

Sustainability and Renewable Energy Challenge
Techno-Economic Assessment of Green Hydrogen Production
Project Number (236)



Team members

Mohamed Khaled Khalaf

Karim Mohamed Mohamed

Aya Hesham Mostafa

Salma Abdelbaset Ali

Mayar Sayed Mohamed

Nourhan Nasser Ahmed

Hazzem Hossam Ibrahim

Supervised by:

Dr. Hany Elsayed – Associate professor at Mechanical power engineering Department, Faculty of Engineering – Ain Shams university, 2019.

Dr. Hamada Galal – Lecturer in Math and physics Engineering Department, Faculty of Engineering, Ain Shams university, Cairo, Egypt, 2019.

Dr. Ashraf Mostafa - Associate Professor at Mechanical Power Engineering Department, Faculty of Engineering – Ain Shams university.

Table of Contents

i.	Abstract	5
ii.	Introduction	5
iii.	Objectives	6
	Integrate Solar Energy:	6
	Incorporate Battery Storage:	6
	MATLAB Modeling:	6
	Cost Analysis:	6
	Optimization Strategies:	6
iv.	Model Overview	6
	Working principles of the model	7
	Solar array	7
	Storage system	8
	Grid	8
	Electrolyzer	9
	Run Explanasion	9
v.	Model challenges and modifications	10
	Challenges	10
	Modifications	10
vi.	Case study: (1 l/min) hydrogen production:	11
	Objective:	11
	Irradiance data:	12
	Detailed explanation of the process flow or system design:	12
	i. Electrolyzer:	12
	ii. Solar power planet:	17
	iii. Batteries:	19
vii.	Market Analysis:	21
	Market Segmentation	22
	i. Applications	22
	ii. Technology:	22
	iii. Region:	22

Market Opportunities	23
Increasing renewable energy expansion:	23
The rising government support and policy incentives:	23
Growing demand in end-use sectors:	23
Countries Covered	23
Selection of Locations.....	24
viii. Techno-economic analysis.....	24
ix. Data Acquisition for the selected location	26
x. Calculations for (150 KW model).....	27
Capital Cost.....	28
Operating Cost (for one year)	28
Integration with the model to analyze the Data.	29
xi. Final version of the model	30
xii. Environmental Impact.....	32
- Reduction in greenhouse gases	32
- Utilization of Renewable Energy Sources	32
- Solar Panel Manufacturing	32
- Electrolysis Disposal.....	32
The risks.....	32
i. ESPS 3: Resource Efficiency and Pollution Prevention	32
xiii. Social and community impact.....	33
Health and Well-being as in.....	33
Job Creation and Economic Opportunities	33
The risks.....	33
i. ESPS 2: Labor and Working Conditions	33
ii. ESPS 4: Community Health and Safety	34
xiv. Innovation and outlook for the future of green hydrogen production:	34
Technologies development:	34
xv. Conclusion	35
xvi. Recommendations.....	35
xvii. Appendices:.....	36
xviii. References	37

Table of Figures

Figure 1: Renewable Energy Resource	5
Figure 2: The MATLAB model	7
Figure 3: Solar array Subsystem	7
Figure 4: Storage (batteries) Subsystem	8
Figure 5: Grid Subsystem	8
Figure 6: Electrolyzer Subsystem	9
Figure 7: Data Inspector analysis	9
Figure 8: Hydrogen Production Plant	11
Figure 9: ASWAN location data	11
Figure 10: Irradianc Data	12
Figure 11: Electrolyzer Control Volume	12
Figure 12: Electrolyzer schematic	13
Figure 13: AWE Schematic	13
Figure 14: Comparison between NaOH & KOH	14
Figure 15: Membrane Sample (Nafion)	14
Figure 16: Solar System Schematic	17
Figure 17: PV module types	17
Figure 18: Data Sheet of the module	18
Figure 19: IV characteristics of the solar system	20
Figure 20: Green Hydrogen applications	21
Figure 21: Comparison between PEM & AWE	22
Figure 22: Selected Locations	24
Figure 23: Relation between electrolyzer capacity and cost of producion of hydrogen	24
Figure 24: Analysis of the highest and lowest cost locations of hydrogen production	25
Figure 25: location of putre	26
Figure 26: Irradiance distribution	26
Figure 27: Irradiance disruption in the year	27
Figure 28: Data Inspection for one day	29
Figure 29: Hydrogen Production in one year	29
Figure 30: Total cost subsystem	30
Figure 31: Measurement subsystem after adding economic signals	30
Figure 32: Capital Cost Subsystem	31
Figure 33: Environmental Impact of hydrogen	32
Figure 34: Social Impact of Hydrogen	33

i. Abstract

This report explores a green hydrogen production system using solar energy and battery storage, modeled, and simulated in MATLAB. The integration aims to enhance efficiency and sustainability. Cost considerations, and operational expenses, are evaluated to assess economic feasibility. Optimization strategies are discussed to achieve an optimal balance between performance and affordability. Overall, the project advances sustainable energy solutions by combining green hydrogen production with renewable sources and efficient storage.

ii. Introduction

Decarbonizing the planet is one of the goals that countries around the world have set for 2050. To achieve this, cleaner alternatives are causing a transformative shift in the global landscape. In a time when addressing climate change and moving toward sustainable energy sources are more important, the creation of the green hydrogen Production Project from Renewable Sources is evidence of human creative ability and environmental consciousness. This innovative project unlocks the enormous potential of green hydrogen by utilizing renewable energy sources, marking a revolutionary step towards a cleaner and more sustainable energy



Figure 1: Renewable Energy Resource

future. Concerns over hydrogen's potential effects on the environment have historically been raised by the fact that it is produced using methods that are high in carbon. But by making renewable energy sources as the basis of its technique, the Green Hydrogen Production Project steers clear of these methods. By changing the approach of hydrogen generation through the creative use of solar, wind, and hydropower technologies, this initiative guarantees that the energy utilized in the process is not only inexhaustible but completely sustainable. This initiative's primary goal is to remove the carbon footprint connected to hydrogen generation, paving the way for a ground-breaking energy source.

Green hydrogen also has enormous potential to support the achievement of the SDGs. The most obvious contributions relate to SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth) and SDG 13 (climate action). In addition, there are direct and indirect contributions that contribute to almost all the SDGs, including SDG 6 (clean water and sanitation) SDG 9 (industry, innovation and infrastructure), SDG 12 (responsible consumption and production), SDG 14 (life below water) and SDG 15 (life on land) that should also be considered. The Standard requires that green hydrogen project operators assess the project's development impact and contribution towards achievement of the SDGs. This work should be undertaken at an early stage, with a view to increasing the development potential to support energy sector development, increase energy security and development opportunities.

iii. Objectives

The objective of this project is to design, analyze, and optimize a green hydrogen production system incorporating solar energy and battery storage. The primary focus is to develop an environmentally sustainable and economically viable solution for hydrogen generation. The project aims to:

Integrate Solar Energy:

Implement solar photovoltaic panels to harness renewable energy for powering an electrolyzer, facilitating the conversion of water into green hydrogen.

Incorporate Battery Storage:

Integrate a battery storage system to mitigate intermittent issues associated with solar power, ensuring a consistent and reliable energy supply for continuous hydrogen production.

MATLAB Modeling:

Utilize MATLAB for modeling and simulation to assess the dynamic behavior of the integrated system under various conditions, optimizing performance parameters such as electrolyzer efficiency and storage capacity.

Cost Analysis:

Conduct a comprehensive cost analysis, considering the initial setup, maintenance, and operational expenses associated with the entire system. Evaluate the economic feasibility and sustainability of the green hydrogen production project over its operational lifespan.

Optimization Strategies:

Identify and implement optimization strategies to enhance overall system efficiency and reduce costs. This involves tuning parameters, such as solar panel configuration and battery capacity, to achieve the optimal balance between performance and affordability.

By achieving these objectives, the project aims to contribute to the advancement of green hydrogen production, aligning with global efforts to transition towards sustainable and clean energy solutions.

iv. Model Overview

The model is a simple model for a hydrogen-producing unit that employs:

- Solar system
- Batteries (storage system)
- Grid
- Water electrolyzer

Working principles of the model

The process works simply by importing solar irradiance, which is used to power the electrolyzer, and charge the batteries, and if there is any excess energy, it is utilized to power the grid. The grid can be used if the power from the solar panels and batteries is insufficient to power the electrolyzer.

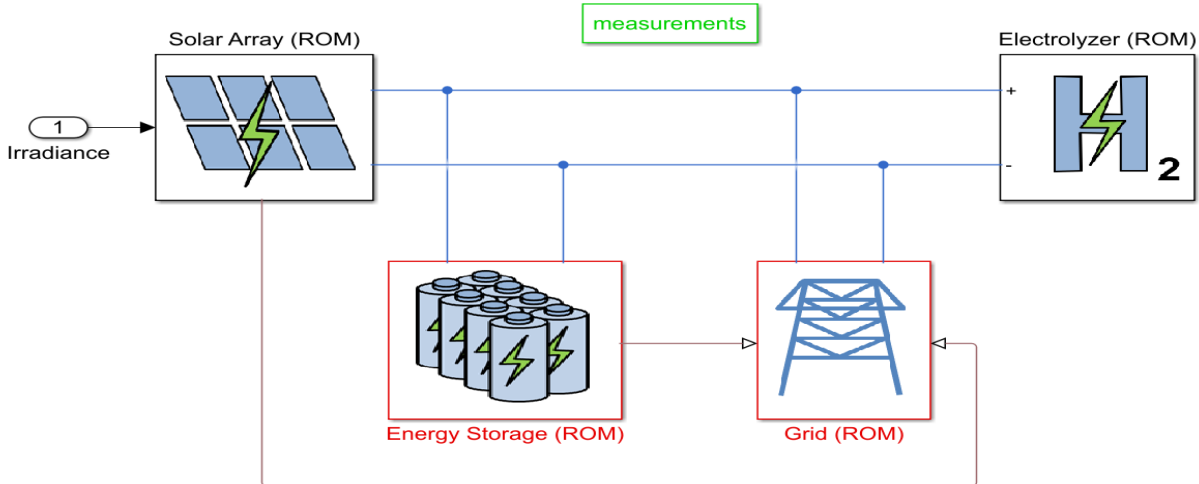


Figure 2: The MATLAB model

The figure shows the model's structure, and all values can be determined in the *measurement subsystem*.

So let`s talk about each subsystem of the model

Solar array

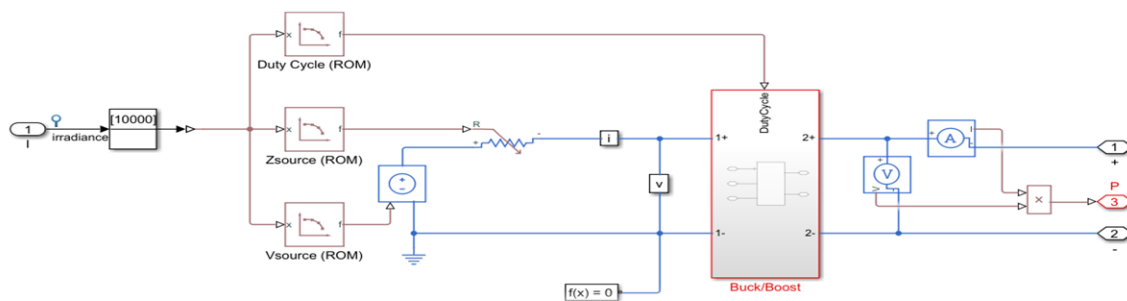


Figure 3: Solar array Subsystem

The solar array system has input that is the solar irradiance then it will be converted to current and voltage according to the electrolyzer voltage then there is a DC/DC converter which runs in buck/boost mode to rise or down the voltage from the solar system to meet the required from the electrolyzer.

