytic methods used to produce clean hydrogen from the sun.

2.1. Steam Methane Reforming (SMR)

This is one of the most common industrial ways of producing hydrogen. When using natural gas as a feedstock the process puts CH₄ into interaction with high pressure and temperature water in a reformer, in the presence of a nickel-based catalyst to produce hydrogen. The following reaction takes place:



Then there is a shift reaction that turns the remaining CO into more hydrogen. This is usually done at two stages with different temperatures called higher and lower shift reactions.



Finally, we have:

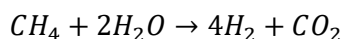


Figure 6 shows a simplified box diagram of one of the most efficient and used production processes of hydrogen from natural gas (methane), called SMR-WGS-PSA route. WGS, for Water-Gas Shift, or else the CO conversion into H₂ and CO₂ and PSA, for Pressure Swing Adsorption, is a system that is added to the SMR unit in order to purify the H₂, by removing CO₂, CO, and CH₄ impurities.

The SMR process has an efficiency of around 85 % methane conversion in H₂.

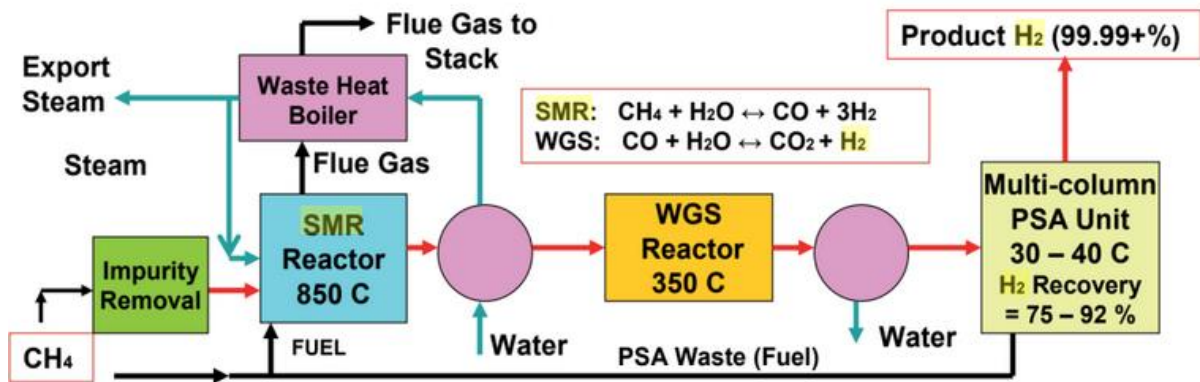
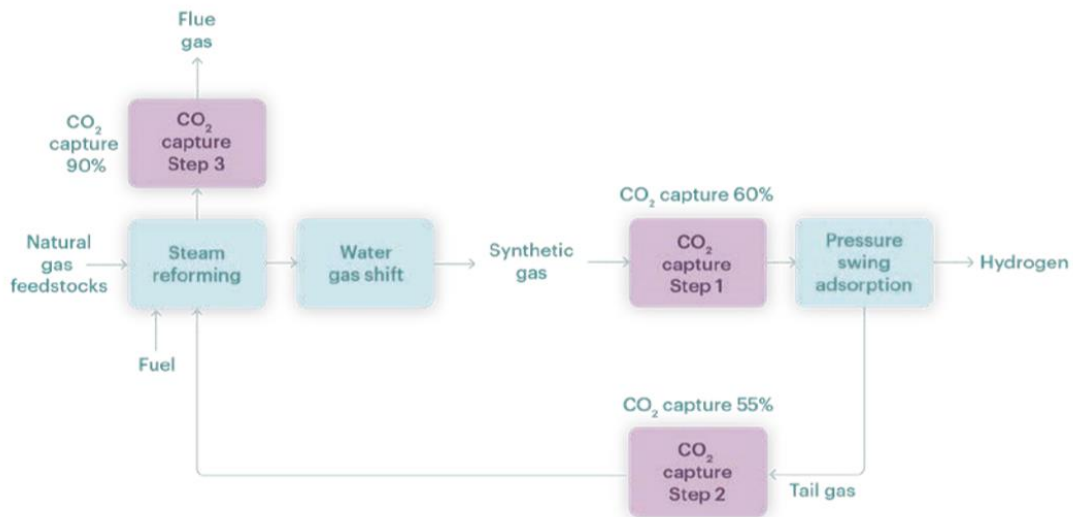


Figure 6 - Conventional steam methane reforming route of H₂ production from natural gas [Michael Beaver and Shivaji Sircar (2010). Decentralized Production of Hydrogen for Residential PEM Fuel Cell from Piped Natural Gas by Low Temperature Steam - Methane Reforming Using a Novel Sorption Enhanced Reaction Concept, Clean Energy Systems and Experiences, Kei Eguchi (Ed.)]

This process is followed by a carbon capture and utilization process (CCU) that can remove up to 90% of the CO₂ emission (Figure 7).



Source: IEAGHG (2017a), "Reference data and supporting literature reviews for SMR based hydrogen production with CCS".

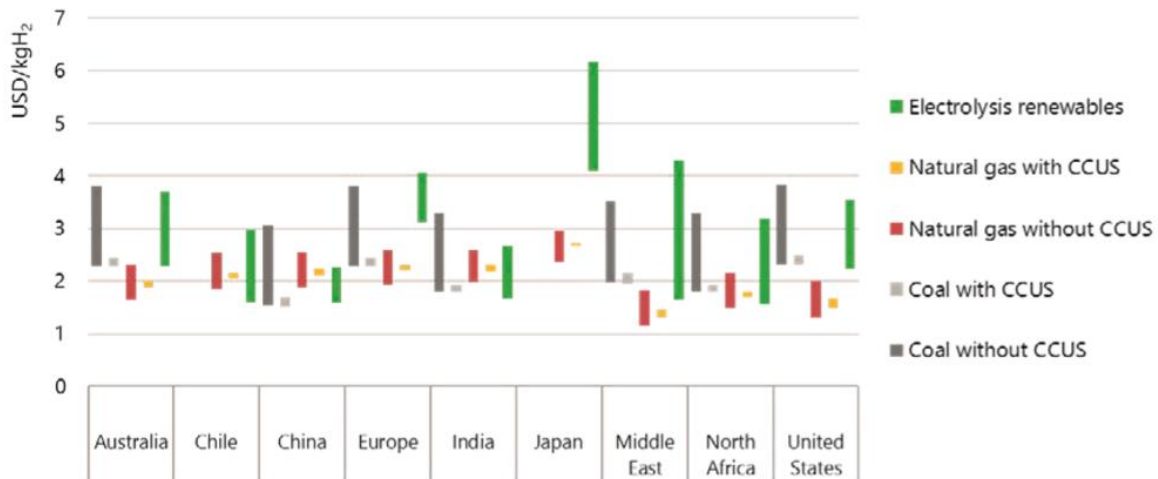
Figure 7 - Carbon capture & storage after reforming

The market for CO₂ utilisation is relatively small, and future markets for CO₂ will have to map and prioritize points of CO₂ emission with utilisation opportunities. Current CCU technologies/processes (Table 1) are at different stages of maturity. Some of the "incremental" technologies could be readily established in existing mature markets e.g. use of CO₂ to boost urea production, whereas others are at theoretical and research phases, or are at the pilot/demonstration phase, and need further development to reach commercial status.

Table 1 - TRL status of a set of CCU technologies and CO₂ applications [4].

CCU category	Technology/application	Technology development and performance (TRL)
CO₂ to fuels	Renewable methanol and methane production	4-8
	Formic acid production	5
	Algae cultivation	3-5
	Helioculture	3
	Counter rotating ring receiver reactor recuperator	3
	Photocatalytic reduction of CO ₂ (metallic)	3
	Photocatalytic reduction of CO ₂ (non-metallic)	3
	Nanomaterial catalysts	2-3
Enhanced commodity production	Enhanced Geothermal System with CO ₂	4
	Supercritical CO ₂ power cycles	3
	Urea yield boosting	9
	Methanol yield boosting (conventional)	9
CO₂ mineralisation	Mineral carbonation	3-7
	Sodium bicarbonate	6
	CO ₂ concrete curing	5
	Bauxite residue carbonation	8
CO₂ as chemicals feedstock	Polymer processing (polycarbonates)	3-5
	Polymer processing (polyurethanes)	3-5
Other existing commercial applications	Food and beverage applications	9
	Horticulture	9
	Other Industrial and technical uses	9

Although the production price of hydrogen without carbon capture is lower nowadays, it is expected that in the long term, the rise of carbon taxes will cause hydrogen production with carbon capture to become the most competitive option (Figure 8). The figure assumes a carbon tax rise from $25 \frac{USD}{ton_{CO_2}}$ to $100 \frac{USD}{ton_{CO_2}}$.



Notes: Bars indicate range between near- and long-term hydrogen production costs, which include a CO₂ price of USD 25/t CO₂ in the near term and USD 100/tCO₂ in the long term. For options from coal and natural gas, the higher value indicates the long-term costs (due to the increasing CO₂ price), whereas for hydrogen from renewable electricity the lower value indicates the long-term costs.

Source: IEA 2019. All rights reserved.

Figure 8 - Price of different hydrogen production technologies around the world in the short term and long term. [2]

2.2. Water splitting technologies using the sun

Water splitting consists of breaking H₂O molecules into hydrogen and oxygen. This reaction can happen using electrons or photons.

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production. These systems are integrated into wind farms and solar farms to store the excess electricity in times of need.

Electrolysers are differentiated by the electrolyte materials and the temperature at which they are operated:

Low temperature electrolysis (LTE) includes alkaline electrolysis, proton exchange membrane electrolysis (PEM), and anion exchange membrane electrolysis (AEM).

High temperature electrolysis notably includes solid-oxide electrolysis (SOE).

