Sustainability and Renewable Energy Challenge

Techno-Economic Assessment of Green Hydrogen Production

Project Number (236)

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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

Figure 1: Renewable Energy Resource (32)

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 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.

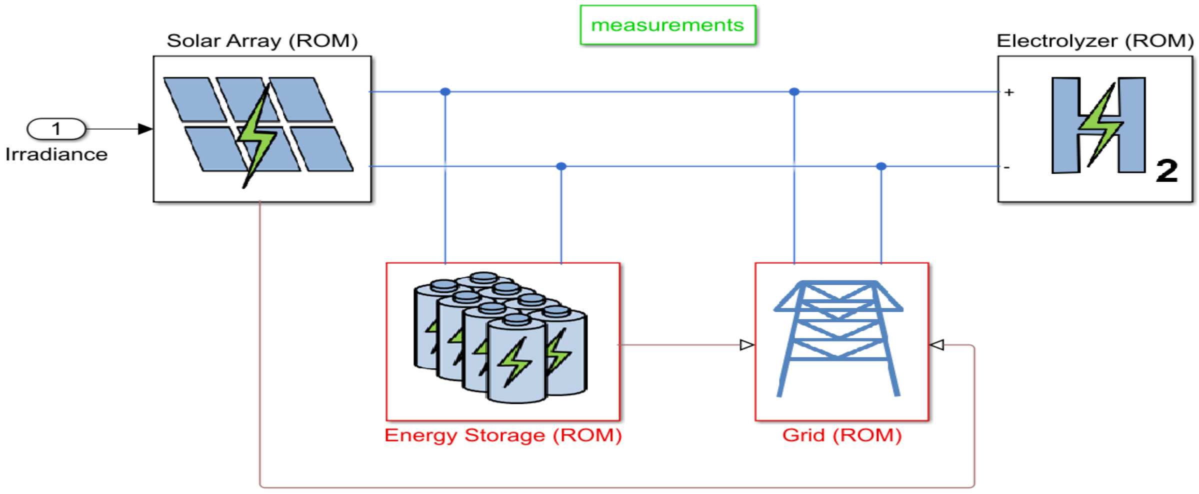


Figure 2: The MATLAB model

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

<u>So let`s talk about each subsystem of the model</u>

Solar array

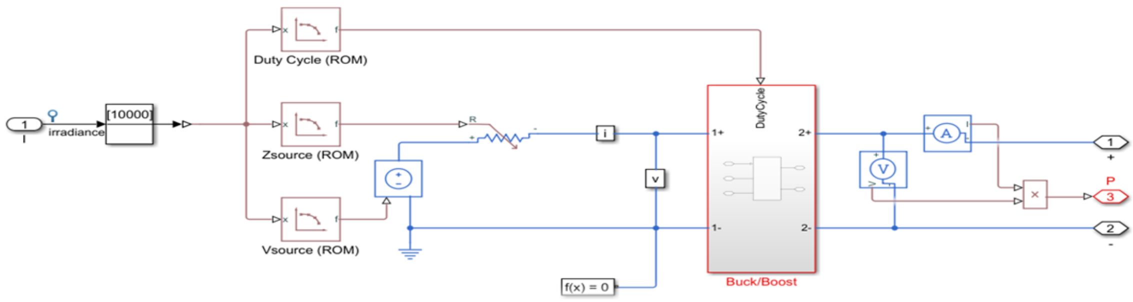


Figure 3: Solar array Subsystem

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 whith 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 multiblied to get the power of the solar system.
- This power is used to operate the electrolyzer and charge the batteries.

Storage system

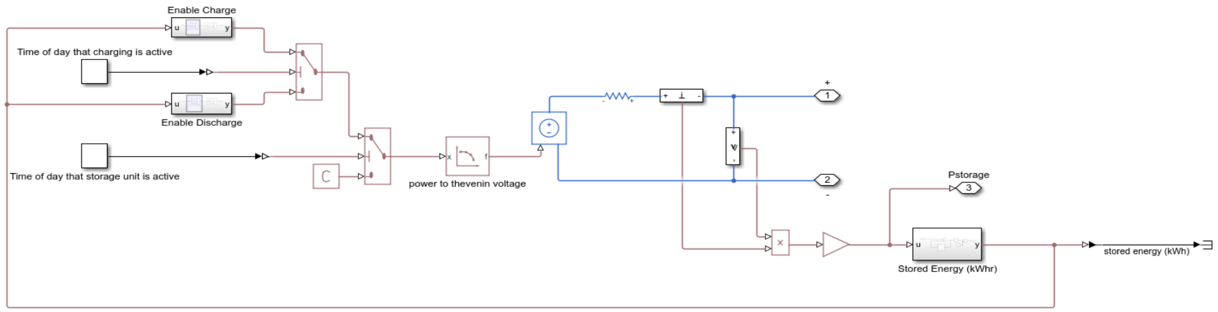


Figure 4: Storage (batteries) Subsystem

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 battries?

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 battries is used to operate the electrolyzer with the solar energy.

Grid

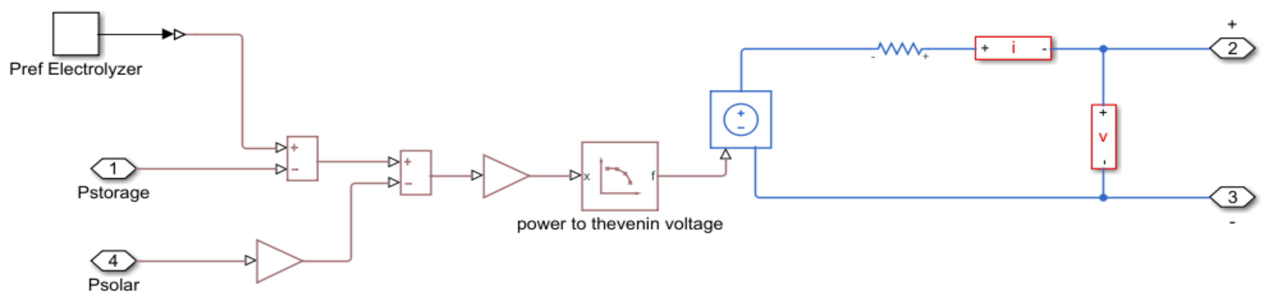


Figure 5: Grid Subsystem

The grid is used as a supplier when the power of the solar and the battries isn`t enough to operate the electrolyzer it can be usd as a power source for the electrolyzer.