- After that the current and voltage are multiplied to get the power of the solar system.
- This power is used to operate the electrolyzer and charge the batteries.

Storage system

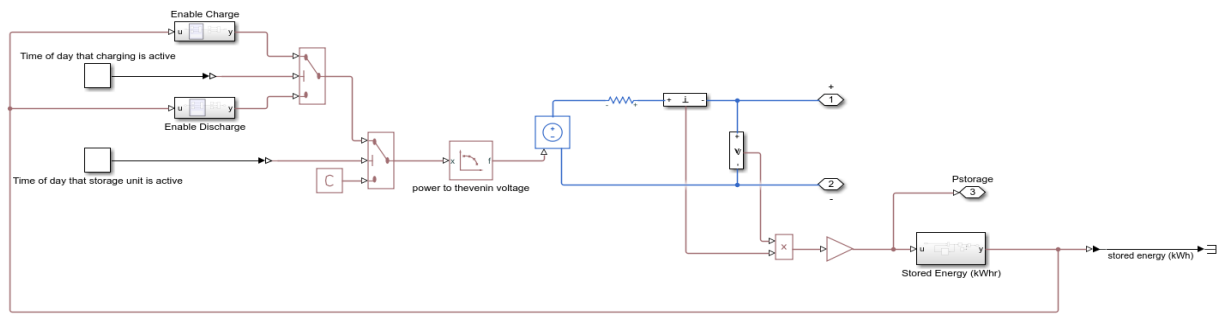


Figure 4: Storage (batteries) Subsystem

The storage system (batteries) is used to discharge the power to operate the electrolyzer and there are two methods to charge the batteries (From Solar or Grid).

How to control the batteries?

From the shown subsystem we can control:

- Time of charge and discharge of the batteries.
- Capacity of the batteries in charging and discharging.

This should be optimized according to the solar irradiance hours, and the electrolyzer working hours. After that the power of the batteries is used to operate the electrolyzer with the solar energy.

Grid

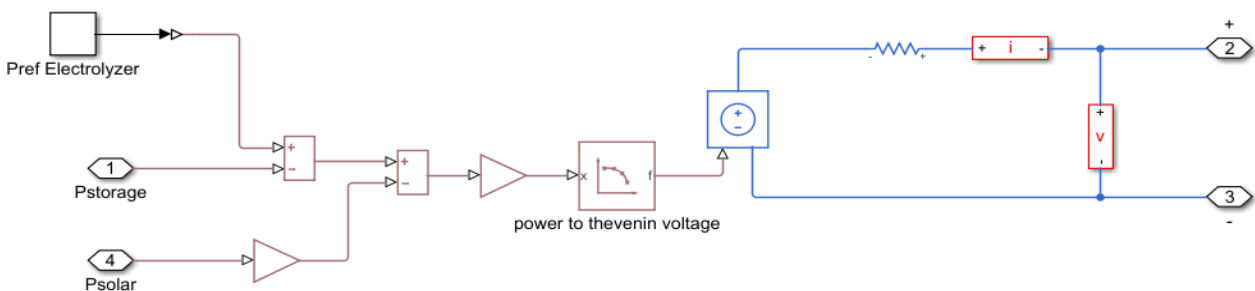


Figure 5: Grid Subsystem

The grid is used as a supplier when the power of the solar and the batteries isn't enough to operate the electrolyzer it can be used as a power source for the electrolyzer.

The curves show the power distribution to produce the hydrogen. The cycle starts by charging the batteries from the grid until the sun starts to rise and the irradiance will provide us solar power.

- For region (1)

The electrolyzer is off, and the batteries are charged from the grid, and there is no solar power generated.

- For region (2)

The electrolyzer is on, and it is run now by solar power and the grid power.

- For region (3)

For this region the electrolyzer is run by the solar, and batteries start to discharge to feed the electrolyzer, also the surplus power will go to the grid.

From this region, we get that the grid makes two tasks:

1st is to supply the electrolyzer in case of shortage of power.

2nd it will take surplus power in case of the electrolyzer is run and this power isn't needed.

- For region (4)

At this region, the solar power is zero and the batteries have discharged all of the capacity so the power of the electrolyzer is totally from the grid.

v. Model challenges and modifications

Challenges

For this model as mentioned before the model has 3 elements to run the electrolyzer (Solar, Batteries and grid). The challenge here is to:

- Minimize the grid supply for the electrolyzer to achieve the green hydrogen principle is to depend on renewable energy resource.
- Make the grid take the surplus power from the solar and batteries.
- Find a way to minimize the cost of the hydrogen by making modifications on the model.

Modifications

There are some modifications we aim to make to meet the challenges that are mentioned above.

The modifications:

- Changing the locations to be run in the model according to the irradiance as higher irradiance gives higher solar power.
- Add the Total cost for the model that includes:
(Capital cost, operating cost, cost of grid which depends on each location)
- Determine the highest and lowest cost when running the 242 locations to know which location is the best one.

- Make techno-economic analysis for the model by making case study for a small-scale model and analyze each component so you can know which element is the most important and what the effects of it on the rest elements are.

vi. Case study: (1 l/min) hydrogen production:

Process flow and design:

Objective:

Green hydrogen production with a rate of 1L/min using a suitable type of electrolyzer using a green source of power like solar energy.

Main points:

1. Choosing a suitable location for the planet.
2. Suitable selection of electrolyzer type.
3. Suitable sizing for the electrolyzer unit.
4. Selection and sizing for the solar energy planet.
5. Selection and sizing for the storage system (as no grid is used).

Location of the planet:

Case study location is chosen to be in one of the highest irradiances in our country “Aswan- Egypt” 22.855619°, 032.816574° Time zone: UTC+02, Africa/Cairo [EET].

Location data:

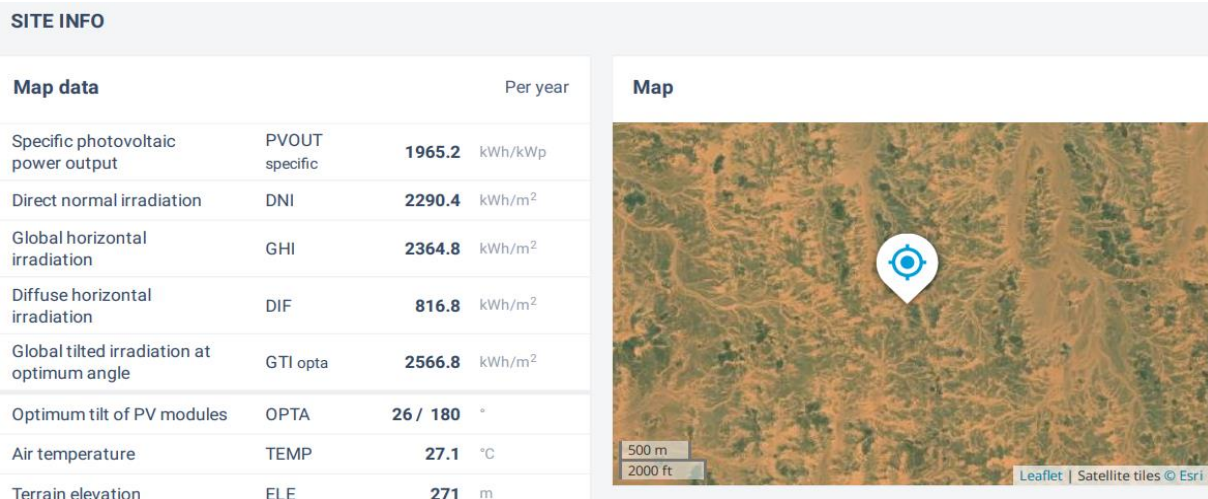


Figure 9: ASWAN location data



Figure 8: Hydrogen Production Plant

Irradiance data:



Figure 10: Irradiance Data

Detailed explanation of the process flow or system design:

i. Electrolyzer:

- Electrolyzer main working idea and structure:

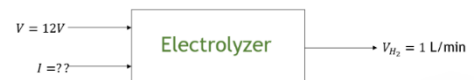


Figure 11: Electrolyzer Control Volume

An electrolyzer is an electrochemical device that conducts electrolytic reactions. An **electrolyte** acts as a medium between the **anode** and **cathode** in an electrolyzer. The concern with electrolyzers is that the process needs electrical energy to be completed. The electrical energy required for the electrolysis reaction should ideally originate from **renewable energy sources** like hydroelectric, solar, or wind energy (**solar** in our design). A few benefits of using electrolyzers are the assurance of the hydrogen's purity, the ability to create it right where it will be needed rather than having to first store it, and the fact that it is significantly less expensive than receiving gas in

high pressure cylinders. The slightly varying ways that various electrolyzers operate are mostly determined by the various types of electrolyte material employed.

- **Chemistry of water electrolysis:**

A basic water electrolysis unit consists of an **anode**, a **cathode**, **power supply**, and an **electrolyte**. A direct current (DC) is applied to maintain the electricity balance and electrons flow from the negative terminal of the DC source to the cathode at which the electrons are consumed by hydrogen ions (protons) to form hydrogen. In keeping the electrical charge (and valence) in balance, hydroxide ions (anions) transfer through the electrolyte solution to anode, at which the hydroxide ions give away electrons and these electrons return to the positive terminal of the DC source. To enhance the conductivity of the solution, electrolytes which generally consist of ions with high mobility are applied in the electrolyzer.

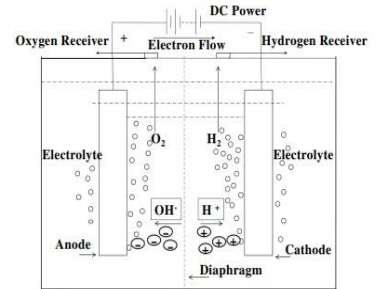
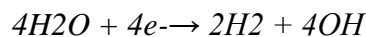
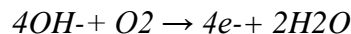


Figure 12: Electrolyzer schematic

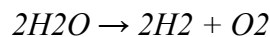
Anode reaction:



Cathode reaction:



Overall reaction:



- **Selection:**

Types of electrolyzers:

1. Alkaline electrolyzer (AEL)
2. Polymer electrolyte membrane electrolyzer (PEMEL)
3. Solid oxide electrolyzer cell (SOEC)
4. Anionic exchange membrane electrolyzer (AEMEL)

The selected electrolyzer type is **alkaline electrolyzer, why?**

They are known for their **efficiency** and **long-term stability**. They are typically **more cost-effective** compared to proton exchange membrane (PEM) electrolyzers. They can operate at a wide range of temperatures, making them versatile for various environments.

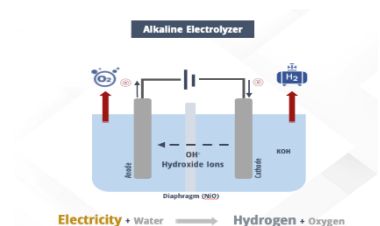


Figure 13: AWE Schematic

- **Selecting Electrolyte:**

Electrolyte types:

The selected electrolyte is with a **30 wt.%** aqueous solution of potassium hydroxide (**KOH**) which enhances the ionic conductivity of the electrolyte.

Why KOH?

Because KOH has higher conductivity than NaOH. The conductivity of KOH is around 40 to 50% higher than the conductivity of a NaOH solution at the optimal weight percentage (30 wt.%).