While electrolysers are already in operations, research continues to further improve them. Research priorities with regard to electrolysers currently include increasing the efficiency of the electrolyser system as a whole, along with its operating life, power density and stack size, reducing costs (especially

material costs), introducing pressurized systems to avoid the need for subsequent compression of the H₂ produced, and not least developing flexible systems adapted to intermittent and fluctuating power supply.

The efficiency of electrolysis is determined by the amount of electricity used to produce an amount of hydrogen. Depending on the method used, the efficiency of water electrolyser is currently in the region of 60 to 80 % (based on the calorific value) [5].

2.2.1. Solar to hydrogen efficiency (STH)

Usually solar to hydrogen efficiency (STH) is used to estimate water splitting hydrogen production efficiency from the sun. A very simple formula for STH, considering a 100% Faradaic efficiency can be described by:

$$\eta_{STH} = \frac{E_{redox} J_{photo}}{P_{Light}} \quad (1)$$

Where E_{redox} is the potential corresponding to the Gibbs energy, J_{photo} is the photocurrent density and P_{light} is the total solar incident energy. The maximum theoretical STH efficiency is about 29.7% [6]. The highest STH efficiency demonstrated to date, 24.4%, was delivered by a PV-electrolysis system using GaInP/GaAs/Ge multi-junction solar cells and polymer electrolyte electrochemical cells [7]. Multi-junction solar cells are solar cells with multiple p-n junctions made of different semiconductor materials. Each material's p-n junction will produce electric current in response to different wavelengths of light.

There are many different systems with different materials and architectures designed to produce hydrogen from the sun.

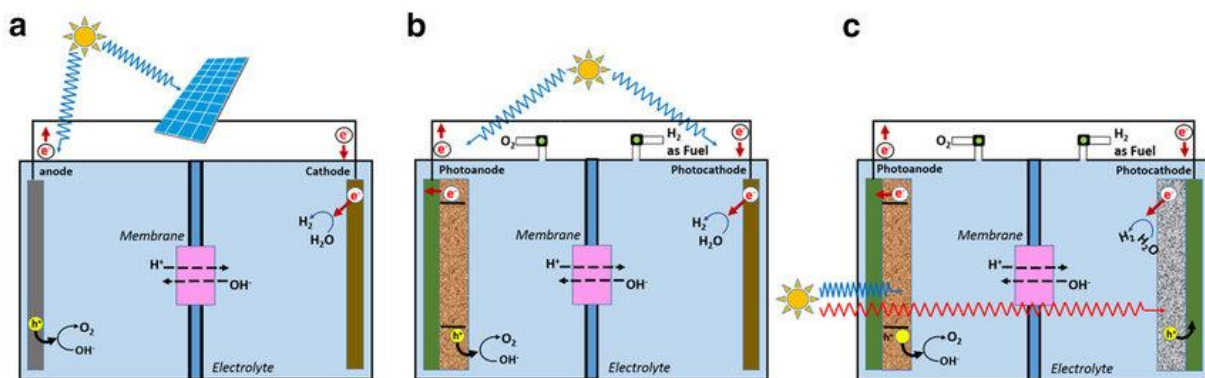


Figure 9 - Different water splitting systems with different architectures [8]

2.2.2. Photovoltaic Plus Electrolyser (PV-E)

While producing hydrogen from water is possible using electricity from any source, this electricity could be provided by PV panels to make it 100% renewable. Photovoltaic and Electrolyser coupling has

many obstacles that need to be overcome. It necessitates DC-DC matching of the two systems. Also, alkaline electrolyzers have a slow startup time and therefore while coupled with PV technologies they suffer in terms of efficiency. In the other hand polymer electrolyte membrane electrolyzers have quicker startup times and are more suitable for coupling with electrolyser systems, yet still suffer from intermittent photovoltaic consequences such as: lack of solar irradiation during night and cloud cover or poor weather resulting in power fluctuations which limit the overall system efficiency. The potential high performing photovoltaic coupled with an electrolyzer has a potential STH efficiency of about 18%; though coupling to an average photovoltaic module in moderately irradiated areas renders this value around 3-8% according to [9]. Within the past few decades, much research has been completed to advance the coupling of these two technologies and to avoid losses typically implicated by PV-electrolyzer coupling. Eventually, this coupled technology may be replaced with a more direct solution to solar hydrogen production by means of PEC systems [9]. The highest STH efficiency demonstrated to date, 24.4%, was delivered by a PV-electrolysis system using GaInP/GaAs/Ge multi-junction solar cells and polymer electrolyte electrochemical cells [7].

2.2.3. Photoelectrochemical water-splitting (PEC)

Photoelectrochemical water splitting is in the very early stages of research, and though offers a great opportunity to produce intellectual properties (PI), to bring new partnership, and find potential projects compatible with IPVF skillset and facilities.

Hydrogen can be produced from water-based electrolyte using sunlight and a semiconductor material which uses light energy to directly dissociate water molecules into hydrogen and oxygen. This process is called photoelectrochemical water-splitting. In a PEC system semiconductors are being used as electrodes. PEC reactors can be constructed in panel form (similar to photovoltaic panels) as electrode systems or as slurry-based particle systems. The electrodes always have to be separated by a membrane in an aqueous electrolyte, to avoid the exothermal reaction between hydrogen and oxygen. The semiconductors are either p-doped with an excess of holes and used as the photocathode or n-doped with an excess of electrons and used as the photoanode. The materials required for the photo-electrodes of PECs should perform two fundamental functions [10]:

- optical function required to obtain maximal absorption of solar energy.
- catalytic function required for water decomposition.

Theoretically three arrangements for a PEC device are possible:

- 1- Photoanode (**n-type** semiconductor) and a **metallic** cathode
- 2- Photoanode (**n-type** semiconductor) and a photocathode (**p-type** semiconductor)
- 3- **Metallic** anode and a photocathode (**p-type** semiconductor)

When the photoelectrode is exposed to light that has an energy higher than the semiconductor bandgap, electrons are excited and rise from the valence band to the conduction band of the semiconductor creating an electron-hole pair in the valence band. The energy of the photon is calculated using the following equation:

$$E = h\nu \quad (2)$$

Where h is the planck constant and ν is the photon's frequency.

The electrons then flow through the external circuit to the cathode. A photocurrent is generated and leads to water splitting through these steps:

- 1- Ionization of semiconductor into electron and holes
- 2- Oxidation of water at the **photoanode**
- 3- Transport of electrons through the external circuit
- 4- Transport of H^+ ions through the electrolyte.
- 5- Reduction of hydrogen at the cathode.

The ionization of semiconducting material into holes and electrons follows this equation.



Where h is Planck's constant and e^- and h^+ are the electrons and holes respectively.

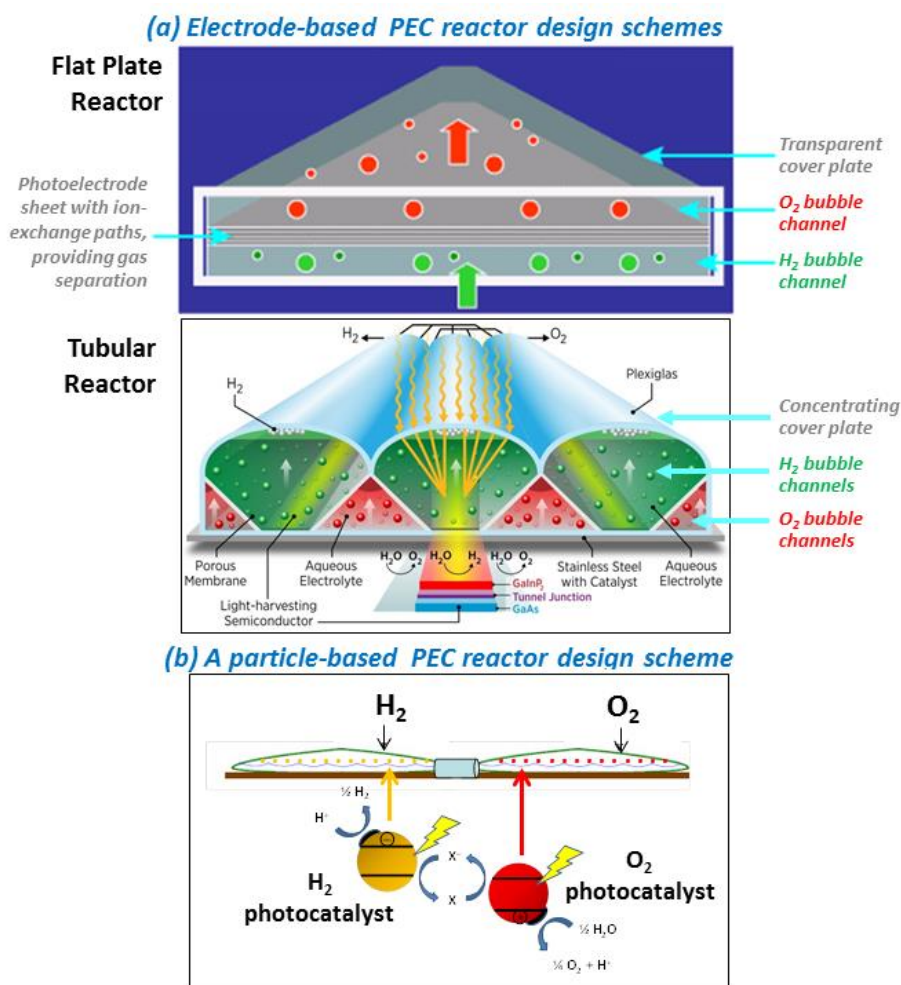


Figure 10: Possible PEC reactor design schemes for (a) electrode systems, including a flat plate and a tubular reactor (providing moderate solar concentration onto one electrode strip); and (b) a plastic "baggie" covered dual bed particle reactor with wide-by-side photocatalyst slurries. From [<https://www.energy.gov/eere/fuelcells/hydrogen-production-photoelectrochemical-water-splitting>]

For the photon to be absorbed in the semiconductor the photon energy must be higher than the bandgap of the cell. Once the holes and electrons are created an electric field is required at the electrode/electrolyte interface to avoid the recombination of carriers. The minority carriers in the

semiconductors can move to the interface between a semiconductor and electrolyte due to the electric field created by the semiconductor- electrolyte depletion zone. The minority carriers (holes in the photoanode and electrons in the photocathode) promote photoelectrochemical reaction at the surface of the semiconductor, leading to the oxidation on the photoanode and reduction on the photocathode. So it is important to have an external bias to keep these charges separated so they don't recombine at the surface.