Working principles:

There is 3 inputs:

- Power of electrolyzer.
- Power of solar.
- Power of storage.

Then, we can know if the grid is needed or not by this equation:

$$P_{grid} = P_{electrolyzer} - P_{solar} - P_{storage}$$

So the grid signal is the net of the subtraction, if the power of the solar and storage is higher than the electrolyzer this power goes to the grid.

Electrolyzer

The electrolyzer is used to split the water to hydrogen to be stored to be used.

The electrolyzer can be controlled by:

- Changing the time of running
- Changing the capacity of the electrolyzer

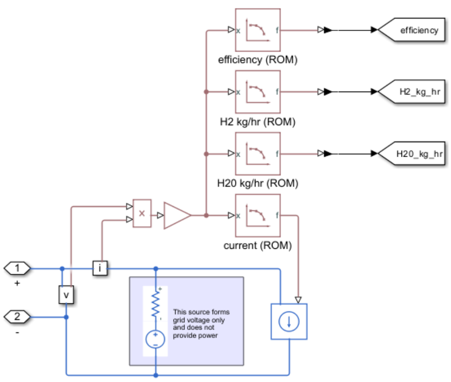


Figure 6: Electrolyzer Subsystem

Run Explanasion

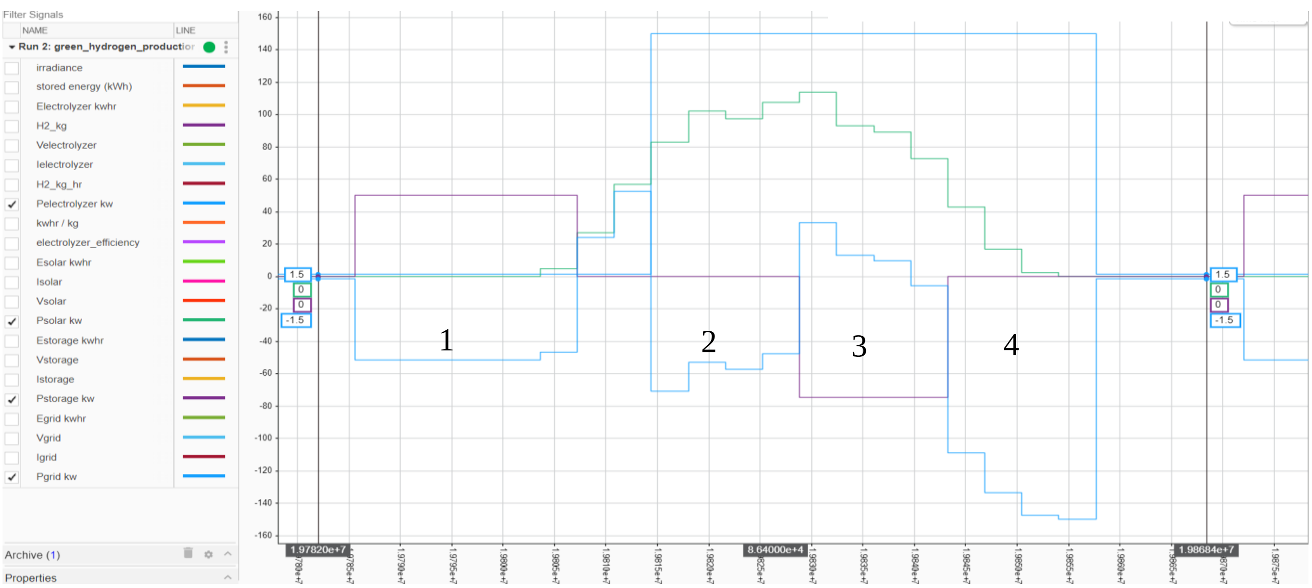


Figure 7: Data Inspector analysis

<u>From the shown figure it is the analysis for one day randomly in loction no (1):</u>

The curves shows the power distribution to produce the hydrogen. The cycle statrs by charging the batteries from the grid untill the sun starts to rise and the irradiace will provide us solar power.

- For region (1)

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

- 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.

Figure 8: Hydrogen Production Plant (33)

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:

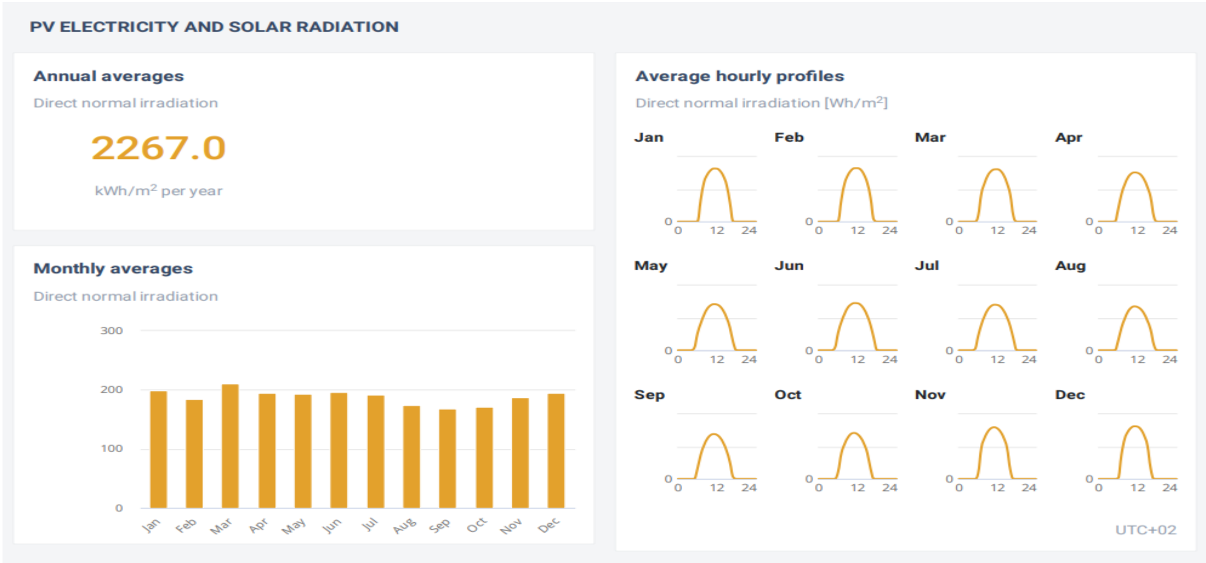
SITE INFO

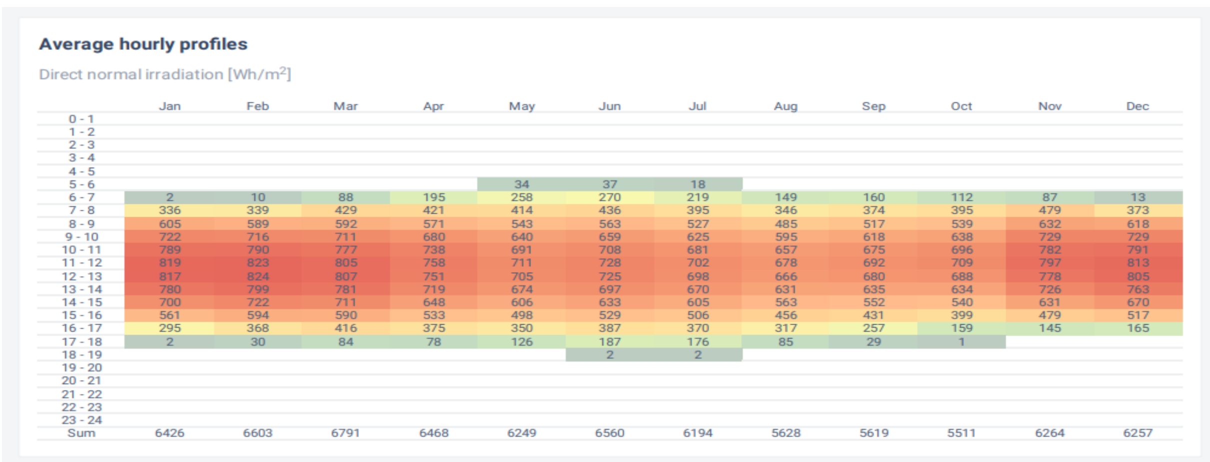
Map data		Per year	
Specific photovoltaic power output	PVOUT specific	1965.2	kWh/kWp
Direct normal irradiation	DNI	2290.4	kWh/m^2
Global horizontal irradiation	GHI	2364.8	kWh/m^2
Diffuse horizontal irradiation	DIF	816.8	kWh/m^2
Global tilted irradiation at optimum angle	GTI opta	2566.8	kWh/m^2
Optimum tilt of PV modules	OPTA	26 / 180	°
Air temperature	TEMP	27.1	°C
Terrain elevation	ELE	271	m

Map

Figure 9: ASWAN location data

Irradiance data:





Average hourly profiles

Direct normal irradiation [Wh/m²]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6					34	37	18					
6 - 7	2	10	88	195	258	270	219	149	160	112	87	13
7 - 8	336	339	429	421	414	436	395	346	374	395	479	373
8 - 9	605	589	592	571	543	563	527	485	517	539	632	618
9 - 10	722	716	711	680	640	659	625	595	618	638	729	729
10 - 11	789	790	777	738	691	708	681	657	675	696	782	791
11 - 12	819	823	805	758	711	728	702	678	692	709	797	813
12 - 13	817	824	807	751	705	725	698	666	680	688	778	805
13 - 14	780	799	781	719	674	697	670	631	635	634	726	763
14 - 15	700	722	711	648	606	633	605	563	552	540	631	670
15 - 16	561	594	590	533	498	529	506	456	431	399	479	517
16 - 17	295	368	416	375	350	387	370	317	257	159	145	165
17 - 18	2	30	84	78	126	187	176	85	29	1		
18 - 19						2	2					
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	6426	6603	6791	6468	6249	6560	6194	5628	5619	5511	6264	6257

Figure 10: Irradianc Data

Detailed explanation of the process flow or system design:

i. Electrolyzer:

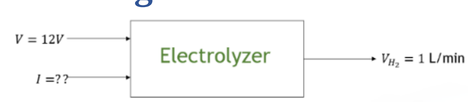


Figure 11: Electrolyzer Control Volume

- **Electrolyzer main working idea and structure:**

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.

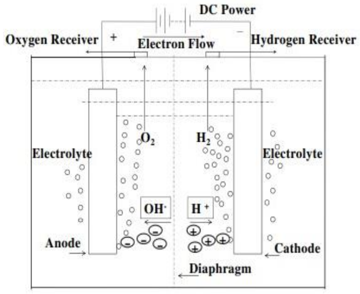


Figure 12: Electrolyzer schematic (34)

Anode reaction:

$$4H_2O + 4e^- \rightarrow 2H_2 + 4OH$$

Cathode reaction:

$$4OH^- + O_2 \rightarrow 4e^- + 2H_2O$$

Overall reaction:

$$2H_2O \rightarrow 2H_2 + O_2$$

- **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)**

<u>The selected electrolyzer type is **alkaline** electrolyzer, **why?**</u>

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.