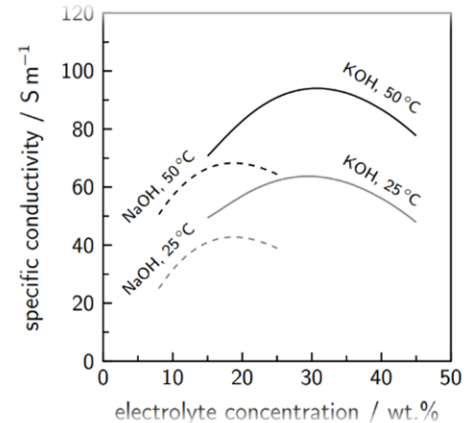


Figure 14: Comparison between NaOH & KOH

Electrodes materials:

The selected material for electrodes is **Stainless Steel 316** plates, with a **desired thickness of 0.8 mm**, why?

1. Stainless steel is a **lower-cost** material compared to Ni-based substrates.
2. The presence of **Cr** provides **corrosion resistance** due to the formation of a thin chromium oxide layer that passes the stainless-steel electrode during operation.
3. Stainless steel 316 contains approximately **11% nickel**, which **improves the electrolysis performance** compared to non-nickel-containing substrates.

- **Membrane materials:**

The selected material is **Nafion N115** and N117.

Nafion 115 shows 0.1 A/cm²

Nafion 115 Thickness 125 μm

Area specific resistance (ASR) 0.52 $\Omega \cdot \text{cm}^2$



Figure 15: Membrane Sample (Nafion)

Why?

1. High conductivity, reliability, and performance that current and future water electrolysis applications need.
2. Operate in higher temperature ranges and lower humidity. Hence, even in the most demanding operating conditions.

- **Design and calculations:**

Assumptions:

- **Bipolar** (series connection) Alkaline water electrolyzer
- H_2 gas flow rate $V(H_2) = 1$ Liter / min
- Electrolyzer pressure = 1 bar

- Electrolyzer temperature = 25°C = 298 K
- No. of electrolyzer cells = 5
- V supply=12 V, Current Density=0.2 Amp.cm⁻²
- Electrolyzer cell voltage = 2.4 V
- Theoretical cell voltage = 1.48 V

Calculations:

1. No of mole of Hydrogen (Ideal Gas Law)

The ideal gas law can be used to calculate the theoretical product gas flow rate V_{H_2} .

- R: the universal gas constant = R = 0.082 L. atm/ K. mol
- P: is operating pressure in atm = 1 atm
- T: is operating temperature in kelvin = 298 K

$$V_{H_2} = \frac{n * R * T}{P}$$

$$n_{H_2} = \frac{V_{H_2} * P}{R * T} = \frac{1 * 1}{0.082 * 298} = 0.0409 \text{ mole/min}$$

2. Current (Amp) (Faraday's Law of Electrolysis):

- I is the current passing through the electrolyser (amp)
- t is the time which the current take in the cell (second)
- no. of cells = 5
- F: faraday's constant = 96485 C/mol
- Z: the electrochemical equivalent, a proportionality constant (ECE)

The value of z is assumed to be 2 based on the electrochemical response of the alkaline electrolysis process.

$$n = \frac{\text{no. of cells} * I * t}{F * Z}$$

$$I = \frac{F * Z * n}{\text{no. of cells} * t} = \frac{96485 * 2 * 0.0409}{5 * 60} = 26.308 \text{ Amp}$$

3. Area of the electrode (Cm2):

$$\text{Area} = \frac{I \text{ (amp)}}{\text{Current density} \left(\frac{\text{amp}}{\text{cm}^2} \right)}$$

$$\text{Area} = \frac{26.3}{0.2} = 131.5 \text{ Cm2}$$

4. Total Power and Ohmic Power:

- V_{cell} : is voltage cell (Volt) = 2.4 V
- I: Electrolyzer input current (I) (Amp) = 26.3 A

$$P_{Total} = \text{no. of cells} * V_{cell} * I = 5 * 2.4 * 26.3 = 315.6 \text{ watt}$$

Parameters related to ohmic resistance of electrolyte

$$r_1 = 8.05 * 10^{-5} \Omega \text{m}^2 \quad r_2 = -2.5 * 10^{-7} \Omega \text{m}^2 \text{ } ^\circ\text{C}$$

$$V_{ohmic} = ((r_1 + r_2 * T)) / \text{Area} * I = ((8.05 * 10^{-5} - 2.5 * 10^{-7} * 25) / 0.01315) * 26.3 = 0.1485 \text{ volt}$$

5. The Electrolysis Power:

$$P_{ohmic} = I^2 * R_{ohmic} * \text{no. of cells} = I * V_{ohmic} * \text{no. of cells} = 20 \text{ watt}$$

$$P_{Electrolysis} = P_{total} - 1.5 * P_{ohmic} = 315.6 - 1.5 * 20 = 285.6 \text{ watt}$$

Note:

We took 1.5 as a safety factor for the ohmic power.

6. Electrolysis Efficiency & Energy Efficiency of the Cell:

$$\eta_{Electrolysis} = \frac{P_{Electrolysis}}{P_{total}} = \frac{P_{total} - P_{ohmic}}{P_{total}} = \frac{285.6}{315.6} = 90\%$$

To determine the electrolysis cell's energy efficiency, by assuming that the theoretical Electromotive Force (EMF) value is 1.48 V.

- Theoretical EMF = 1.48 V
- Cell voltage = 2.4 V

$$\text{Efficiency of the cell} = \frac{\text{Theoretical EMF}}{\text{Cell voltage}} = 61.67\%$$

Design Calculations Summary:

No. of hydrogen moles (mol)	Electrolyzer current (amp)	Plate Area (Cm ²)	Ohmic Voltage (volt)	Cell Voltage (volt)	Total Voltage (volt)	Total power (watt)
0.01092	26.3	131.5	0.1485	2.4	12	315.6
Ohmic Power (watt)	Electrolyzer Power (watt)	Electrolyzer efficiency	Cell energy efficiency	Electrolyzer pressure (bar)	Electrolyzer Temperature (Celsius)	No of cells
20	286.6	90%	61.67%	1	25	5

ii. Solar power planet:

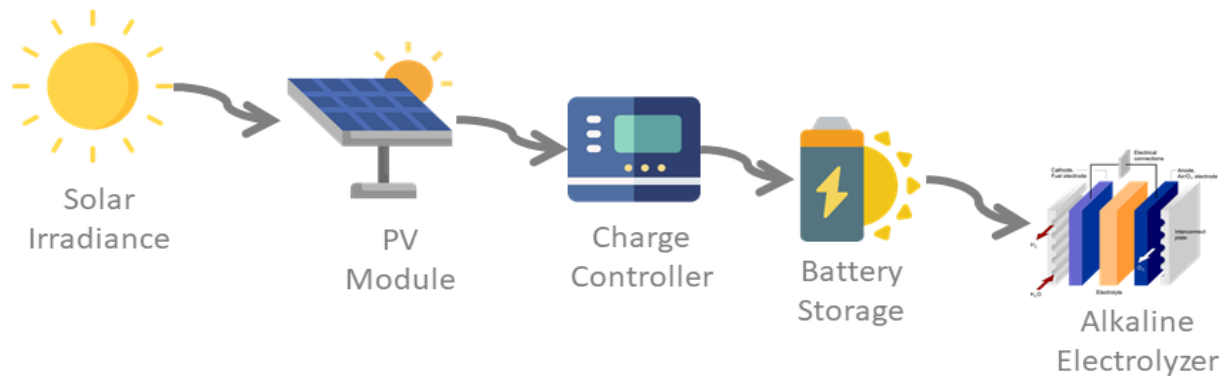


Figure 16: Solar System Schematic

• **Construction of PV system:**

1. PV modules
2. Charge controllers
3. Battery

• **PV modules:**

PV Types:

The three general types of photovoltaic cells made from silicon are:

1. Mono-crystalline Silicon – also known as single-crystal silicon.
2. Poly-crystalline Silicon – also known as multi-crystal silicon.
3. Thin Film Silicon.

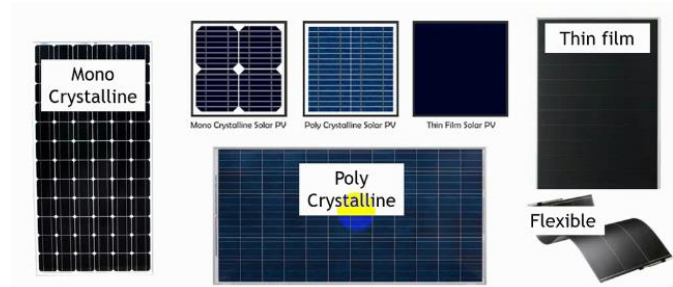


Figure 17: PV module types

PV type	Description (Color and texture)	Module efficiency	Surface area for 1kWp system (m ²)
Monocrystalline (m-Si)	Blue, grey, black, high light absorption	14-19%	7
Polycrystalline (p-Si)	Bright bluish speckled tone	12-15%	9
Thin film Amorphous silicon	Reddish-black, very flexible/durable	6-8%	17

- **Design and selection:**

Objective:

Design a PV system that supplies 335 w for electrolyzer power.

Selection of PV module:

The selected type is the monocrystalline type, why?

They are made from a single piece of silicon; it is easier for electricity to flow through. They have a pyramid cell pattern which offers a larger surface area to collect a greater amount of energy from the sun's rays.

The selected PV module specs:

P- Type mono-crystalline.

SPECIFICATIONS				
Module Type	JKM440M-60HL4		JKM445M-60HL4	
	JKM440M-60HL4-V		JKM445M-60HL4-V	
	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	440Wp	327Wp	445Wp	331Wp
Maximum Power Voltage (Vmp)	33.72V	31.39V	33.82V	31.56V
Maximum Power Current (Imp)	13.05A	10.43A	13.16A	10.49A
Open-circuit Voltage (Voc)	41.02V	38.72V	41.10V	38.79V
Short-circuit Current (Isc)	13.73A	11.09A	13.79A	11.14A
Module Efficiency STC (%)	20.39%		20.62%	

Figure 18: Data Sheet of the module

- **Calculations of PV system:**

Assumptions of calculations:

- Battery efficiency = 90%
- Charge controller efficiency= 100%
- Derating factor=25%

1. sizing of the PV array is to get the energy:

$$E_{Load} = E_{electrizer} * daily runtime = 335 * 20 = 6700Whr$$

2. calculate the total energy:

$$E_{In} = \frac{E_{Load}}{\eta_{battery} \eta_{charge controller}} = \frac{6700}{0.9} = 7444.44Whr$$

$$E_{pv} = \frac{E_{In}}{1 - derating factor} = \frac{7444.44}{1 - 0.25} = 9925.92 Whr$$

3. calculate the rated Power:

$$P_{max} = \frac{E_{pv}}{T_{psh}} = \frac{9925.92}{5} = 1985.184W$$

Where T_{min} is the minimum peak sun hours, it's assumed to be 5 in Egypt.

4. calculate the number of series and parallel modules:

For the total no of modules, from data sheet $P_{Module} = 440 \text{ W}$

$$N_{module} = \frac{P_{max}}{P_{Module}} = \frac{1985.184}{440} = 4.512 \approx 5 \text{ Modules}$$

5. For Series:

$$N_{pvs} = \frac{V_{Dc}}{V_{pv}} = \frac{12}{33} = 0.36364 \approx 1 \text{ Module in series}$$

6. For parallel:

$$N_{pvp} = 5 \text{ modules in paralles}$$

iii. Batteries:

- **Lead Acid Batteries**

Lead-acid batteries are **most common in PV systems**, as they are cheap, reliable and have relatively good energy storage density.