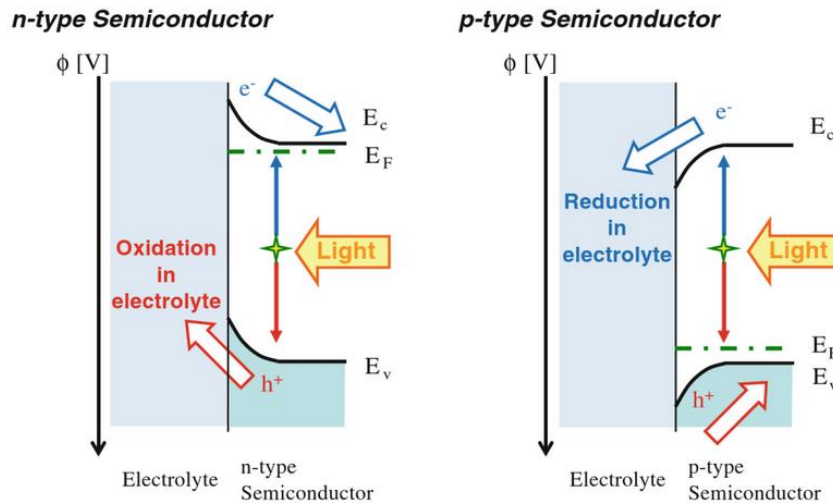


Figure 11 : Schematic diagram for the photoelectrochemical reaction occurring at n-type and p-type semiconductors and electrolyte interfaces without bias. [Masakazu Suqiyama, Katsushi Fujii and Shinichiro Nakamura, Solar to Chemical Energy Conversion, Lecture Notes in Energy, Livre 32, Springer, 2016]

At the photoanode the following reaction happens:



The H⁺ ions move inside the electrolyte towards the cathode. At the cathode they react with the electrons incoming from the electrical circuit.



The overall reaction is as follows:



For equation (6) to happen a reaction energy of 237,141 kJ/mol is needed. Using the Nernst equation this translates into 1,23 eV (1000 nm of photon wavelength). Meaning that the photons that are absorbed must have at least this amount of energy. So theoretically a material with a minimum bandgap of 1,23 eV is needed. Such a material would be able to absorb a high percentage of the solar spectrum. But there are some issues. The losses in the system causes an additional bandgap requirement of about 0,8 eV [10]. These losses are mainly caused by:

- Contact voltage losses

- Polarization within the PEC
- Recombination of electron hole pairs within in the photo-anode or photocathode
- Electrode and electrical resistance

Electron-hole recombination is the most important loss mechanism in water splitting reactors. Nanostructuring can enhance light harvesting, charge transport and kinetics while it has a significant disadvantage of reducing power conversion efficiency and the durability of the device [6].

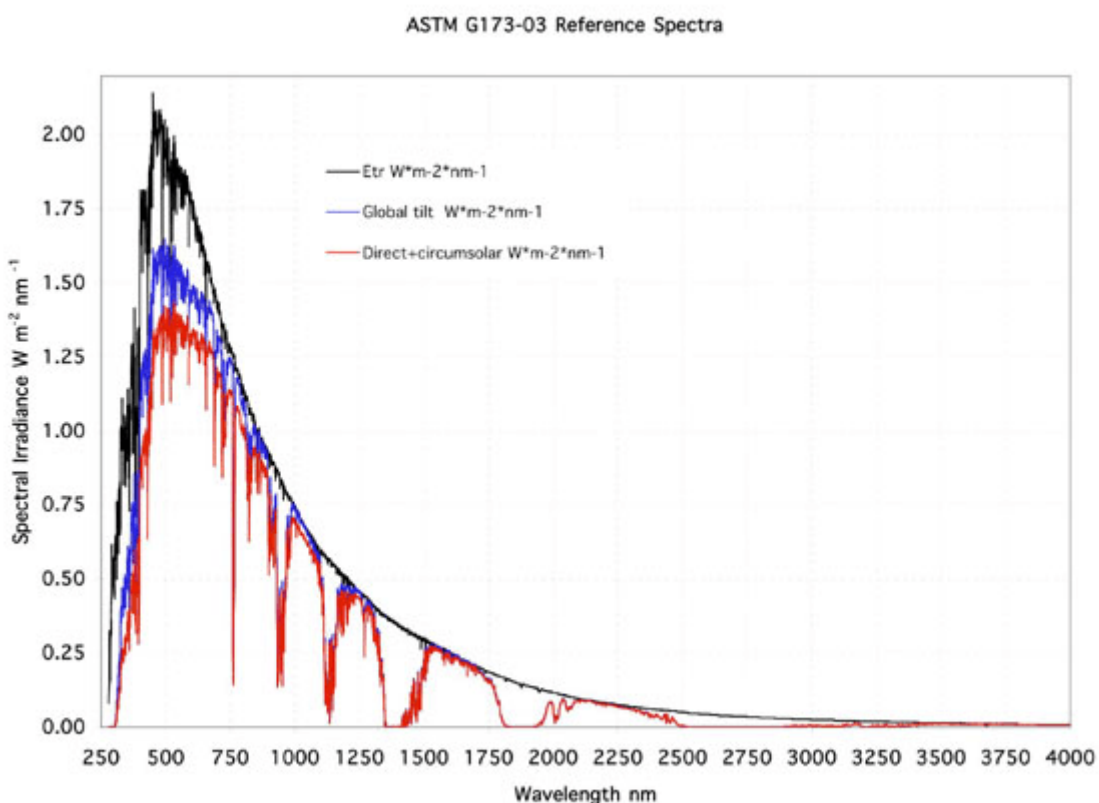


Figure 12 - Solar Spectrum (from <https://rredc.nrel.gov/solar//spectra/am1.5/>) where the black line represents AM0 (extraterrestrial illumination), the blue line is AM1.5, and the red line is direct irradiation only.

So an optimum band gap for the photoanode would be around 2 eV (619 nm wavelength). Therefore, any material with a bandgap lower than 2 eV is inapplicable. it's easy to find a material with such a bandgap but the problem is the durability of the material in aqueous environment. A material currently used is TiO₂. TiO₂ has a bandgap of about 3 eV (413 nm), that means that it cannot absorb more than 5% of the solar spectrum [10].

The challenge is to find a material with lower bandgap that is durable in aqueous environment. Other solutions are also possible such as using ALD (atomic layer deposition) to protect the electrodes from corrosion. Chor Seng Tan et al. were able to design a rather stable system with an efficiency higher than 10% for unassisted water splitting using ALD-protected silicon heterojunction solar cells [11].

2.2.3.1. Single photoelectrode PEC

Single photoelectrode devices can either have single photoanode (n-doped) or photocathode (p-doped) with a metallic anode/cathode pair. In a photoanode-metal system, the electrons move through the bulk to the external wire and then to the metallic cathode where reduction occurs. The

generated holes move to the photoanode-electrolyte surface where oxidation occurs. In a photocathode-metal system the electrons flow to the photocathode-electrolyte interface where water reduction happens.

It has been reported that single photoelectrode systems have many disadvantages. The most important one is unfavorable band edge positions, also an external bias is needed when the band edges don't overlap water splitting potential or to delay electron hole recombination in the bulk of wide bandgap semiconductors [6].

2.2.3.2. Dual photoelectrode PEC

A dual photoelectrode system, compared to a single one has the ability to absorb a higher range of the solar spectrum and overcomes the problem of water redox overlap. The photoelectrodes are usually composed of different semiconductor materials with different bandgaps to cover a broader range of the solar spectrum and they are usually designed as p/n tandem cells. The voltage of the two sub cells added together can reach the required voltage for water splitting. In the case of tandem design, the high bandgap solar cell should be placed first to allow lower energy photons to pass to the next semiconductor with lower bandgap. In this setup it is crucial that conduction band edge of the n-type electrode must be greater than the valence band edge of the p-type semiconductor. If else, the electrons wont flow through the external circuit [6].

There are multiple ways this tandem arrangement can be set up. The electrodes are either physically separated or combined into a monolithic cell. Different possible configurations are shown in Figure 13.