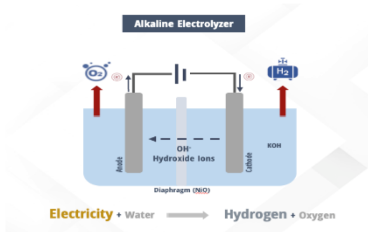


Figure 13: AWE Schematic (35)

- **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.%).

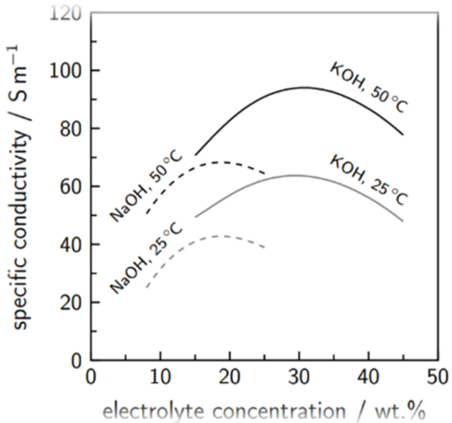


Figure 14: Comparison between NaOH & KOH (1)

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) $0.52\Omega.cm^2$

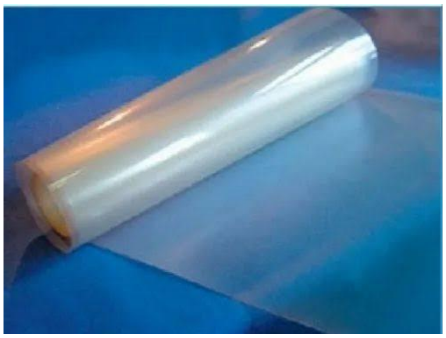


Figure 15: Membrane Sample (Nafion) (36)

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
- $H2$ gas flow rate $V(H2)$ = 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 rateV_{H2}.

- 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

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

$$n_{H2} = \frac{V_{H_2} * P}{R * T} = \frac{1 * 1}{0.082 * 298} = 0.0409\ mole/min$$

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.

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

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

3. Area of the electrode (Cm2):

$$Area = \frac{I\ (amp)}{Current\ density\ (\frac{amp}{cm2})}$$

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

4. Total Power and Ohmic Power:
   - $Vcell$: is voltage cell (Volt) = 2.4 V
   - I: Electrolyzer input current (I) (Amp) = 26.3 A

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

Parameters related to ohmic resistance of electrolyte

$r_1 = 8.05 * 10^{-5}\Omega\text{m2}$ $\quad\quad$ $r_2 = -2.5 * 10^{-7}\ \Omega\text{m2℃}$

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

5. The Electrolysis Power:

$Pohmic = I\text{^}2 * Rohmic * no.\ of\ cells = I * V\_ohmic * no.\ of\ cells = 20watt$

$P\_Electrolysis = P\_total - 1.5 * P\_ohmic = 315.6 - 1.5 * 20 = 285.6$ watt

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

6. Electrolysis Efficiency & Energy Efficiency of the Cell:

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

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

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

Design Calculations Summary:

No. of hydrogen moles (mol)	**Electrolyzer current (amp)**	**Plate Area (Cm2)**	**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**	**Electolyzer pressure (bar)**	**Electolyzer Temperature (Celsius)**	**No of cells**
20	286.6	90%	61.67%	1	25	5

ii. Solar power planet:

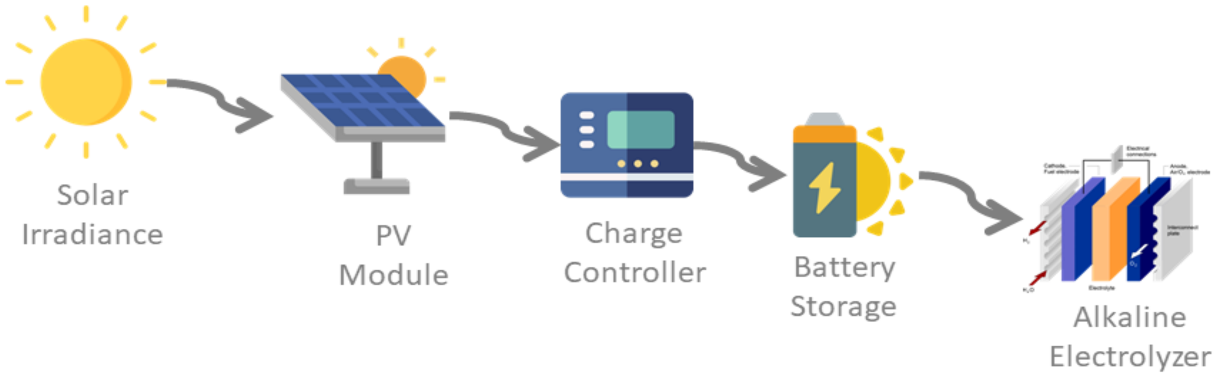


Figure 16: Solar System Schematic

- **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.