Sealed batteries are spill proof and do not require periodic maintenance. Also known as Valve regulated lead acid (**VRLA**) batteries these contain electrolyte, which is immobilized in some manner. Under excessive overcharge, the normally sealed vents open under gas pressure through a pressure regulating mechanism. Electrolyte cannot be replenished in these battery designs; therefore, they are intolerant of excessive overcharge. VRLA batteries are available in two different technologies: Absorbed Glass Mat (**AGM**) and Gelled Electrolyte. AGM lead acid batteries have become the industry standard, as they are **maintenance free** and particularly suited for **grid-tied systems** where batteries are typically kept at a full state of charge. Gel-cell batteries, designed for freeze-resistance, are generally a poor choice because any overcharging will permanently damage the battery.

The selected battery is (**UB-8D AGM - 250 AH, 12V-DC**).

- **Calculations of Batteries:**

- Total Average Energy Use = 6700 Wh.
- Days of autonomy or the no-sun days = 1 day.
- The amount of energy storage required is $E_{rough} = 6700 \times 1 = 6.7 \text{ kWh}$

For Energy safety:

$$E_{safe} = \frac{E_{rough}}{MDOD} = \frac{6.7}{0.8} = 8.375 \text{ KWh}$$

The capacity of the battery bank needed can be evaluated:

$$c = \frac{E_{safe}}{v_b} = \frac{8375}{12} = 697.917 \text{ Amp h}$$

The total number of batteries is obtained by:

$$N_{batteries} = \frac{c}{c_b} = \frac{697.917}{250} = 2.79 \approx 3 \text{ batteries}$$

The number of batteries in series equals to:

$$N_s = \frac{12}{12} = 1$$

Then number of parallel paths N_p is obtained by:

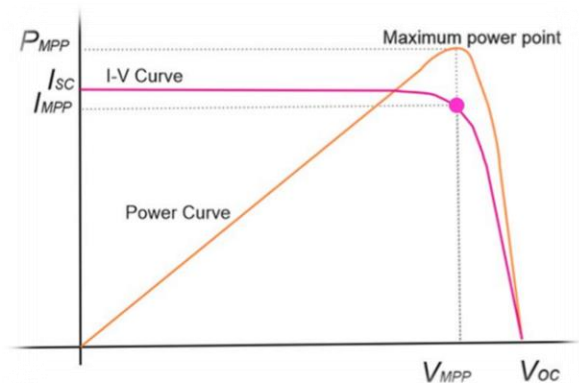
$$N_p = \frac{3}{1} = 3$$

The number of batteries needed is $N_{batteries} = 3$ batteries (3 parallel branches and 1 series battery).

- **Charge controller (MPPT):**

MPPT "maximum power point tracking"

Maximum power point tracking (MPPT) is an algorithm implemented in photovoltaic (PV) inverters to continuously adjust the impedance seen by the solar array to keep the PV system operating at, or close to, the peak power point of the PV panel under varying conditions, like changing solar irradiance, temperature, and load.



- **Function:**

Figure 19: IV characteristics of the solar system

MPPT solar regulators reduce losses because they always work at the most appropriate voltage and can extract the maximum power and obtain greater performance from photovoltaic modules.

- **The selected charge controller Smart Solar Charge Controllers MPPT 150/100.**

SmartSolar Charge Controller	150/45	150/60	150/70	150/85	150/100
Battery voltage	12 / 24 / 48V Auto Select (software tool needed to select 36V)				
Rated charge current	45A	60A	70A	85A	100A
Nominal PV power, 12V 1a,b)	650W	860W	1000W	1200W	1450W
Nominal PV power, 24V 1a,b)	1300W	1720W	2000W	2400W	2900W
Nominal PV power, 36V 1a,b)	1950W	2580W	3000W	3600W	4350W
Nominal PV power, 48V 1a,b)	2600W	3440W	4000W	4900W	5800W
Max. PV short circuit current 2)	50A (max 30A per MC4 conn.)			70A (max 30A per MC4 conn.)	
Maximum PV open circuit voltage	150V absolute maximum coldest conditions 145V start-up and operating maximum				
Maximum efficiency	98%				
Self-consumption	Less than 35mA @ 12V / 20mA @ 48V				
Charge voltage 'absorption'	Default setting: 14,4 / 28,8 / 43,2 / 57,6V (adjustable with: rotary switch, display, VE.Direct or Bluetooth)				
Charge voltage 'float'	Default setting: 13,8 / 27,6 / 41,4 / 55,2V (adjustable: rotary switch, display, VE.Direct or Bluetooth)				
Charge voltage 'equalization'	Default setting: 16,2V / 32,4V / 48,6V / 64,8V (adjustable)				
Charge algorithm	multi-stage adaptive (eight preprogrammed algorithms) or user defined algorithm				
Temperature compensation	-16 mV / -32 mV / -64 mV / °C				
Protection	Battery reverse polarity (fuse, not user accessible) PV reverse polarity / Output short circuit / Over temperature				
Operating temperature	-30 to +60°C (full rated output up to 40°C)				
Humidity	95%, non-condensing				
Maximum altitude	5000m (full rated output up to 2000m)				
Environmental condition	Indoor, unconditioned				
Pollution degree	PD3				
Data communication port	VE.Direct or Bluetooth				

- **Sizing of the Voltage Controller:**

The result gives the rated current of the voltage regulator I:

$$I_{rcc} = I_{sc}^M * N_{pm} * F_{safe} = 13.73 * 5 * 1.25 = 85.8125 \text{ amp}$$

Number of charger controllers:

$$N_{cc} = \frac{I_{rcc}}{I_{cc}} = \frac{85.8125}{100} = 0.858125 \cong 1 \text{ charger controller}$$

- **Design Calculations Summary:**

Energy of load (Whr)	Energy of PV Plant (Whr)	Power of PV plant (W)	Power of PV module (W)	Number of PV module	Number of Series PV module	Number of parallel PV module
6700	9925.92	1985.184	440	5	1	5
Energy of storge (Whr)	capacity of the battery bank (Ahr)	capacity of the battery (Ahr)	Number of batteries	Number of Series batteries	Number of Parallel batteries	Number of charger control
8375	697.917	250	3	1	3	1

vii. Market Analysis:

The global market for green hydrogen gas produced through electrolysis, a procedure that uses renewable energy sources such as solar or wind power, is referred to as the "green hydrogen market". Green Hydrogen Market Size was valued at USD 0.28 billion in 2021. The green hydrogen market industry is projected to grow from USD 0.44 billion in 2022 to USD 10.55 billion by 2030, exhibiting a compound annual growth rate (CAGR) of 55% during the forecast period (2022-2030). Growing demand for renewable energy resources and the need to reduce carbon emissions are the key Green Hydrogen Market drivers enhancing the market growth. According Custom Market Insights the chart describe the Green Hydrogen Market as shown in the fig.20

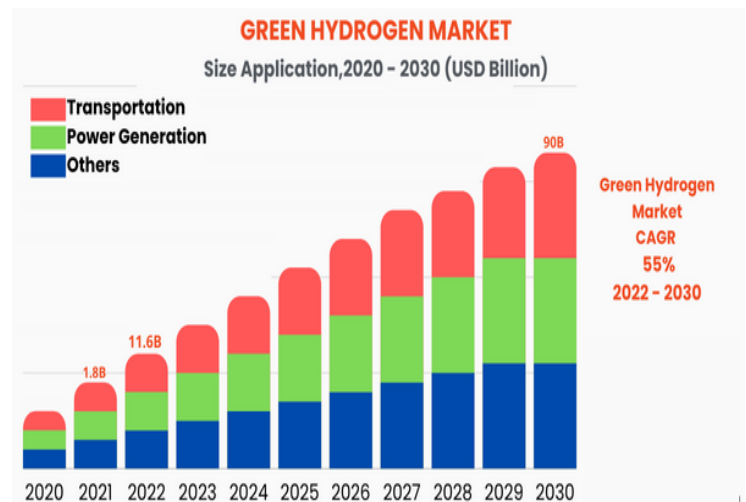


Figure 20: Green Hydrogen applications

Market Segmentation

i. Applications

By end-use industry, the global green hydrogen market is divided into food & beverages, medical, chemical, petrochemicals, glass, and others.

- In 2020, the petrochemicals segment dominated the market and was projected to remain the fastest-growing segment. It is estimated to reach a predicted value of USD 9925 million by 2030 at a CAGR of 55%. In the petrochemical industry, hydrogen is already being used and is expected to be used in the future. This is particularly real in areas where heavy oil reserves are abundant. Furthermore, CO₂ from these refineries and chemical plants could be combined with hydrogen to create a renewable synthetic fuel
- The food & beverages segment is predicted to expand at a moderate rate during the forecast period. It is estimated to reach a predicted value of USD 5115 million by 2030 at a CAGR of 55%. Fuel cells are used by several businesses in the U.S. food industry to provide electricity and, in some cases, heating and cooling manufacturing sites. These businesses are saving money on various levels, including pollution, energy costs, and water use. Using waste as a fuel source is expected to help save money, which in turn propels market growth
- The medical segment is the third-largest market. It is estimated to reach a predicted value of USD 2320 million by 2030 at a CAGR of 55%. Hydrogen (H₂) has been a preventative and therapeutic benefit in various organs, including the brain, heart, pancreas, lungs, and liver. Hence, the use of hydrogen in the medical sector propels the growth of the hydrogen market. Oil and gas is anticipated to be one of the prominent end-use markets for green hydrogen during the forecast period 2022-2030.

ii. Technology:

The alkaline electrolyzers segment dominates the global market and is projected to remain the fastest-growing segment. It is predicted to reach an expected value of USD 12495 million by 2030 at a CAGR of 55%, the electrolyte in an alkaline electrolyzer is a liquid alkaline solution of potassium hydroxide and has a longer operating time than PEM electrolyzers. Furthermore, alkaline electrolyzers are less expensive than PEM electrolyzers, which is expected to boost segment growth in the future. Based on technology, the green hydrogen market is estimated to be led by alkaline electrolyzer during the forecast period, 2022-2030.

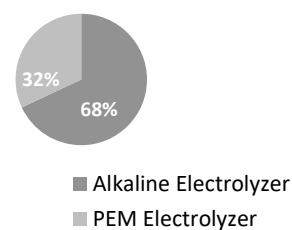


Figure 21: Comparison between PEM & AWE

iii. Region:

In the global green hydrogen market, Europe and North America are anticipated to gain traction in terms of green hydrogen production, owing to the continuous growth in the oil and gas industry and the presence of the world's largest manufacturers in those regions.

Market Opportunities

Increasing renewable energy expansion:

The rapid growth of renewable energy sources, such as wind and solar, provides a reliable and abundant supply of electricity required for green hydrogen production. As renewable energy capacity continues to expand, the availability and affordability of green hydrogen increase, driving market growth. The growing demand in end-use sectors

The rising government support and policy incentives:

Governments around the world are implementing supportive policies, regulations, and financial incentives to promote the development and adoption of green hydrogen. These measures include grants, tax incentives, subsidies, and renewable energy targets, which provide a favorable environment for the growth of the green hydrogen market.

Growing demand in end-use sectors:

The increasing demand for clean and sustainable energy solutions in sectors such as transportation, chemical production, and power generation is driving the demand for green hydrogen. Green hydrogen can be used as a feedstock, fuel, or energy carrier, offering versatile applications across various industries.