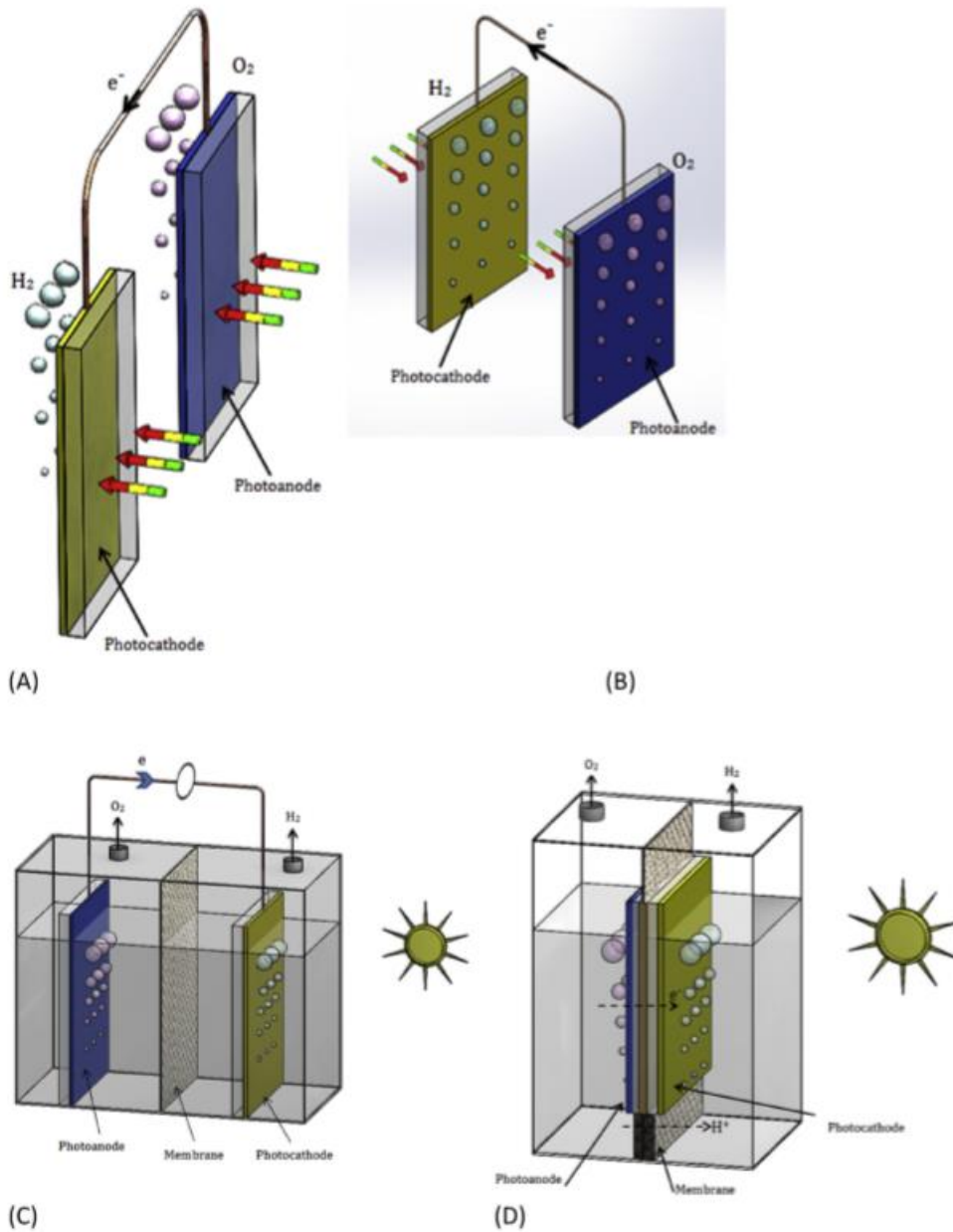


Figure 13 - Dual photoelectrode architectures [6]

Also, mirrors can be added to expose the system to sunlight from both sides. This arrangement has higher maintenance and capex costs.

Numerous materials have been tested for double electrode installations. A list of these photoanode and photocathode materials are listed in Table 2. You can also see their respective STH efficiency and electrolyte solution. The attained STH efficiency is still below 1% and this is mainly due to the lack of materials with suitable bandgaps and sufficient photon energy in both electrodes. Also well adopted bandgap energies and band edge positions of the n/p photoelectrodes are still needed. [6]

Table 2 - List of photoanode and photocathode materials for dual unbiased PEC systems [6]

Photoanode	Photocathode	STH %	Electrolyte
Fe ₂ O ₃	GaInP ₂	0.00022	KNO ₃ /Pi(pH5.7)
WO ₃	GaInP ₂	0.0025	3MH ₂ SO ₄
WO ₃	NiO _x /Cu ₂ O	0.04	Na ₂ SO ₄ (pH 6)
TiO ₂	CdTe	0.044	1 M NaOH
CoO _x /TiO ₂ /BiVO ₄	NiO/Ni(OH) ₂ /TiO ₂ /Si	0.05	Bi/K ₂ SO ₄ (pH 9.2)
Si-doped a-Fe ₂ O ₃	Mg-doped a-Fe ₂ O ₃	0.05	0.1 M Na ₂ SO ₄
TiO ₂	GaP	0.098	1 M NaOH
BaTaO ₂ N/Co	La ₅ Ti ₂ Cu _{1-x} Al _x S ₅ O ₇ /Pt	0.1	0.1 M Na ₂ SO ₄
a-Fe ₂ O ₃	Zn-doped a-Fe ₂ O ₃	0.11	0.1 M H ₂ SO ₄
IrO _x /TiO ₂	Pt/Si	0.12	0.5 M H ₂ SO ₄
WO ₃ /w	Pt/n ⁺ p Si	0.15	KH ₂ PO ₄ (pH 7)
IrO _x /ZnS/CdS/TiO ₂	CdSe/NiO	0.17	0.5 M Na ₂ SO ₄
TiO ₂ /CdS/ZnS/IrO _x	NiS/ZnS/CdSe/NiO	0.17	0.5 M Na ₂ SO ₄
TiO ₂	Fe ₂ O ₃ /TiO ₂ /Si	0.18	Na ₂ SO ₄ /Pi (pH 7)
WO ₃ /FTO/p ⁺ nSi	Pt/TiO ₂ /Ti/n ⁺ p Si	0.24	1 M HClO ₄
TiO ₂	GaP	0.25	0.2 M H ₂ SO ₄
TiO ₂	CuTiO _x	0.3	KOH/Pi
1%W-BiVO ₄ /Bi ₄ V ₂ O ₁₁	BiVO ₄ /Bi ₄ V ₂ O ₁₁	0.32	0.5 M Na ₂ SO ₄
CdS/ZnO	Cu ₂ S/Cu ₂ O	0.38	0.5 M Na ₂ SO ₄
ZnO/CdS	Cu ₂ O/Cu ₂ S	0.38	0.5 M Na ₂ SO ₄
TiO ₂	np ⁺ Si	0.39	1 M KOH
BiVO ₄ /Co-Pi	Cu ₂ O/RuO _x	0.5	0.5 M Na ₂ SO ₄ /0.09 M KH ₂ PO ₄ /0.01 M K ₂ HPO ₄
Co-Pi/W:BiVO ₄	RuO _x /TiO ₂ /Al:ZnO/Cu ₂ O	0.5	Na ₂ SO ₄ /Pi (pH 6)
Co-Pi/BiVO ₄	Pt/TiO ₂ /Zn-InP	0.5	Pi (pH 7)
Co-Pi/Mo:BiVO ₄	Pt/Si	0.57	Pi (pH 5.5)
SrTiO ₃	GaP	0.67	1 M NaOH
NiOOH/FeOOH/Mo: BiVO ₄	Pt/CdS/CuGa ₃ Se ₅ /(Ag, Cu)GaSe ₂	0.67	Pi (pH 7)
Mo-BiVO ₄ /FeOOH/NiOOH	Pt _{CdS} /CuGa ₃ Se ₅ /(Ag,Cu)GaSe ₂	0.67	KH ₂ PO ₄
NiFeO _x /Fe ₂ O ₃	Pt/a-Si	0.91	Pi (pH 11.8)
1%W- BiVO ₄ /Bi ₄ V ₂ O ₁₁ /FeOOH/NiOOH	BiVO ₄ /Bi ₄ V ₂ O ₁₁ /Pt	0.95	0.5 M Na ₂ SO ₄

The solar to hydrogen efficiency has been improved to more than 12.3% for PEC Tandem water splitting systems according to [8].

The maximum theoretical STH efficiency is about 29.7%. Finding more adaptable material with better photon absorption and band edge positions will get us closer to this limit [6].

2.2.3.3. Integrated PEC/PV

These systems are the result of coupling photocathode or photoanodes with PV systems to form PEC/PV tandem designs. The photovoltaic part of the system can be conventional PV, DSSC or perovskite solar cells.

Conventional PV/PEC hybrids

In conventional PV/PEC hybrids, the coupling results in unassisted water splitting. PV cells can provide enough photovoltage for the photoelectrodes to be driven only by sunlight without the need for an external bias. It is very important to have a balance of solar light absorption between the PEC and PV cells in order to achieve the highest STH efficiency. The most widely recognized photoelectrode/PV device is a monolithic GaAs p/n junction coupled to a p-type gallium indium phosphide (p-GaInP₂) photocathode [6]. The upper p/n-GaInP₂ junction with a bandgap of 1.83 eV absorbs the visible part of the solar spectrum and the lowest GaAs p/n junction with a bandgap of 1.42 absorbs the near-infrared part of the spectrum.

In a device designed by Han et al. an efficiency of 5.2% was observed using W:BiVO₄ photoanode combined with a micromorph a-Si:H/nc-Si:H cell [6].

Multijunction PV/PEC hybrids

In the design of multijunction PV/PEC hybrids, the main objective is to attain high efficiency of multijunction amorphous silicon devices. The design strategy is to try to match the current in each junction by the adjustment of the absorption spectra through bandgap tailoring.

Miller et Al. stated that an STH efficiency of 7.8% was attained for a triple-junction amorphous silicon/germanium photoelectrode deposited on glass/ITO with a separate anode [6]. Many other works and efficiencies were reported which are listed in Table 3.

The major problem in the PV units is the instability to the aqueous environment, so the protection of the PV device in PEC/PV hybrids is of major importance. However, PEC/PV tandem triple junctions are considered the most practical hydrogen production techniques with the highest efficiencies. The utilization of earth-abundant metal oxide photoelectrodes in the PEC/PV designs can decrease both the cost and the device complexity. State of the art efficiencies using different materials and architectures are shown in Table 3. As it can be seen, an STH efficiency of over 10% can be obtained by introducing interconnected PV/PEC tandem configurations.