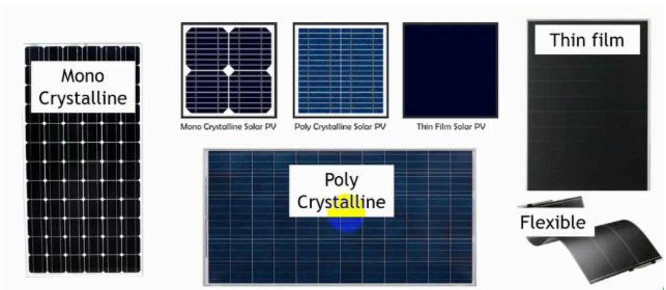


Figure 17: PV module types (37)

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, **<u>why?</u>**

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 JKM440M-60HL4-V		JKM445M-60HL4 JKM445M-60HL4-V	
	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	$\boxed{\text{440Wp}}$	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 (38)

- **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:

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

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

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 $P_{Module} = 440\ W$

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

5. For Series:

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

6. For parallel:

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

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× 1 = 6.7 kWh

For Energy safety:

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

The capacity of the battery bank needed can be evaluated:

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

The total number of batteries is obtained by:

$$N_{batteries} = \frac{c}{c_b} = \frac{697.917}{250} = 2.79 \simeq 3 \; batteries$$

The number of batteries in series equals to:

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

Then number of parallel paths Np 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.

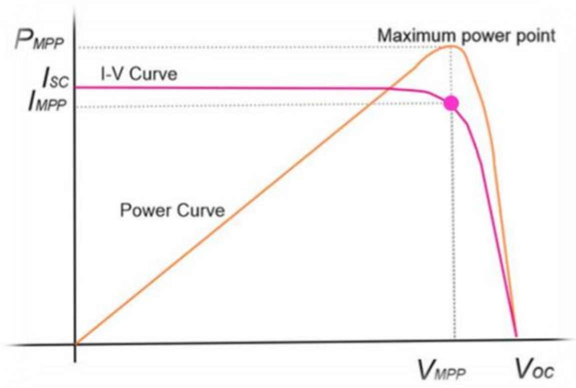


Figure 19: IV characteristics of the solar system (29)

- **Function:**

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.

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

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:

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

Number of charger controllers:

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

- **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 descripe the Green Hydrogen Market as shown in the fig.20

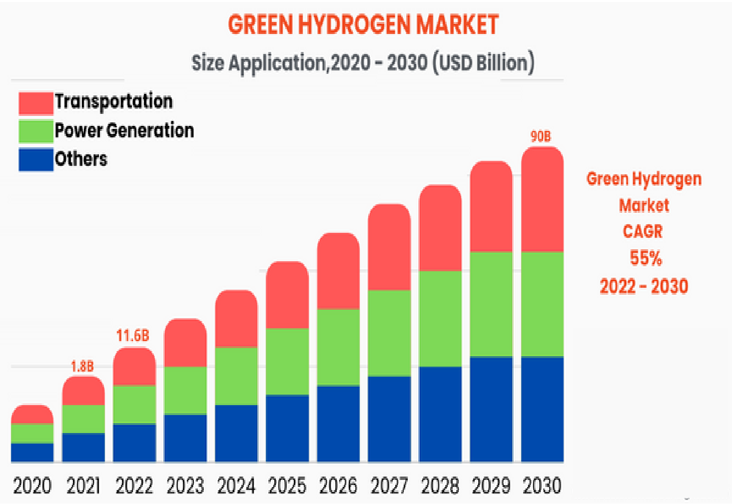


Figure 20: Green Hydrogen applications (39)

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 electrolyzes 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.

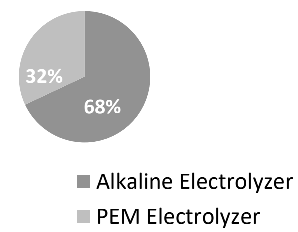


Figure 21: Comparison between PEM & AWE

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.

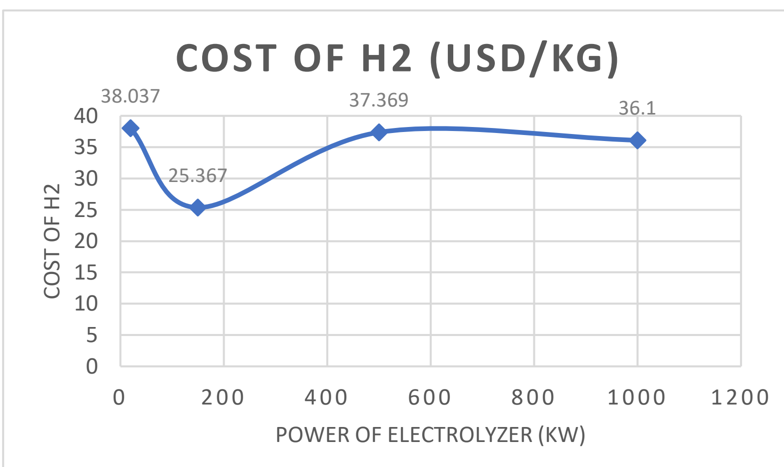


Figure 23: Relation between electrolyzer capacity and cost of producrion of hydrogen