Countries Covered

Based on Global Green Hydrogen Market Industry Trends and Forecast to 2030.

North America	(U.S., Canada, and Mexico)
South America	(Brazil, Argentina, and Rest of South America),
Europe	(Germany, France, Italy, U.K., Belgium, Spain, Russia, Turkey, Netherlands, Switzerland, and the rest of Europe)
Asia-Pacific	(Japan, China, India, South Korea, Australia, Singapore, Malaysia, Thailand, Indonesia, Philippines and the rest of Asia-Pacific)
Middle East and Africa	(U.A.E, Saudi Arabia, Egypt, South Africa, Palestine and the rest of Middle East and Africa)

Selection of Locations

According to the market research, the selection of 242 Location was not based on one continent or country but on six continents (Asia, Africa, North America, South America, Antarctica, Europe, and Australia), countries and cities are shown in Figure 24.



Figure 22: Selected Locations

viii. Techno-economic analysis

Cost of kg hydrogen for different scales:

We used the modified MATLAB model to compare economically between different scales of electrolyzer power and found that the most economic power= 150KW as shown in the graph.

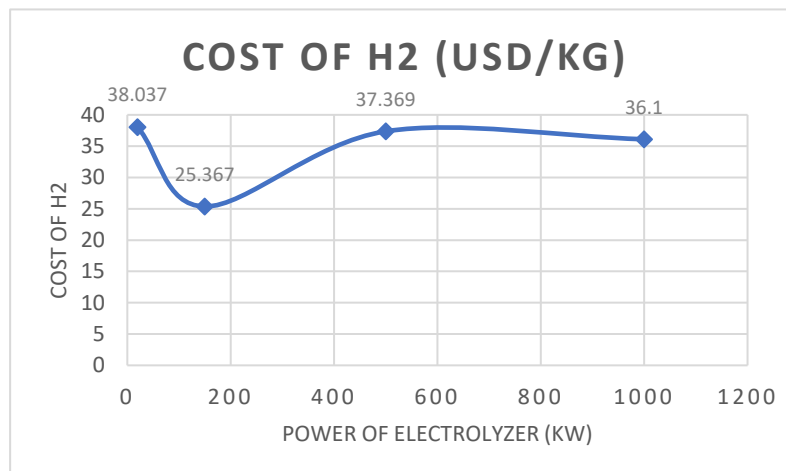


Figure 23: Relation between electrolyzer capacity and cost of production of hydrogen

Alkaline Electrolyzer Capacity (KW)	Cost of H ₂ (USD/kg)
20	38.037
150	25.367
500	37.369
1000	36.1

Cost of Hydrogen in 242 locations

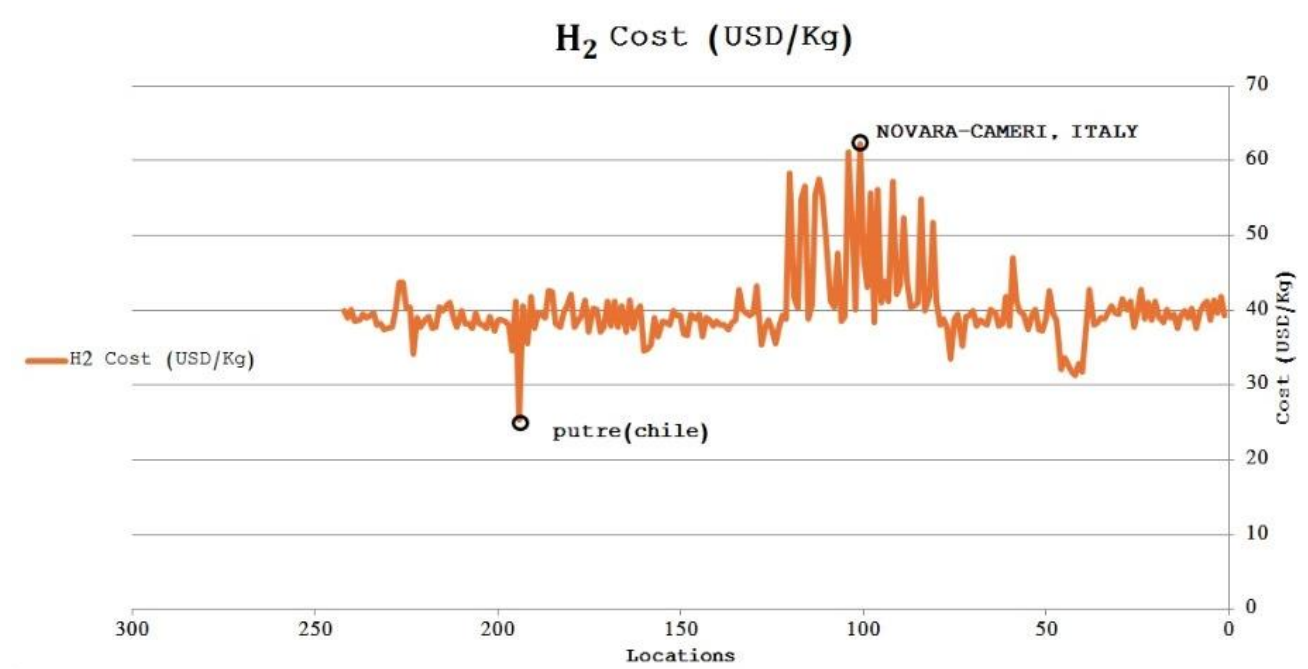


Figure 24: Analysis of the highest and lowest cost locations of hydrogen production

H ₂ Cost (USD/Kg)	Location Name
62.334	'NOVARA-CAMERI, ITALY'
25.367	Putre (chile)

After running our Model for the 242 locations, we noticed that the highest price for a kilogram of hydrogen is in **Novara-Cameri city, Italy**, and the lowest price is in **Putre city, Chile**.

ix. Data Acquisition for the selected location

Putre -18.196382°, -069.559224°, Chile Time zone: UTC-03, America/Santiago [CLST] Putre is a Chilean town and commune, capital of the Parinacota Province in the Arica-Parinacota Region. It is located 130 km (81 mi) east of Arica, was selected as a green H₂ production site based on the solar radiation data obtained from (GLOBAL SOLAR ATLAS) (<https://globalsolaratlas.info/>). As shown in Fig., solar radiation Specific photovoltaic power output PVOUT specific is 2136.7kWh/kWp.

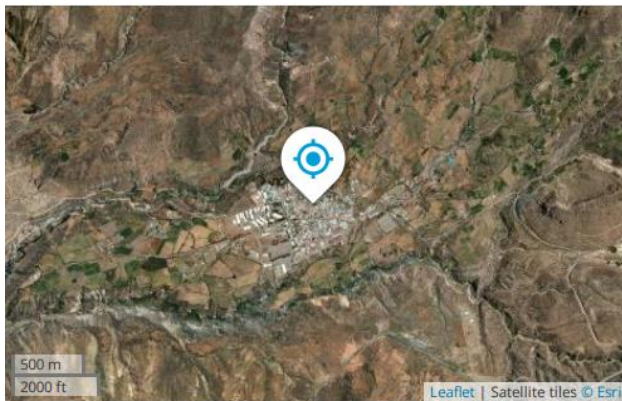
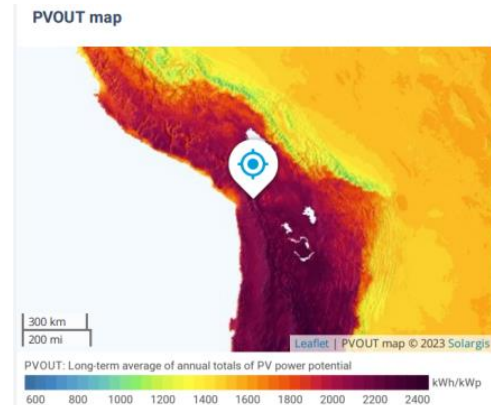


Figure 25: location of putre



- Monthly averages (Direct normal irradiation)

Direct normal irradiation

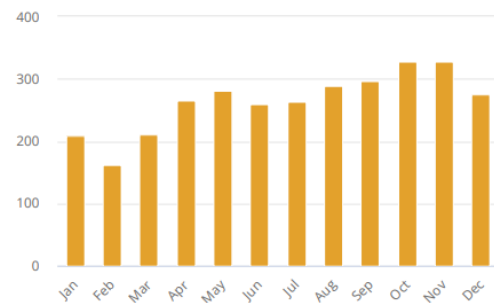
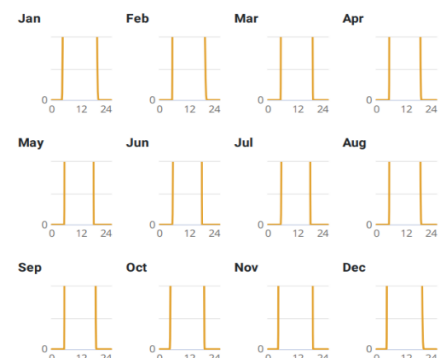


Figure 26: Irradiance distribution

Average hourly profiles (Direct normal irradiation [Wh/m])



- Average hourly profiles



Figure 27: Irradiance disruption in the year

x. Calculations for (150 KW model)

Table (1)

All information required for calculation of capital and operating costs.

Item	Value
Lifetime	25Years
Capital cost	
AWE capacity	0.335 , 20, 150, 500,1000 KW
AWE cost	588.7 USD kW– 1
BOP (Balance of plant)	50% of AWE capital expenditure
PV module (JKM460M-60HL4-V) 988 modules	99 USD / module.
Charge Controller (MPPT PWM Charger 10KW 96Volt 200amp Solar Battery Charge Controller for Solar Panel)	\$890.00
44 Controller	
Battery (Hyundai 2000W Portable Power Station HPS-1100)	\$1130
125 batteries	
Supplement cost	20% of total capital costs
Operating cost	
Labor	0.3% of total capital costs
Water Supply	0.0014 USD L-water– 1
Maintenance	2% of total capital costs
Other Costs	1% of total capital costs

Capital Cost

- AWE Cost = AWE capacity \times 588.7 USD kW⁻¹ = 150 \times 588.7 = **88,305 USD**
- BOP Cost = 50% of AWE capital = 50% \times 88,305 = **44,152.5 USD**
- PV Cost = 99 $\frac{\text{USD}}{\text{module}}$ = 99 \times 988 (module) = **97,812 USD**
- Charger Controller Cost = 890 USD \times No. of Charger Controller
= 890 \times 44 = **39,160 USD**
- Battery Cost = 1130 USD \times No. of Batteries
= 1130 \times 125 = **141,250 USD**
- Capital Cost = **410,679 USD**

Supplement Cost = 20% of Capital Costs = 20% \times 410,679 = **82,135.8 USD**

Total capital cost = 410,679 + 82,135.8 = **492,814.8 USD**

Operating Cost (for one year)

- Labor Cost = 0.3% of total capital cost = 0.3% \times 492,814.8 = **1478.44 USD**
- Water Supply Cost = 0.0014 $\frac{\text{USD}}{\text{Liter}}$
= 0.0014 \times 284230 = **397.922 USD**
- Maintenance Cost = 2% of total capital cost
= 2% \times 492,814.8 = **9856.296 USD**
- Other Costs = 1% of total capital cost = 1% \times 492,814.8 = **4928.148 USD**
- Total Operating Cost = 1478.4444 + 397.922 + 9856.296 + 4928.148
= **16,660.8104 USD**
- Annual Grid Revenue = Electricity price USD per kWh \times Energy used kWh
= 0.172 \times 961026.392681852 = **165,296.5395 USD/KWh**

Note: Due to the high irradiance in Putre site, the excess energy from the solar power, this feeds the Grid network (desired solution)

Total Annual Cost (per year) = Capital Costs + Annual Operating Costs – Annual Grid Revenue
(12)

$$= 492,814.8 + 16,660.8104 - 165,296.5395 = \mathbf{344,179.0709 \text{ USD}}$$

$$\text{Unit H}_2 \text{ Production Cost} \left(\frac{\text{USD}}{\text{KgH}_2} \right) = \frac{\text{Total Annual Cost (USD y}^{-1}\text{)}}{\text{Annual H}_2 \text{ Production rate (KgH}_2 \text{ y}^{-1}\text{)}} \quad (13)$$

$$= \frac{344,179.0709}{13630.6} = 25.2504 \frac{\text{USD}}{\text{KgH}_2} = 25.2504 \div 14.128 = \mathbf{1.787 \frac{\text{USD}}{\text{Liter}_{\text{H}_2}}}$$

- [This is achieved by running the model for the minimum cost location of the 242](#)

$$\text{LCOH} = \frac{\text{Net Present Value of total Cost (CAPEX plus OPEX) over the lifetime of the plant}}{\text{Net Present Value of total hydrogen production over the lifetime}} \quad (14)$$

$$= \frac{344,179.0709}{13630.6 \times 25} = \mathbf{1.01 \text{ (USD/KWh H}_2 \text{ HHV)}}$$

Integration with the model to analyze the Data.