Table 3 – List of PEC/PV systems and their respective efficiencies [6]

Photoelectrodes	PV cells	STH %
Pt cathode	Mn-doped Fe ₂ O ₃ photoanode and a single perovskite solar cell in series(photoanode)	2.4
FeOOH/BiVO ₄ photoanode	Si-solar-cell	2.5
a triple junction, amorphous silicon 3jn-a-Si photoanode	NiMoZn cathode (wireless)	2.5
W:BiVO ₄	a-Si:H	4.6
a triple junction, amorphous silicon 3jn-a-Si photoanode	NiMoZn cathode (wired)	4.7
Pt cathode	Co-Pi-W: BiVO ₄ and 2jn-a-Si (photoanode).	4.9
W:BiVO ₄	a-Si:H/a-Si:H	5.1
W:BiVO ₄	a-Si:H/nc-Si:H	5.2
Ruthenium oxide (RuO ₂) (anode)	a-Si/a-Si tandem cells (photocathode)	5.54
Ruthenium oxide (RuO ₂) (anode)	a-Si:H/μc-Si:H/μc-Si:H	5.9
Ni or Pt (cathode)	triple-junction amorphous silicon (a-Si) (Photoanode)	6.2
Ruthenium oxide (RuO ₂) (anode)	a-Si:H/a-Si:H with a ZnO:Al/Ag/Pt layer (photocathode)	6.8
Ruthenium oxide (RuO ₂) (anode)	a-Si:H/a-Si:H/μc-Si:H/μc-Si:H	7.6
Pt (cathode)	Dual photoelectrode: Fe ₂ O ₃ /TiO ₂ -BiVO ₄ /Ni ₂ FeOx/c-Si (2p c-Si)	7.7
Ni/FeNiOx anode	triple junction amorphous silicon (photocathode)	7.8
Ruthenium oxide (RuO ₂) (anode)	a-Si:H/a-Si:H/mc-Si:H/mc-Si:H with a ZnO:Al/Ag/Pt layer (photocathode)	7.8
Pt (cathode)	WO ₃ -NRs/BiVO ₄ +CoPi hetero-junction GaAs/AlGaAsP solar cells (photoanode)	8.1
Ruthenium oxide (RuO ₂) (anode)	a-Si:H/a-Si:H/μc-Si:H	8.7
Ruthenium oxide (RuO ₂) (anode)	a-Si:H/a-Si:H/μc-Si:H with a Pt layer (photocathode)	9.5

PEC/Perovskite solar cells

Perovskite solar cells (PSCs) have very good semiconductor properties. An appropriate bandgap, good light absorption coefficient, and high charge carrier mobility. They can be combined with PEC systems to achieve unbiased water splitting. Up to now some works have been done using PSC integrated in PEC. An efficient, stable and cost effective system with a STH efficiency of 2.4% was developed using Mn-doped Fe₂O₃ photoanode and an organic-inorganic halide perovskite (CH₃NH₃PbI₃) solar cell in series [6].

Another design was conducted using $BiVO_4/WO_3/SnO_2$ triple layer planar heterojunction photoanode. A list of the designs and their efficiencies are listed in Table 4.

Table 4 - List of PSCs/PEC architecture electrodes [6]

Electrodes	PV cells	STH %
Wired Pt (Cathode)	Mn-doped Fe_2O_3 photoanode and a single perovskite solar cell ($CH_3NH_3PbI_3$)-photoanode)	2.4
IrO_2 (Anode)	Cu_2O coated $Al:ZnO/TiO_2$ overlayers/perovskite solar cell ($(FAPbI_3)_{3-x}(MAPbI_3)_x$)-(photocathode)	2.5
DSA, Ir and Ru-coated Ti plate (Anode)	$CuIn_xGa_{1-x}Se_2$ (CIGS)/perovskite solar cell ($CH_3NH_3PbI_3$)-(photocathode)	2.6
Pt (Cathode)	Co-Ci/H/Mo: $BiVO_4$ /perovskite solar cell ($CH_3NH_3PbI_3$)- (photoanode)-wireless	3
Wired Pt (Cathode)	Fe_2O_3 nanorods- SnO_x /perovskite solar cell ($CH_3NH_3PbI_3$)-(photoanode)	3.4
Pt coil (cathode)	$BiVO_4/WO_3/SnO_2$ triple-layer planar heterojunction/perovskite solar cell ($CH_3NH_3PbI_3$)- (photoanode)	3.5
Pt (Cathode)	Co-Ci/H/Mo: $BiVO_4$ /perovskite solar cell ($CH_3NH_3PbI_3$)- (photoanode)-wired	4.3
Ir and Ru-coated Ti plate (Dimensionally Stable Anode-DSA)	$CuIn_xGa_{1-x}Se_2$ (CIGS)/perovskite solar cell ($CH_3NH_3PbBr_3$)-(photocathode)	6.2
Pt (Cathode)	Mo: $BiVO_4/Fe(Ni)OOH$ /perovskite solar cell ($CH_3NH_3PbBr_3$)-(photoanode)	6.2
Wired Pt (Cathode)	CdS/TiO_2 /perovskite solar cell ($Cs_{0.05}(MA_{0.17}FA_{0.83})_{0.95}Pb(I_{0.83}Br_{0.17})_3$)-(photoanode)	10

2.2.4. Materials

Usually, the **ideal photoanode material** must satisfy several criteria to carry out the water photoelectrolysis:

- 1- To display a strong (visible) light absorption with a band gap varying between 1.8 and 2.4 eV.
- 2- To display great chemical inertness both in the darkness and under illumination.
- 3- Band edge energy position that supports the water redox potentials.
- 4- To effectively separate/transport the charge carriers (to keep the rate of water splitting faster).
- 5- Low resistance at the semiconductor-liquid interface.
- 6- Low cost and abundance.

There are many materials that are good candidates for photocathode and photoanode application in PEC systems. We have only explained in detail some of the most commonly used materials such as TiO_2 and $BiVO_4$.

Other candidate materials for the cathodes include:

Cu_2O , CuO , NiO , $CuFeO_2$, $LaFeO_3$, $CaFe_2O_4$, Chalcogenides, $CuInS_2$, $CuGaS_2$, III – V Semiconductors (GaP , InP , $Silicon$)

And candidate materials for the photoanode include:

TiO_2 , ZnO , WO_3 , $\alpha - Fe_2O_3$, $BiVO_4$, $CuWO_4$, $TaON$, Ta_3N_5 , ZnS

Titanium dioxide

TiO_2 seems to be the best contender for water splitting due to its:

- High bandgap edges
- Great optical stability
- Non toxicity
- Great chemical inertness
- Photostability
- Cost efficiency

Recent investigations and advancements:

Until now, sensitization of TiO_2 electrode surface with a smaller band-gap semiconductor/dyes, nonmetal, and metal nanoparticles doping has been mostly employed to improve the PEC performance of TiO_2 materials. [12]

Although, in most of these doping strategies, since there is no significant band gap change, no considerable improvement in PEC performances has been reported. [12]

Mao et al. advanced black-colored hydrogenated TiO_2 nanocrystals, relating to a **band gap energy of 1.0 eV rather than the 3.2 eV** usually observed for pure TiO_2 , favoring a much superior PEC efficiency.

Surface plasmon resonance (SPR) has been used in PEC water electrolysis process with extended light absorption in the whole UV-visible region of the solar spectrum. [12]

Significant research works have been undertaken on Ag doping on TiO_2 electrode; the Ag nanoparticles act as an electron sink in the role of Ag SPR effect for the photoinduced electron-hole pairs and thus results in improved PEC performance [12]

Moreover, the PEC results demonstrated that the maximal photocurrent density of Ag/meso- TiO_2 nanospheres photoanodes reaches 1.0 mA/cm² (for [AgNO₃] = 1 mM) which is nearly a two-fold enhancement over that of meso- TiO_2 photoanodes. [12]

Under illumination condition, the enhanced photocurrent at lower potential shows that the incorporation of Ag particles reduced the recombination of electron/hole pairs. [12]

Recently, Choi et al. developed a heterojunction CdTe/ TiO_2 photoelectrodes, enhancement in PEC performance credited to the optimization of Fermi level, band positions, and the conductivity of CdTe layer. [12]

Bismuth vanadate

Another good material is $BiVO_4$ (bismuth vanadate) a mixed-metal oxide. Metal oxides are generally very stable in aqueous solutions and cheap, but their photochemical activity is usually limited by poor charge carrier separation [13].

- N-type semiconductor with bandgap size of 2.4-2.5 eV
- Engrosses full visible light region of solar spectrum
- Nontoxicity
- Relatively cheap

- A solar-to-hydrogen efficiency of 4.9%, which is the highest efficiency yet reported for a stand-alone water-splitting device based on a metal oxide photoanode. 4 mA cm⁻² photocurrent. [13]
- STH Efficiency of 8.1% via double junctioned GaAs/InGaAsP PV device [12].
- Tandem configuration with a single perovskite solar cell resulted in unaided water splitting with a STH efficiency of 6.2% [12].
- Low transportation characteristics.
- Investigations are ongoing on the amount of this material existing in the crust of earth.

Recent investigations and advancements:

The functional properties of BiVO₄ photoanodes have been advanced by heterostructuring strategies with Fe₂O₃.

The problem of transportation can be solved by introducing a gradient dopant concentration in the metal oxide film, thereby creating a distributed $n^+ - n$ homojunction and carrier-separation efficiencies of up to 80% are achievable. By combining this state-of-the-art photoanode with an earth-abundant cobalt phosphate water-oxidation catalyst and a double- or single-junction amorphous Si solar cell in a tandem configuration, stable short circuit water-splitting photocurrents of 4 and 3 mA.cm⁻², respectively, are achieved under 1 sun illumination. The 4 mA.cm⁻² photocurrent corresponds to a solar-to-hydrogen efficiency of 4.9%, which is the highest efficiency yet reported for a stand-alone water-splitting device based on a metal oxide photoanode. [14]

2.2.5. Opportunities and Future Directions

Trying to improve the design of water splitting systems some adjustments could be of interest for a research topic. Firstly, the design should be improved to achieve maximum light exposure. There are many tools, such as light collectors and mirrors that are used for this purpose. But the more complex the system the higher the CAPEX (capital expenditure) and OPEX (operation and maintenance expenditure) of the system will be.