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

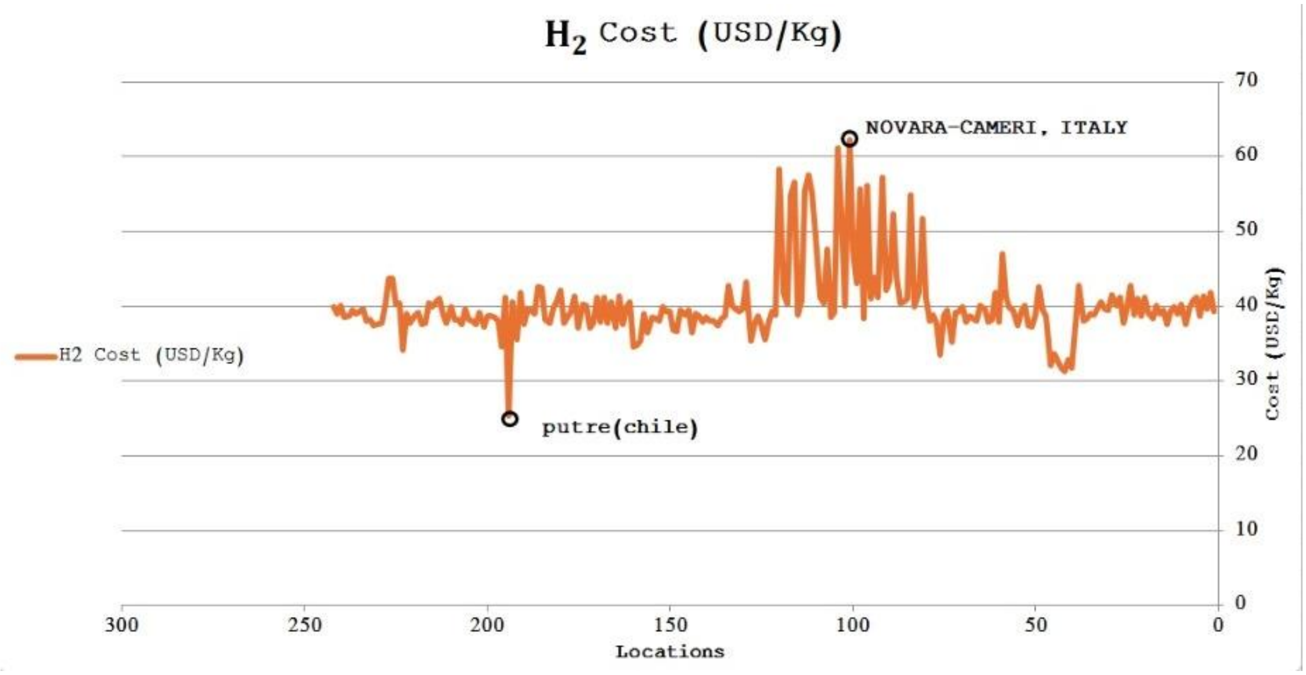


Figure 24: Analysis of the highest and lowest cost locations of hydrogen production

H2 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 Fig25., solar radiation Specific photovoltaic power output PVOUT specific is 2136.7kWh/kWp.

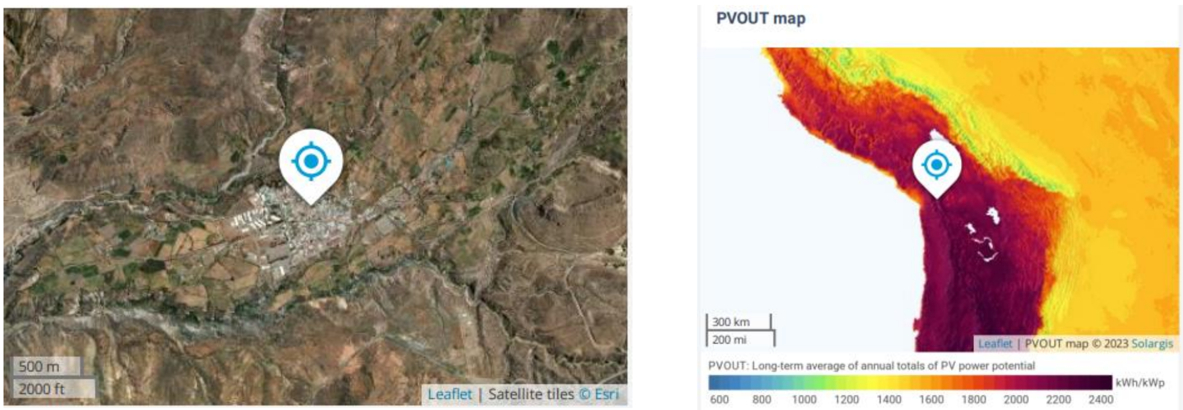


Figure 25: location of putre

- **Monthly averages** (Direct normal irradiation)

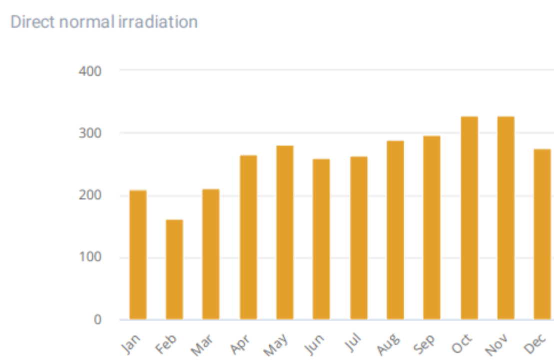
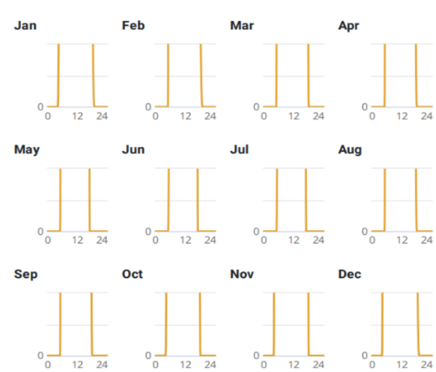


Figure 26: Irradiance distribution

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



- **Average hourly profiles**

Average hourly profiles

Direct normal irradiation [Wh/m²]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6	94									153	326	254
6 - 7	566	463	283	320	316	151	143	308	527	780	835	708
7 - 8	729	655	707	788	801	756	727	792	847	912	954	846
8 - 9	796	748	816	889	900	872	847	896	933	980	1020	910
9 - 10	788	757	843	940	950	928	905	951	976	1017	1041	921
10 - 11	733	705	824	962	977	954	936	981	999	1036	1047	893
11 - 12	666	607	752	956	984	964	949	988	1006	1034	1028	850
12 - 13	570	475	657	937	973	955	943	982	1000	1017	991	767
13 - 14	474	386	573	883	949	929	916	957	974	977	956	700
14 - 15	399	326	476	811	901	879	866	913	925	924	905	642
15 - 16	339	265	403	720	819	789	785	835	841	834	819	574
16 - 17	301	227	344	563	484	446	472	652	676	693	710	492
17 - 18	252	174	146	61				68	153	212	295	321
18 - 19	14	8										13
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	6722	5796	6823	8828	9054	8623	8490	9323	9856	10570	10925	8892