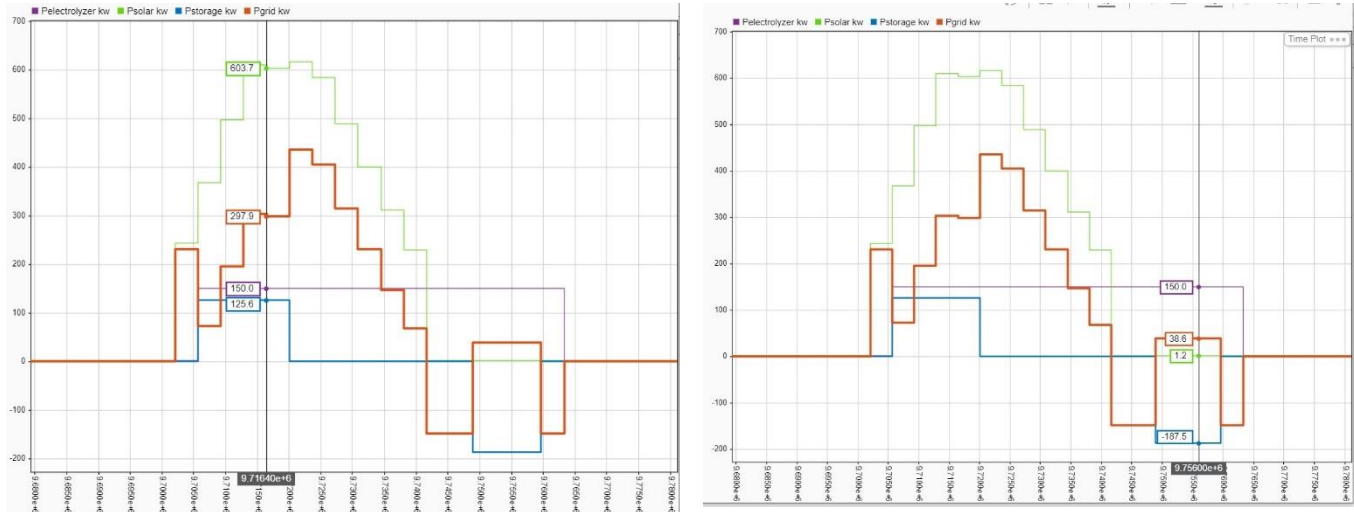


Figure 28: Data Inspection for one day

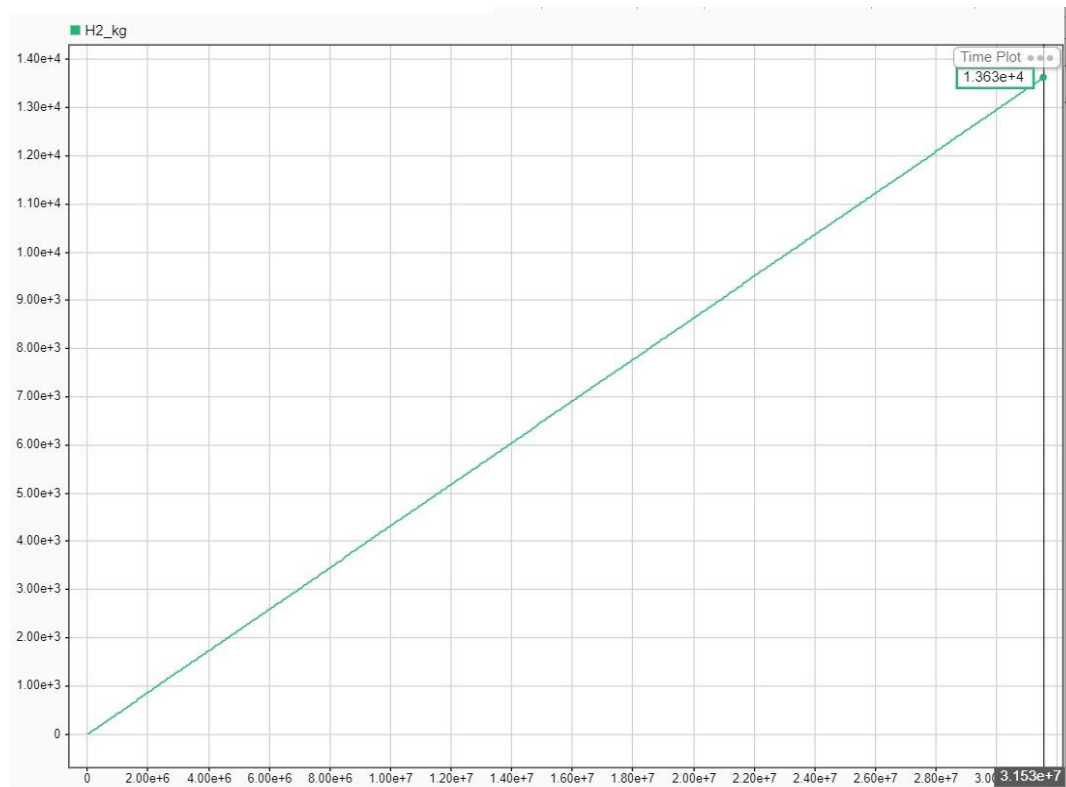


Figure 29: Hydrogen Production in one year

Note that this data is for **location Putre (Chile)** that has the best performance compared to the other locations and produces the hydrogen with the lowest cost that is the main target of the simulation.

The cost is equal to **25.367 USD/Kg** of hydrogen after running the model at the same conditions for all locations.

xi. Final version of the model

After presenting the challenges and the modifications let`s talk about the final version of the model

The model will run at the new conditions (power of electrolyzer = 150KW) such as the case study

Figures of the model (economic signals)