Band edge positions are also of importance. In p/n tandem designs under optimized light exposure we need to conduct more researches in band edge matching to allow the system to function without a need for external bias. In systems coupling PV panels with PEC, we have more options and material availability since the PV panels have no direct contact with the water redox.

Bubble evolution is an issue that affects device performance. It could be addressed in future researches since its easily modeled using numerical coding.

The temperature of the system can have significant effect on its performance. Thermal aspects of water splitting devices, the spectra absorbed and transmitted, the thermal conductivity of the materials and etc. could be of research interest.

The transport of charge carriers in the materials are also of high research importance in affecting the current, and therefore the power output of the system. Materials with low carrier transport rate will also have a lot of recombination loss. For narrow bandgap photo electrodes doping will help with the transport issue. We can also dope the wide bandgap material to help them absorb more light.

Carrier recombination drastically affects the efficiency of the system. Proper surface treatments can help reducing recombination losses in watersplitting systems. Nanostructured systems can decrease

the charge transfer length and therefore reduce recombination. They can also increase the surface contact area to improve the STH.

Since the devices are commonly illuminated through the aqueous electrolyte, sunlight absorption in water has a critical impact on solar fuel generation by direct photoelectrolysis. [15]

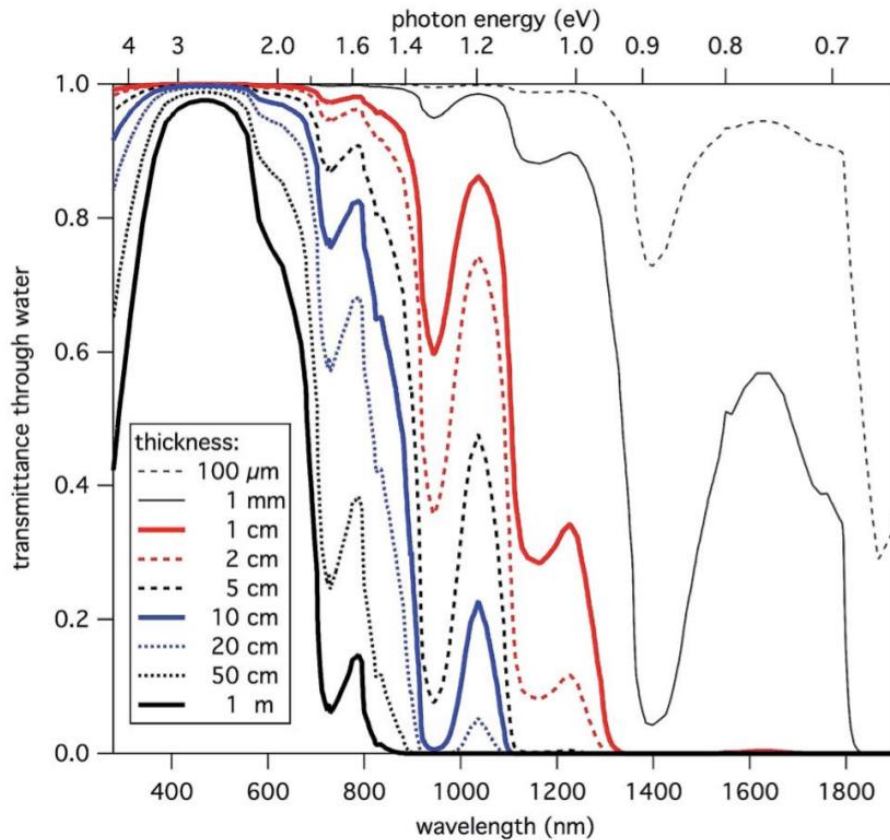


Figure 14 - Optical transmission through water for various thicknesses.

Non-optical aspects of the system are also important such as improving the membrane to avoid gas leakage. Improving the system against H₂ and O₂ mixture is an important safety concern to avoid exothermal reactions. Studying the difference between vertical and horizontal systems could be of interest, for example vertical systems have an easier architecture to allow gas extraction compared to horizontal ones.

3. Technoeconomical review of watersplitting technologies

According to a technoeconomic review on PEC and PV-E systems [15] it was observed that the current price of hydrogen production using SMR (1,39 \$/kg) is currently lower than the US average electricity price. This paper claims that a CO₂ cost of 800\$ per ton is necessary for PEC hydrogen to reach price

parity with hydrogen derived from SMR. According to the IEA report on Hydrogen in 2019 [2], it has been claimed that a carbon tax price of 100\$/ton is enough to reach parity between SMR and electrolysis in most part of the world [15]. See Figure 8.

Also the author suggests that achieving solar-to-hydrogen system efficiencies of greater than 20% within current embodiments of solar H₂ generators, is not sufficient to achieve hydrogen production costs competitive with fossil-fuel derived hydrogen [15].

Comparing PV-E with PEC, this study shows a comparable price while another paper by Jong suggests that it is considered unlikely for a PEC system to beat a PV-E system in cost versus performance in the medium till long-term. [17]

This study analyses 4 kinds of different systems:

- I. PEC without solar concentration
- II. PEC with 10x solar concentration
- III. PV-E disconnected form grid
- IV. PV-E connected to grid

The key active components of PEC-based systems are currently the subject of intense research and development. Many potential configurations exist, including non-concentrating and concentrating planar semiconductor designs. Accordingly, the costs of PEC systems are less well understood as compared to PV-E systems, because no commercial PEC systems have been constructed and operated to date.

For the two latter systems (3 and 4), grid electrolysis with proton-exchange membrane electrolyzers and PV-E designs using discrete photovoltaic modules and electrolyser units were analyzed.

In each case, a basecase system that used established designs and materials was compared to prospective systems that might be envisioned and developed in the future with the goal of achieving substantially lower overall system costs.

The results were as follows.

3.1. PV-E Without grid supplementation:

Given the base-case capital and operating expenses, and the technical parameter assumptions, the LCH (levelized cost of hydrogen) and total capital expense values for the base-case PV-E system were found to be \$12.1 /kg and \$371 per meter squared (Figure 15 and Figure 16) [15].

This analysis thus indicates that improving the plant efficiency has the largest impact on the LCH.

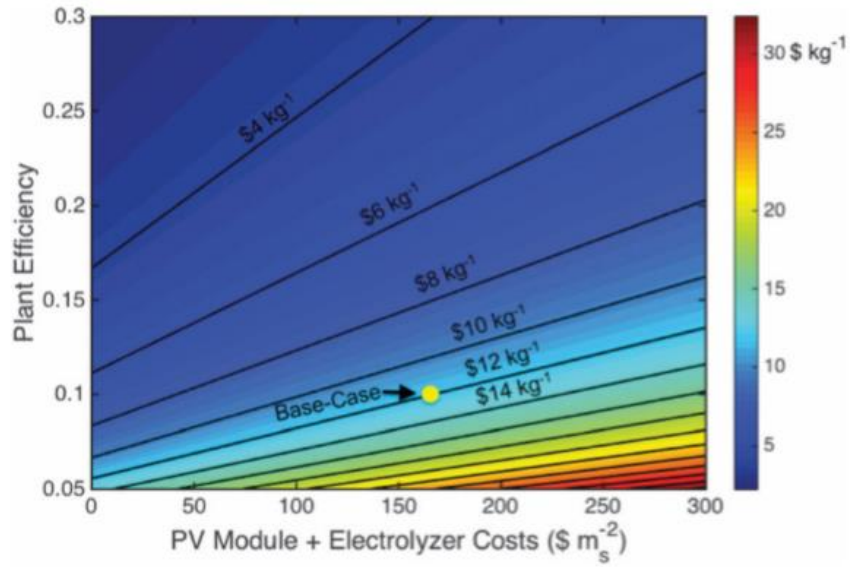


Figure 15 - PV-E costs vs plant efficiency [15]

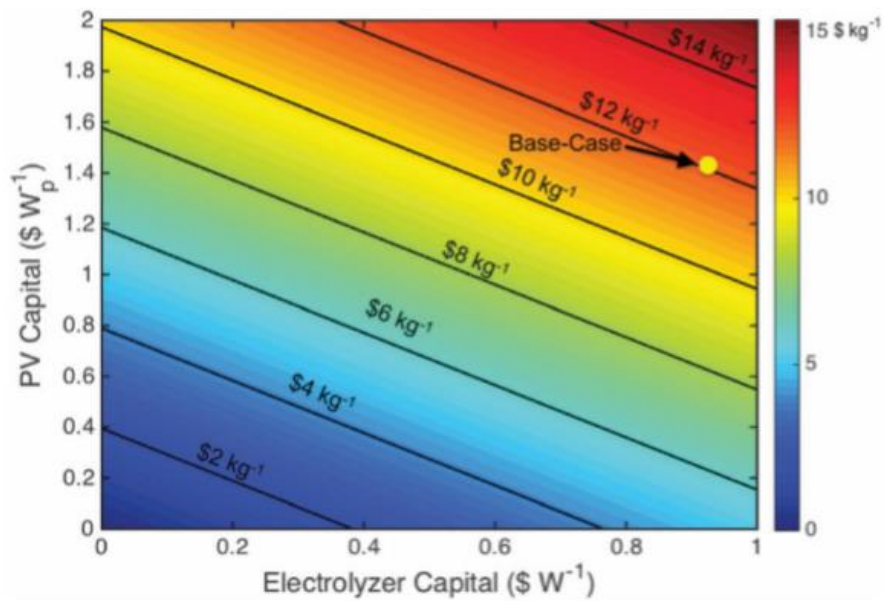


Figure 16 - PV capital vs electrolyser capital [15]

3.2. Grid Supplemented PV-E:

The LCH and total capital expense values for the GSPV-E system are \$6.1 /kg and \$441 per meter squared respectively [15].