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) 44 Controller	$890.00
Battery (Hyundai 2000W Portable Power Station | HPS-1100) 125 batteries	$1130
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×588.7 USD kW− 1= $150 \times 588.7 = \mathbf{88,305}$ USD
- BOP Cost= 50% of AWE capital $= 50\% \times 88{,}305 = \mathbf{44,152.5}$USD
- PV Cost= $99\,\frac{\mathrm{USD}}{\mathrm{module}} = 99 \times 988(\mathrm{module}) = \mathbf{97,812}$ USD
- Charger Controller Cost $= 890$ USD $\times$ No. of Charger Controller

  $= 890 \times 44 = \mathbf{39{,}160}$ USD
- Battery Cost= 1130 USD $\times$ No. of Batteries

  $= 1130 \times 125 = \mathbf{141,250}$ USD
- Capital Cost= $\mathbf{410,679}$ USD

Supplement Cost $= 20\%$ of Capital Costs $= 20\% \times 410{,}679 = \mathbf{82,135.8}$ 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 $= 0.3\% \times 492{,}814.8 = \mathbf{1478.44}$ USD
- Water Supply Cost $= 0.0014\,\frac{\mathrm{USD}}{\mathrm{Liter}}$

  $= 0.0014 * 284230 = \mathbf{397.922}$ USD
- Maintenance Cost $= 2\%$ of total capital cost

  $= 2\% \times 492{,}814.8 = \mathbf{9856.296}$ USD
- Other Costs= 1% of total capital cost $= 1\% \times 492{,}814.8 = \mathbf{4928.148}$ USD
- Total Operating Cost $= 1478.4444 + 397.922 + 9856.296 + 4928.148$

  $= \mathbf{16,660.8104}$ USD
- Annual Grid Revenue = Electricity price USD per KWh $\times$ Energy used kWh

  $= 0.172 \times 961026.392681852 = \mathbf{165,296.5395}$ 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)

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

$$\textbf{Unit } \mathbf{H_2} \textbf{ Producation Cost } \left(\frac{\mathbf{USD}}{\mathbf{Kg_{H2}}}\right) = \frac{\text{Total Annual Cost (USD } y^{-1})}{\text{Annual } H_2 \text{ Produation rate } (Kg_{H2}\ y^{-1})} \qquad (13)$$

$$= \frac{344{,}179.0709}{13630.6} = 25.2504\,\frac{USD}{Kg_{H2}} = 25.2504 \div 14.128 = \mathbf{1.787}\,\frac{\mathrm{USD}}{\mathrm{Liter_{H2}}}$$

- <u>This is achieved by running the model for the minimum cost location of the 242</u>

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

$$= \frac{344{,}179.0709}{13630.6 * 25} = \mathbf{1.01}\ (\mathrm{USD/KWh}\ H_2\ \mathrm{HHV})$$

Integration with the model to analyze the Data.