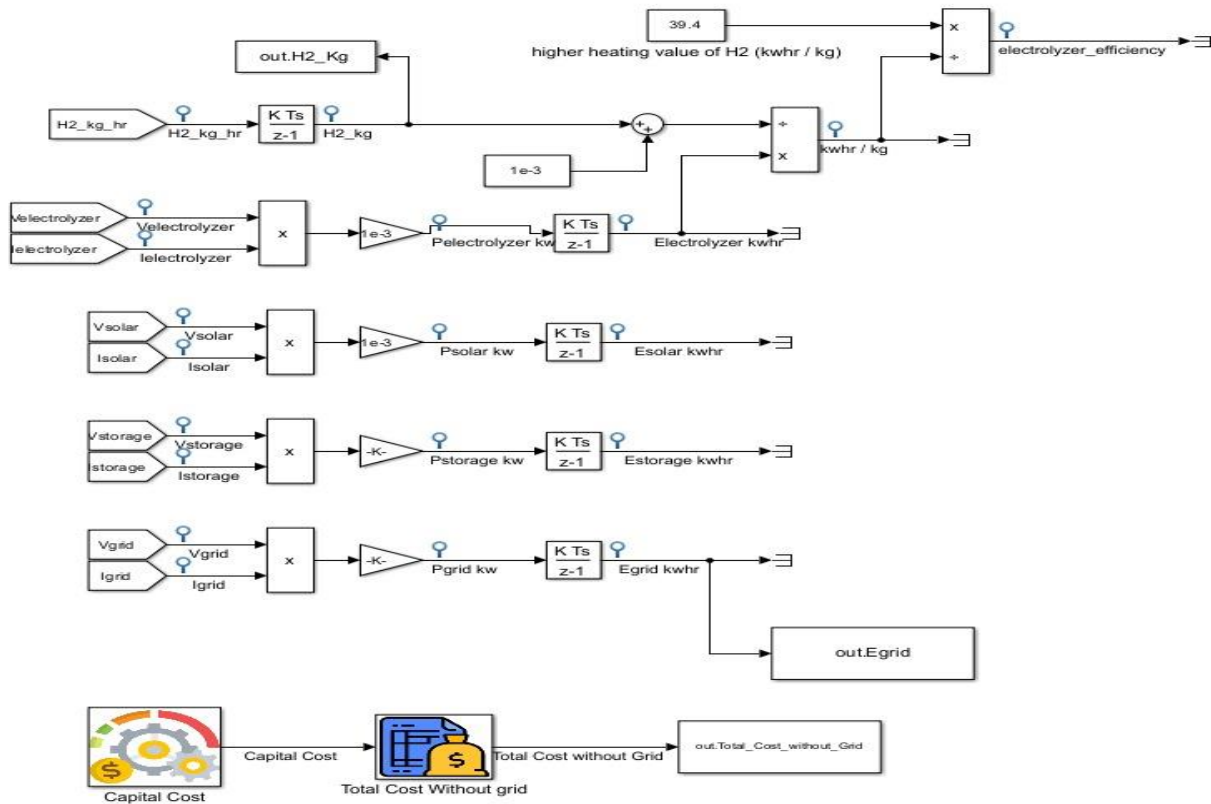


Figure 31: Measurement subsystem after adding economic signals

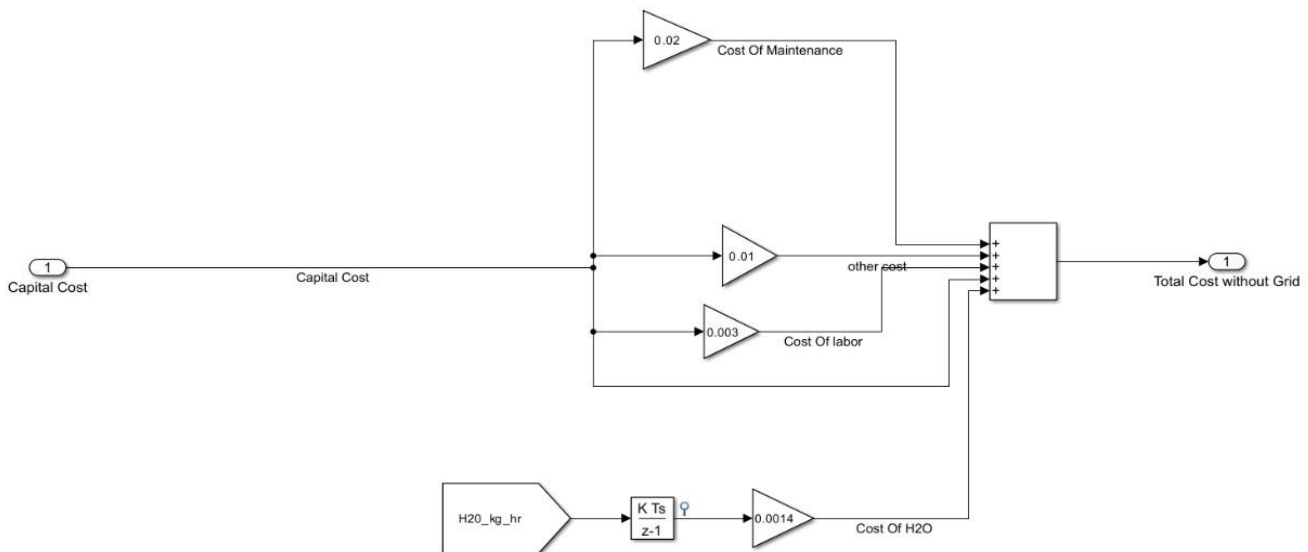


Figure 30: Total cost subsystem

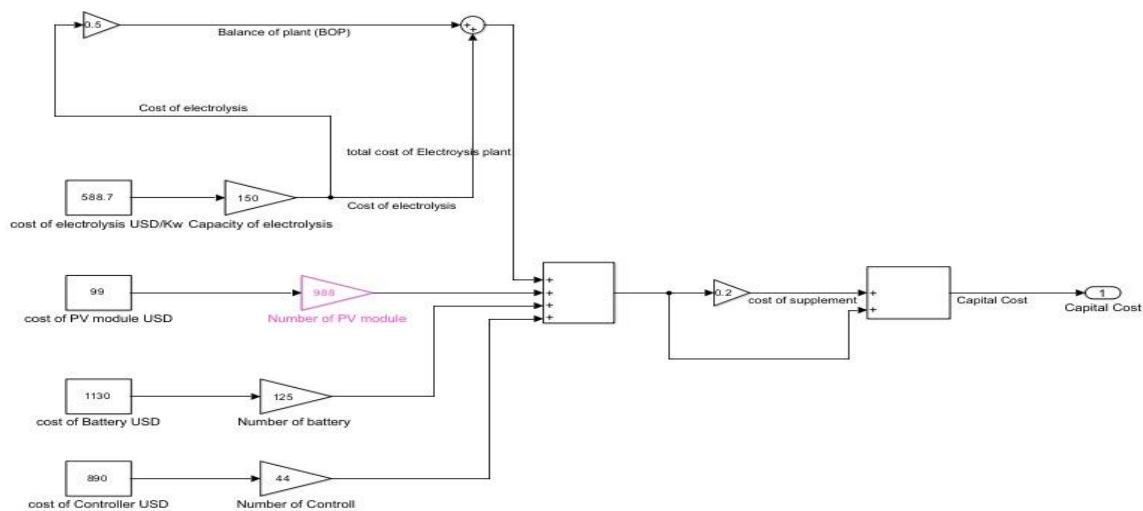


Figure 32: Capital Cost Subsystem

- From the shown figures there are economic signals that includes the total cost (capital cost, operating cost and grid cost).
- The run will be in new 242 location that is around the world according to high solar irradiance.
- There are also changes in the run time for the electrolyzer, charging and discharging of the batteries and the grid.

Operating time of the electrolyzer = 16 hours.

Time of charging of the batteries = 6 hours.

Time of discharging of the batteries = 10 hours.

- Changing the power required for the electrolyzer to operate and the capacity of the batteries and the solar system.

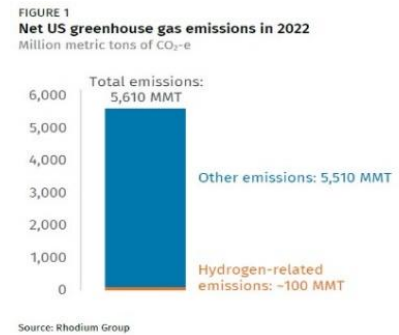
Power of the electrolyzer = 150 KW

Batteries capacity = 187.5 KW at charge, 125.625 KW at discharge.

- The cost of water is also added for the model to know the cost of water consumed in the simulation to produce the hydrogen.

xii. Environmental Impact

The effect of hydrogen generation on the environment depends on the production process and related by products, the hydrogen obtained from renewable energy such as solar energy “our scoop” is environmentally clean during the cycle of its generation and combustion, also has positive impact on many different environmental aspects such as:



- Reduction in greenhouse gases

Figure 33: Environmental Impact of hydrogen

As in our project green hydrogen is produced through solar energy and that leads to substantial reduction in greenhouse gas emissions and reduce the carbon footprint in the world.

- Utilization of Renewable Energy Sources

As it's offering a departure from fossil fuels and their damaging impact on air quality and ecosystems.

- Solar Panel Manufacturing

As the manufacture process of it can generate emissions as it requires processing of raw materials.

- Electrolysis Disposal

As proper recycling of electrolysis at the end of their life cycle should be managed to minimize environmental impact.

Note In our project, we use water by electrolysis to generate hydrogen and there is a short time use for electricity grid. This process also contributes to the emission of greenhouse gases during the stage of the consumption of electricity.

The risks

There is a basis for determining impact and risks, which is the **ESPS** (Environmental and Social Performance Standards) that has been determined by the **ESPF** (environmental and social policy framework). And it has 3 standards of ESPS to do with our scoop of hydrogen production.

i. ESPS 3: Resource Efficiency and Pollution Prevention

One of the main environmental risks associated with green hydrogen is the potential for water scarcity. The production of green hydrogen requires a significant amount of water and, in some areas where water is already scarce, this increase in demand could outrage existing water shortages. While the use of deionized water produced by desalination plants may reduce freshwater demand, it generates a need to discharge a stream of brine into the water sources and soils.

ESPS 3 requires that a comprehensive risk assessment that considers the potential impacts on the environment and develop appropriate measures to minimize the potential for contamination due to hazardous materials and substances that may be released by the project. The policy standard also requires the adoption of appropriate waste management practices and the implementation of measures to prevent contamination and reduce water consumption, and requires projects to assess and manage water risks, including the potential impact of the production of green hydrogen on water resources.

xiii. Social and community impact

Green hydrogen has also a **vital** impact on people's life and not only on environment such as:

Health and Well-being as in

Green hydrogen production from renewable sources has minimal adverse health effects on nearby communities. Improved air quality and reduced exposure to harmful pollutants contribute to enhanced public health, fostering a healthier and more livable environment for residents.

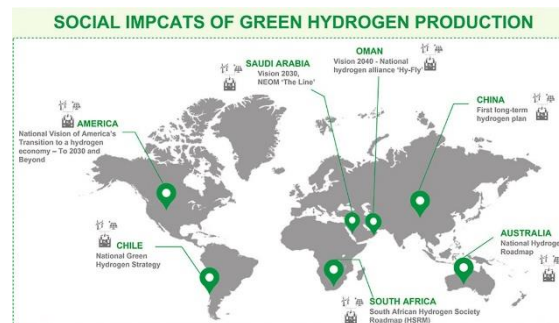


Figure 34: Social Impact of Hydrogen

Job Creation and Economic Opportunities

As from the installation and maintenance of solar energy infrastructure to the operation of electrolysis facilities and related services, communities benefit from such a rise in employment. This job creation not only supports economic stability but also empowers individuals with the skills and expertise required for the renewable energy sector.

The risks

i. ESPS 2: Labor and Working Conditions

One of the most significant risks associated with green hydrogen production is occupational health and safety. Hydrogen is a highly flammable gas and, if not handled properly, it can pose a significant risk to workers' safety during production, transportation, and storage. The production process involves the operation of complex and potentially dangerous high-pressure equipment and the handling of hazardous chemicals, which can lead to accidents and injuries.

But the solution is in **ESPS 2**, as it requires to assess and manage the potential risks to labor and working conditions. This includes identifying potential hazards, evaluating the risks associated with each hazard, and implementing measures to minimize or eliminate risks. Project developers should also provide appropriate training and protective equipment to workers and establish emergency response plans in case of accidents in the hydrogen production plant.

ii. ESPS 4: Community Health and Safety

One of the main concerns among public authorities and citizens related to the use of green hydrogen is the risk posed to community health and safety, which is addressed by **ESPS 4**, as hydrogen storage and transport require the use of high-pressure containers and pipelines, which can be a threat to nearby communities in case of leaks or explosions. Accidents involving the transport of hydrogen can also lead to explosions and fires, potentially causing harm to both people and the environment.

ESPS 4 requires managing the potential risks to community health and safety. This involves identifying potentially affected communities in influence of a green hydrogen project, evaluating the risks associated with each hazard, and implementing measures to avoid or minimize risks. **ESPS 4** also highlights the need to engage with communities early and often to ensure that they understand the potential risks and their rights to information and consultation and mandates the adoption of appropriate safety standards for the transport and storage of hydrogen and the use of renewable energy sources. Furthermore, it requires borrowers to develop emergency preparedness and response plans and conduct regular safety drills to prepare for potential incidents.

xiv. Innovation and outlook for the future of green hydrogen production:

The future of green hydrogen production holds significant promise with ongoing innovation. Advancements in electrolyzer technology, renewable energy integration, and storage solutions are key drivers. The emergence of low-cost and scalable electrolysis methods, coupled with improved efficiency, is expected to make green hydrogen more economically viable. Additionally, innovative approaches to address challenges like intermittent renewable energy supply and storage are shaping the outlook. Collaborations between industries and governments worldwide further underscore the commitment to advancing green hydrogen, indicating a bright future for sustainable and clean energy production.

Innovation in clean energy technologies needs to accelerate for hydrogen to play its role in the clean energy transition. The level of maturity of hydrogen-related technologies varies widely across the supply chain, with technologies for low emission hydrogen supply much more developed than for end uses (except for established applications in refining and the chemical industry).

Technologies development:

Alkaline and proton exchange membrane (PEM) electrolyzers are commercially available, but manufacturers have a strong innovation focus to keep decreasing equipment costs. Reducing critical material loads is a good example. Solid oxide electrolyzers (SOEC), the most efficient electrolysis technology, are quickly approaching commercialization. The two largest demonstrations. SOEC started operating in 2023, one by Sunfire (2.6 MW) and the other by Bloom Energy (4 MW). Anion exchange membrane (AEM) electrolyzers are at an earlier stage of development, but the technology is also evolving rapidly and Enapter launched the world's first megawatt AEM electrolyzer in May 2023. In addition, direct electrolysis of seawater was demonstrated for the first time in an offshore platform in China in June 2023. In August 2023

Hysata opened its new electrolyzer manufacturing facility, where it will build a demonstrator (5 MW) of its advanced alkaline capillary-fed electrolyzer – claiming up to 95% efficiency – with the view to reach commercial-scale units by 2025.

Most technologies for hydrogen transport and storage are mature, although still at small scale. Innovation and demonstration efforts are underway to bring these technologies to the scale needed to facilitate the adoption of hydrogen as a clean energy vector. In April 2023, the world's first pure hydrogen storage facility in an underground porous reservoir started operation (~3 GWh of hydrogen).