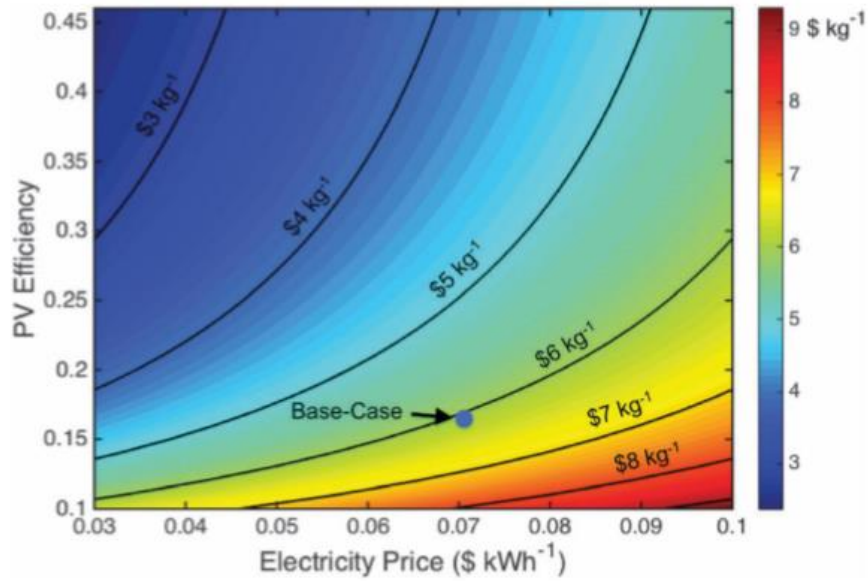


Figure 17 - GSPV-E electricity price vs PV efficiency [15]

This analysis suggests that at high photovoltaic efficiencies, higher than 25%, the electricity price has the largest impact on the LCH (Figure 17) [15].

3.3. Grid Electrolysis:

A base-case LCH and capital cost for grid electrolysis of \$5.5/ kg and \$48.6 \$ per meter squared respectively is estimated [15].

3.4. PEC Unconcentrated:

Base-case LCH and capital cost values are \$11.4/kg and \$293 per meter squared, respectively, which are lower than the LCH for the comparable base-case PV-E systems [15].

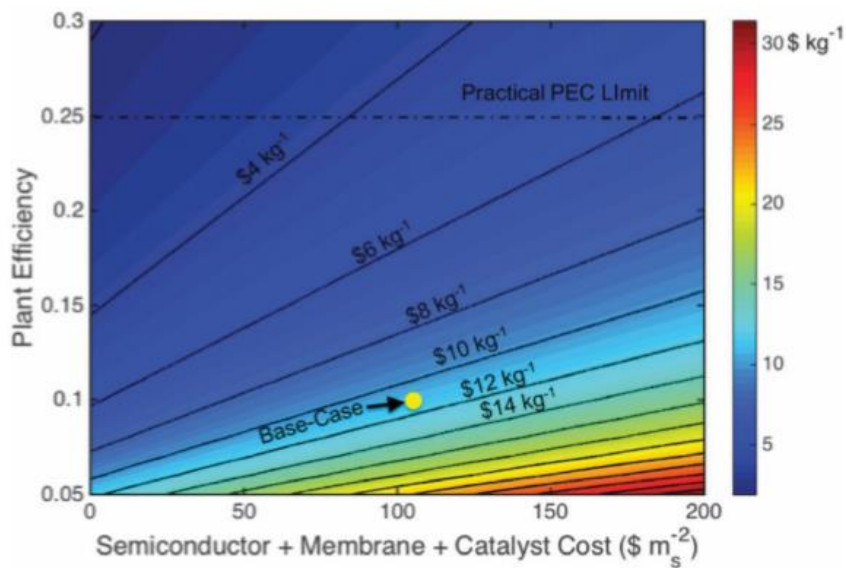


Figure 18 - Unconcentrated PEC, plant efficiency vs cost [15]

3.5. PEC Concentrated:

Base-case LCH and capital cost values were \$9.2 /kg and \$428 per meter squared respectively and are also lower than the LCH of the base-case PV-E system. The PV-E system must exhibit an efficiency of higher than 16% or must have a decrease in capital expense to 251 \$ per meter squared to overcome this difference and reach cost parity with the base-case concentrated PEC.

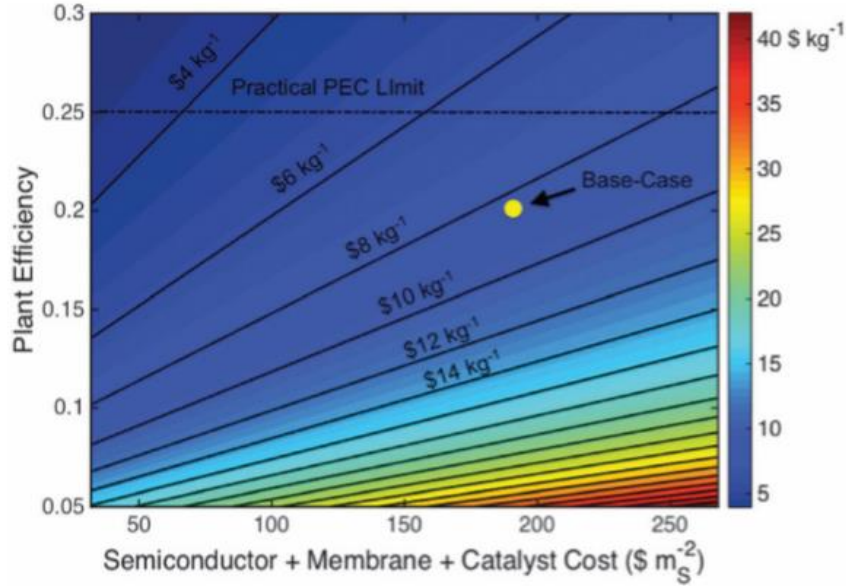


Figure 19 - Concentrated pec cost vs efficiency [15]

Here we can summaries the whole technoeconomical study into a few key bullet points:

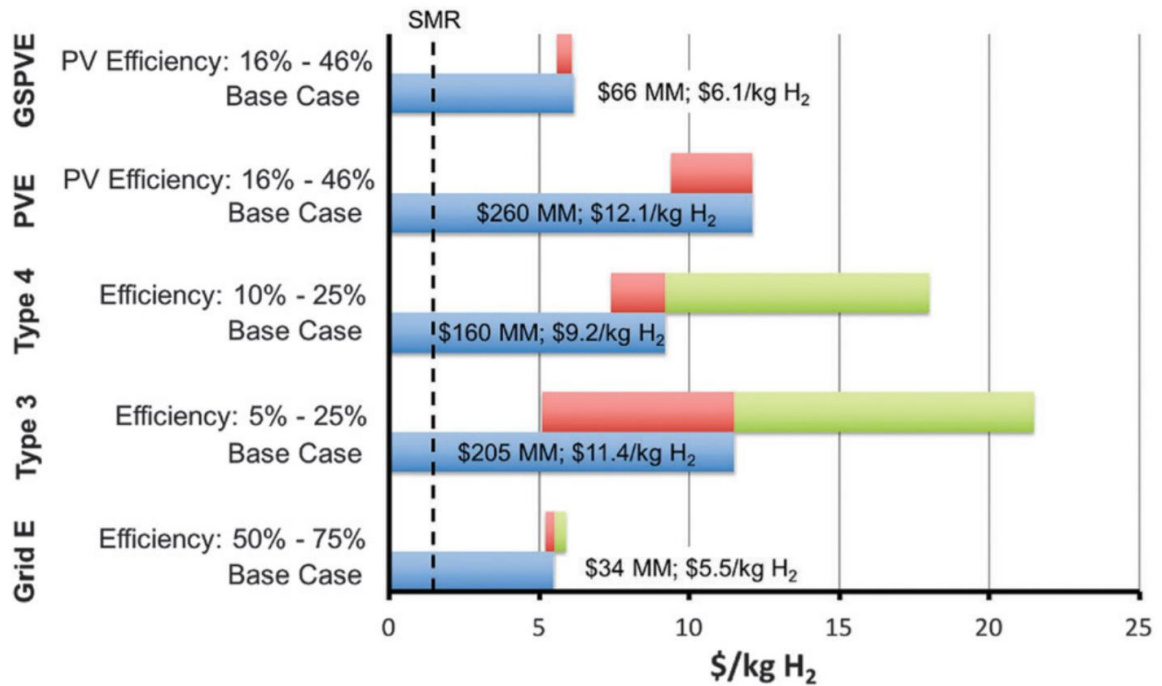


Figure 20 - A summary of the base-case scenario results with the current and future predicted market hydrogen value without a CO2 tax. (Dashed line is current SMR price). (Type 3 is unconcentrated PEC and type 4 is 10x light concentrated PEC) [15]

- Efficiency has the greatest impact on LCH, by virtue of the areal dependencies of most of the component costs.
- No single or combination of technical advancements based on currently demonstrated technology can provide sufficient cost reductions to allow solar hydrogen to directly compete on a levelized cost basis with hydrogen produced from fossil energy. A CO₂ tax of \$1000 (per ton CO₂), \$800 (per ton CO₂), \$1200 (per ton CO₂) and \$450 (per ton CO₂) would be required to increase the price of SMR to parity with the base-case unconcentrated PEC, concentrated PEC, PV-E and GSPV-E (assuming CO₂-free electricity) technologies, respectively [15].
- The results indicate an estimated levelized cost of hydrogen (LCH) for base-case unconcentrated PEC and concentrated PEC systems of \$11.4/kg and \$9.2/kg, respectively. For comparison, the estimated LCH for base-case PV-E and GSPV-E systems were \$12.1 /kg and \$6.1/kg, respectively.
- The results indicate that aggressive performance improvements and capital cost reductions are required simultaneously for solar hydrogen to achieve parity with fossil-fuel-derived hydrogen costs. Specifically, achieving a maximum practical plant efficiency of 25% at the base-case PEC costs is not sufficient to attain this goal
- The base-case PEC systems are advantaged over the base-case PV-E systems because hydrogen transport from the panels to compression units is less expensive than electricity transport and conditioning from the PV panels to the electrolyzers.
- The capacity factor of presently known solar-based energy systems is their fundamental limitation; any capital item used only 20% or less of the day will be at a disadvantage to capital used more effectively.