In end-use technologies, the situation is different: the technologies in sectors in which emissions are hard to abate, where hydrogen is expected to play a more important role for decarbonization, are much less mature and innovation is taking place at a slower pace. Nevertheless, there are some positive signs of progress, such as in industry, where RD&D in the use of hydrogen for high temperature heat in ancillary processes moved forward last year. In 2023, 30 international partners from 12 European countries launched HyInHeat to demonstrate the use of hydrogen in ancillary processes in aluminium and steel. The Japanese utility Tokyo Gas and building materials manufacturer Lixil tested hydrogen instead of natural gas for heat treatment of aluminium⁷⁰, finding that this seemed to have no adverse effect on the quality of products.

xv. Conclusion

The production of green hydrogen using solar energy and battery storage systems holds immense promise as a clean and sustainable alternative to traditional fossil fuels. This project has investigated the feasibility and economic viability of this technology, not just for a specific location, but with a global perspective.

Our findings indicate that green hydrogen production, while dependent on factors like solar energy costs and regional infrastructure, can be a globally competitive option for decarbonizing various sectors.

xvi. Recommendations

- **Infrastructure Development:** Significant investments are needed in renewable energy infrastructure, battery storage capacity, and hydrogen transportation networks.
- **Policy and Regulatory Support:** Governments must introduce supportive policies, including carbon pricing and subsidies, to accelerate green hydrogen adoption and level the playing field with fossil fuels.
- **Public Awareness and Education:** Raising public awareness about the benefits of green hydrogen is crucial for driving consumer demand and fostering social acceptance.

In conclusion, green hydrogen production powered by solar energy and battery storage presents a transformative opportunity for achieving a sustainable energy future. With concerted global efforts in infrastructure development, policy support, and public education, we can unlock the potential of this clean fuel and pave the way for a cleaner, more secure, and prosperous future for all.

xvii. Appendices:

Electrolyzer

$$V_{H_2} = \frac{n * R * T}{p}$$

$$n = \frac{\text{no. of cells} * I * t}{F * Z}$$

$$\text{Area} = \frac{I \text{ (amp)}}{\text{Current density} \left(\frac{\text{amp}}{\text{cm}^2}\right)}$$

$$P_{\text{Total}} = \text{no. of cells} * V_{\text{cell}} * I$$

$$V_{\text{ohmic}} = (((r_1 + r_2 * T)) / \text{Area}) * I$$

$$P_{\text{ohmic}} = I^2 * R_{\text{ohmic}} * \text{no. of cells}$$

$$P_{\text{Electrolysis}} = P_{\text{total}} - 1.5 * P_{\text{ohmic}}$$

$$\eta_{\text{Electrolysis}} = \frac{P_{\text{Electrolysis}}}{P_{\text{total}}} = \frac{P_{\text{total}} - P_{\text{ohmic}}}{P_{\text{total}}}$$

$$\text{Efficiency of the cell} = \frac{\text{Theoretical EMF}}{\text{Cell voltage}}$$

PV system

$$E_{\text{Load}} = E_{\text{electrizer}} * \text{daily runtime}$$

$$E_{\text{In}} = \frac{E_{\text{Load}}}{\eta_{\text{battery}} \eta_{\text{charge controller}}}$$

$$E_{\text{pv}} = \frac{E_{\text{In}}}{1 - \text{derating factor}}$$

$$P_{\text{max}} = \frac{E_{\text{pv}}}{T_{\text{psh}}}$$

$$N_{\text{module}} = \frac{P_{\text{max}}}{P_{\text{Module}}}$$

$$N_{\text{pvs}} = \frac{V_{\text{Dc}}}{V_{\text{pv}}}$$

- Batteries

$$E_{\text{safe}} = \frac{E_{\text{rough}}}{\text{MDOD}}$$

$$c = \frac{E_{\text{safe}}}{v_b}$$

$$N_{\text{batteries}} = \frac{c}{c_b}$$

Charge controller

$$I_{\text{rcc}} = I_{\text{sc}}^M * N_{\text{pm}} * F_{\text{safe}}$$

$$N_{\text{cc}} = \frac{I_{\text{rcc}}}{I_{\text{cc}}}$$

Compound Annual Growth Rate

$$\text{CAGR} = \left(\left(\frac{\text{EV}}{\text{BV}} \right)^{\frac{1}{n}} - 1 \right) * 100$$

EV = Ending Value

BV = Beginning Value

n = Number of years

Cost

AWE Cost = AWE capacity × 588.7 USD/kW

BOP Cost = 50% of AWE capital cost

PV Cost = USD/module * no of modules

Charger Controller Cost = 862.00

USD × No. of charger controller

Battery Cost = 1130 USD × No. of Batteries

Capital Cost = AWE Cost + BOP Cost + PV

Cost + Charger Controller Cost + Battery

Cost

Supplement Cost = 20% of capital costs

Total Capital Cost = Capital Cost +

Supplement Cost

Operating Cost (for one year)

Labor Cost = 0.3% of total capital cost

Water Supply Cost = 0.0014 USD/Liter

Maintenance Cost = 2% of total capital cost

Other Costs = 1% of total capital cost

Total Operating Cost = Labor Cost + Water

Supply Cost + Maintenance Cost + Other

Costs

xviii. References

1. [Yakdehige Sanath Kumara De Silva, **Design of an Alkaline Electrolysis Stack**, University of Agder, 2017.](#)
2. [. Robert Phillips, Charles Dunnill, **Zero Gap Cell Design for Alkaline Electrolysis**, March 2019.](#)
3. [Chijindu Ikechukwu Igwe, Chinonso Hubert Achebe, Arinze Chinweze, **Design of an Alkaline Water Electrolyzer for Hydrogen Production**, Article in American Journal of Mechanical and Industrial Engineering · January 2023.](#)
4. [Pavlos Nikolaidis, Andreas Poullikkas, **A comparative overview of hydrogen production processes**, Department of Electrical Engineering, Cyprus University of Technology, 18 September 2016.](#)
5. [Diego Bairrão, João Soares, José Almeida, John F. Franco, Zita Vale, **Green Hydrogen and Energy Transition: Current State and Prospects in Portugal**, 3 January 2023.](#)
6. [Ying Zhou, Ruiying Li, Zexuan Lv, Jian Liu, Hongjun Zhou, Chunming Xu, **Green hydrogen: A promising way to the carbon-free society**, 14 February 2022.](#)
7. [Armand Fopah-Lele, Amelie Kabore-Kere, Jean Gaston Tamba, Isdeen Yaya-Nadjo, **Solar electricity storage through green hydrogen production: A case study**, Department of Renewable Energies and Energy Efficiency, 26 February 2021.](#)
8. [Benedetto Nastasi, Gianluigi Lo Basso, **Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems**, Department of Astronautics, Electrical and Energy Engineering Sapienza University of Rome, 22 April 2016.](#)
9. [SeyedEhsanHosseini, MazlanAbdulWahid, **Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development**, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 7January2016.](#)
10. [Gaetano Squadrito, Gaetano Maggio, Agatino Nicita, **The green hydrogen revolution**, 14 July 2023.](#)
11. [Furat Dawood, Martin Anda, G.M. Shafiullah, **Hydrogen production for energy: An overview**, College of Science, Health, Engineering and Education, Murdoch University, Perth, WA, Australia, 11 January 2020.](#)
12. [David Martinez, Ramon Zamora, **MATLAB Simscape Model of An Alkaline Electrolyser and Its Simulation with A Directly Coupled PV Module**, Electrical and Electronic Engineering Department, Auckland University of Technology, Auckland 1010, New Zealand, 28.01.2018.](#)
13. [Ja'far Saif Edden Abdel Hafeath Jallad, **Design and Simulation of a Photovoltaic System with Maximum Power Control to Supply a Load with Alternating Current**, Degree of Master in Clean Energy and Energy Conservation Strategy Engineering, Faculty of Graduate Studies, at An-Najah National University, Nablus, Palestine, 2012.](#)
14. [Mirza Mursalin Iqbal, Kafiul Islam, **Design and Simulation Of A PV System With Battery Storage Using Bidirectional DC DC Converter Using Matlab Simulink**, July 2017.](#)
15. [Md.W.Shah, Robert L.Biate, **Design and Simulation of Solar PV Model Using Matlab/Simulink**, March-2016.](#)

16. [Evgeny M. Gordievsky, Alexey Miroshnichenko, Askar Kulganatov, **Simulation Model of Solar Power Installation in Matlab Simulink Program**, Department of Electric Stations, Grids and Systems South Ural State University November 01,2020.](#)
17. [Mohammed Salameh Ibbini, Mohammad A. Masadeh, Shadi Mansi, **Simscape Solar Cells Model Analysis and Design**, April 2014.](#)
18. [Bader N. Alajmi, Khaled H. Ahmed, Member, IEEE, Stephen J. Finney, and Barry W. Williams, **A Maximum Power Point Tracking Technique for Partially Shaded Photovoltaic Systems in Microgrids**, APRIL 2013.](#)
19. [Thomas Longden, Frank Jotzo, Andreas Löschel, **Conditions for low-cost green hydrogen production: mapping cost competitiveness with reduced-form marginal effect relationships** Crawford School of Public Policy Centre for Climate & Energy Policy, August 2021.](#)
20. [Seddiq Sebbahi, Nouhaila Nabil, Amine Alaoui-Belghiti, Said Laasri, Samir Rachidi, Abdelowahed Hajjaji, **Assessment of the three most developed water electrolysis technologies:Alkaline Water Electrolysis, Proton Exchange Membrane and Solid-Oxide Electrolysis**, 29 April 2022.](#)
21. [Matheus T. de Groot, Joost Kraakman, Rodrigo Lira Garcia Barros, **Optimal operating parameters for advanced alkaline water electrolysis**, 6 September 2022.](#)
22. [Boreum Lee, Hyun-Seok Cho, Heehyang Kim, Dongjun Lim, Wonchul Cho, Chang-Hee Kim, Hankwon Lim, **Integrative techno-economic and environmental assessment for green H2 production by alkaline water electrolysis based on experimental data**, December 2021.](#)
23. [S. Shiva Kumar, Hankwon Lim, **An overview of water electrolysis technologies for green hydrogen production**, November 2022.](#)
24. [Hyunjun Lee, Bomin Choe, Boreum Lee, Jiwon Gu, Hyun-Seok Cho, Wangyun Won, Hankwon Lim, **Outlook of industrial-scale green hydrogen production via a hybrid system of alkaline water electrolysis and energy storage system based on seasonal solar radiation**, 1 December 2022.](#)
25. [Lei Wan, Ziang Xu, Baoguo Wang, **Green preparation of highly alkali-resistant PTFE composite membranes for advanced alkaline water electrolysis**, 15 December 2021.](#)
26. [Qian Zhou, Liling Liao, Haiqing Zhou, Dongyang Li, Dongsheng Tang, Fang Yu, **Innovative strategies in design of transition metal-based catalysts for large-current-density alkaline water/seawater electrolysis**, September 2022.](#)
27. Grid electricity prices: <https://www.globalpetrolprices.com/>
28. [Max Patel, Sumit Roy, Anthony Paul Roskilly, Andrew Smallbone, **The techno-economics potential of hydrogen interconnectors for electrical energy transmission and storage**, 10 February 2022.](#)
29. [Emilio García, Eduardo Quiles, Antonio Correcher and Francisco Morant, **Predictive Diagnosis Based on Predictor Symptoms for Isolated Photovoltaic Systems Using MPPT Charge Regulators**, 14 October 2022.](#)
30. Solar data: <https://globalsolaratlas.info/map> / <https://pvwatts.nrel.gov/pvwatts.php>
31. [Guda, H. A, Aliyu U. O, **Design of a Stand-Alone Photovoltaic System for a Residence in Bauchi - International Journal of Engineering and Technology Volume 5 No,1, January 2015.**](#)