4. Conclusion

Here are some conclusions that recaps the findings of this internship and hopefully will help IPVF to define a proper project on solar to hydrogen:

- Solar driven hydrogen production is an ideal pathway to produce green energy but it faces many challenges to achieve this goal. Significantly, several factors such as stability, electronic properties, structure, surface states, cost, and toxicity need to be carefully considered to drastically improve the hydrogen production efficiency through solar water splitting in practical applications.
- The development of solar water splitting devices can be promised through various aspects. These developments aim to overcome the design challenges, scaling up the system, operation stability and affect the performance of these systems. Research could be conducted in improving the energy band gap, carrier recombination, stability and photocorrosion and photocurrent density.
- The solar to hydrogen efficiency of different approaches has been improved to more than 12.3% and 22.4% for PEC Tandem and PV-PEC water splitting systems, respectively [8]. The maximum theoretical STH efficiency is about 29.7%. Finding more adaptable material with better photon absorption and band edge positions will get us closer to this limit
- ALD (Atomic Layer Deposition) of materials such as TiO₂ can help protect the electrodes against corrosion and augment the lifetime of the system [11]
- A challenge is to find electrode material with low enough bandgap and appropriate band edge positions that is durable in aqueous environment. See Figure 21.

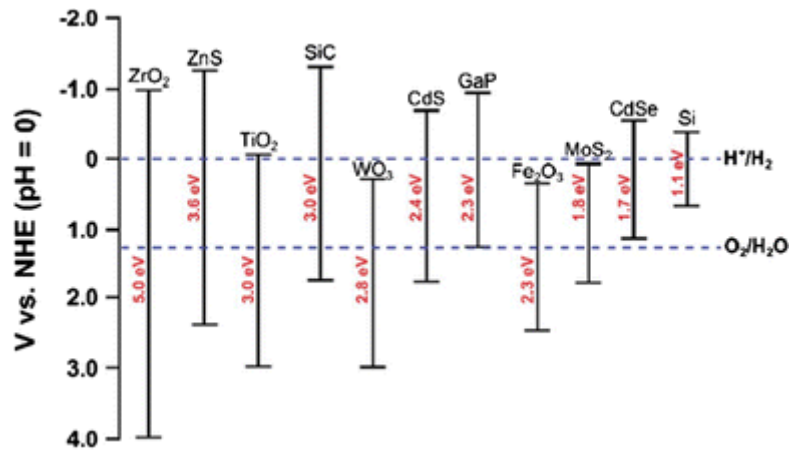


Figure 21- Different bandgaps and band edge positions of candidate materials for PEC applications. <https://rd.springer.com/article/10.1007/s40243-017-0088-2>

- Due to the difficulties in designing PEC tandem cell with sufficient bandgap energies and band edge positions of photocathodes and photoanodes; photovoltaic-integrated photoelectrochemical cells are an attractive approach for mitigating this aspect.
- Electron-hole recombination is the most important loss mechanism in water splitting reactors. Nanostructuring can enhance light harvesting, charge transport and kinetics while it has a significant disadvantage of reducing power conversion efficiency and the durability of the device [6].
- A comparison with low CO₂ and CO₂-neutral energy sources indicated that base-case PEC hydrogen is not currently cost-competitive with electrolysis using electricity supplied by nuclear power or from fossil-fuels in conjunction with carbon capture and storage [15], but according to [9] in the long term it is believed that PEC as a more direct solution to hydrogen production, will replace coupled PV-E systems.
- For PEC systems, both the efficiency and the cost of the system must improve in order for it to reach cost parity with fossil fuel hydrogen [15].
- The current TRL levels of the solar to hydrogen systems can be seen in Figure 22.

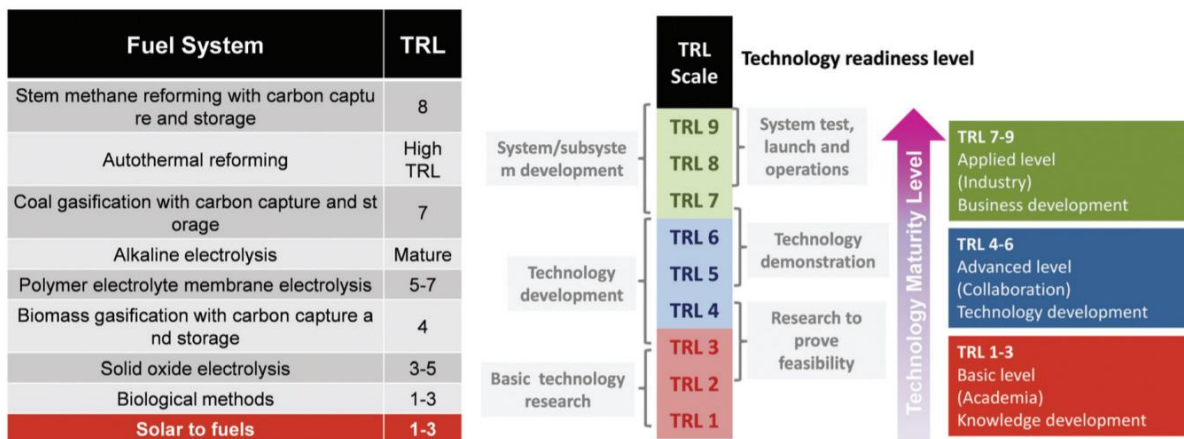


Figure 22 - Technical readiness level (TRL) of solar hydrogen production technology [17]

- The current state of the art efficiency levels of the solar to hydrogen systems compared to their complexity can be seen in Figure 22. It is seen that the high efficiency systems have a very complex architecture and therefore high prices. [17]

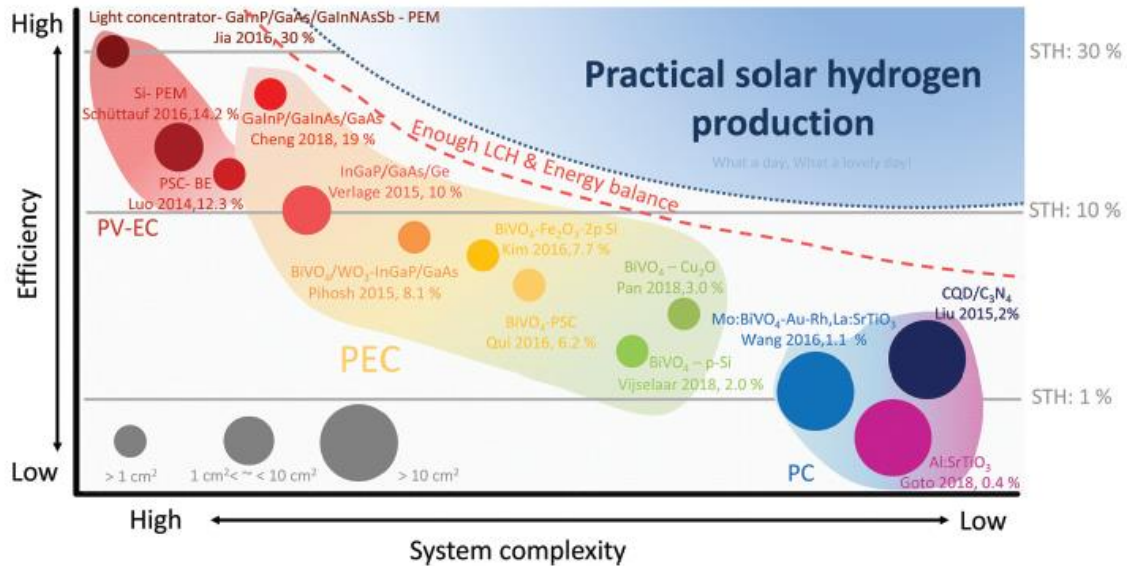


Figure 23 - Technological map showing various photon-driven water splitting approaches for solar energy conversion and specific experimental [17]

From my point of view there are many fields that IPVF could be involved in. IPVF has a very wide platform for PEC characterization (other than efficiency) such as lifetime, losses and etc. Also it has a very strong background in ALD (Atomic Layer Deposition) that can be used to protect thin layers from corrosion. Also IPVF has many funding opportunities from the European Commission and other enterprises. Some of these are as follows:

- ARENA awards \$22.1 million to 16 renewable hydrogen export research projects – Sept 2018
- European Commission H2020 : Converting Sunlight to storable chemical energy ID: LC-SC3-RES-29-2019 TRL 4-5
- Sunrise initiative –TRL 7-9 by 2030
 - o PEC : find better light absorbers and catalysts e.g. by high-performance computing
 - o Renewables + E : replace rare elements in catalysts

The U.S. Department of Energy announced up to \$51.5 million for new and innovative research of technologies for trucks, off-road vehicles, and the fuels that power them in march 2019. Innovative Concepts for Hydrogen Production and Utilization (up to \$12 million) including advanced water splitting materials, affordable domestic hydrogen production technologies, co-production of hydrogen for additional sources of revenue, and reversible fuel cell technologies.

It is expected that solar hydrogen has a great potential for IPVF to work on.

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