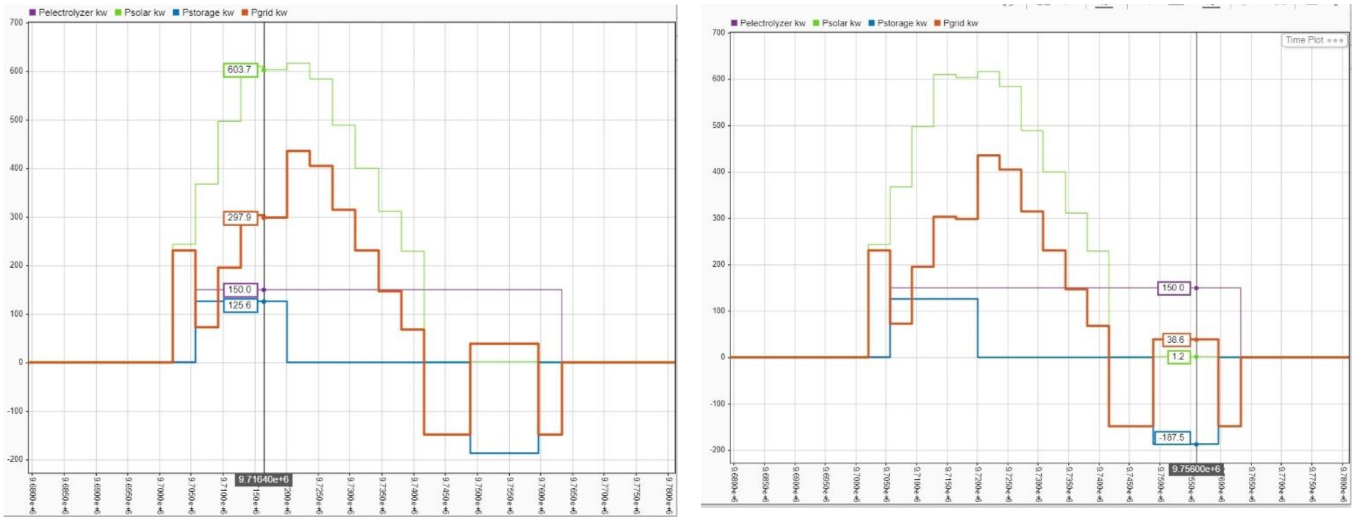


Figure 28: Data Inspection for one day

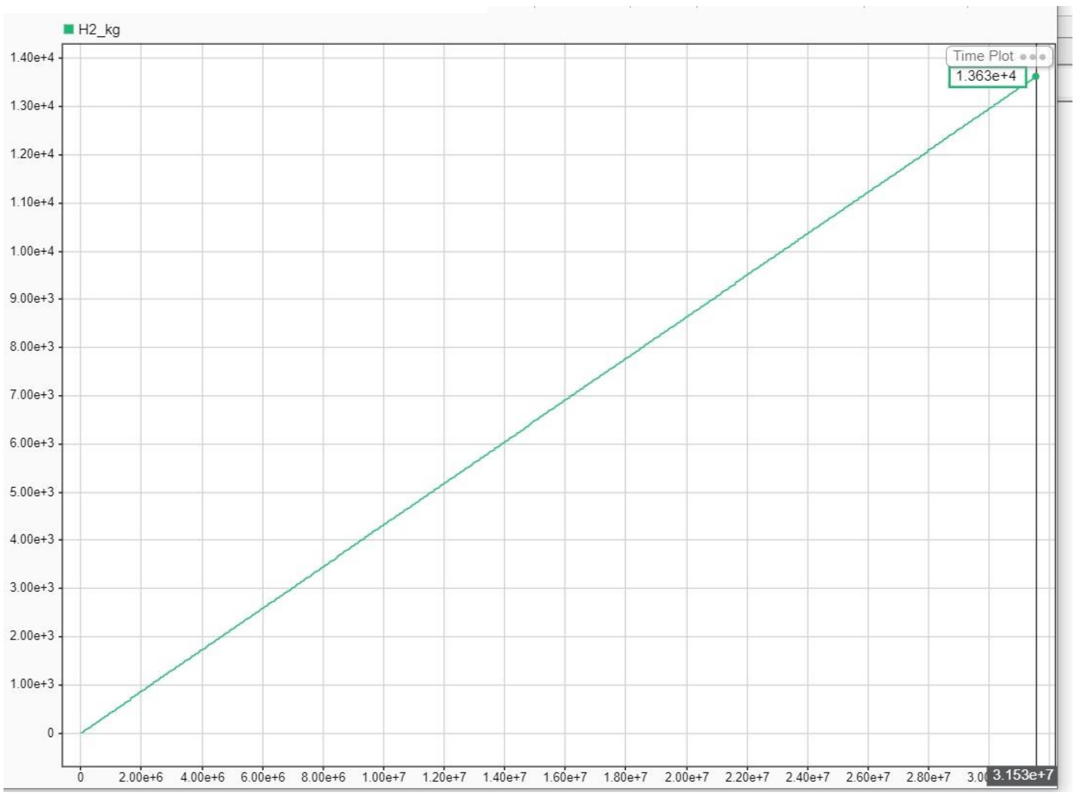


Figure 29: Hydrogen Production in one year

Note that this data is for **location Putre (Chile)** that has the best performance compared to the other locations and produces the hydrogen ith 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)

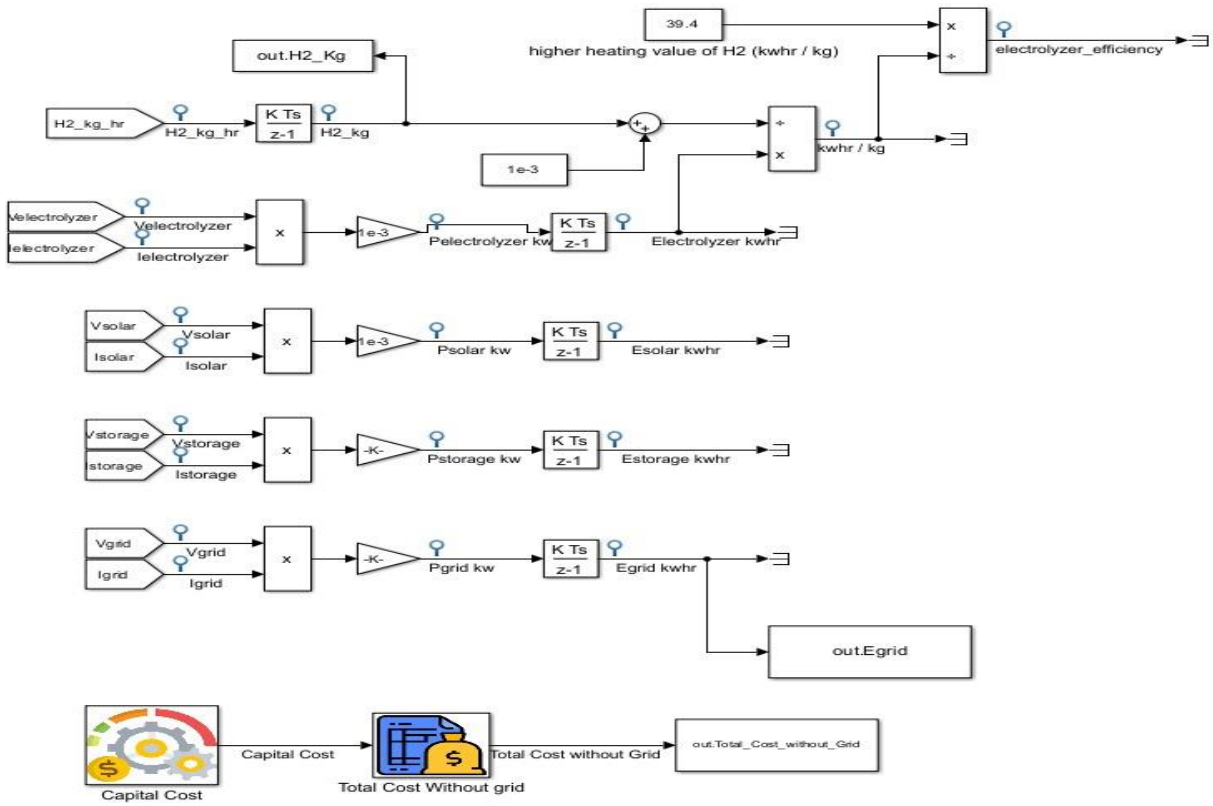


Figure 31: Measurement subsystem after adding economic signals

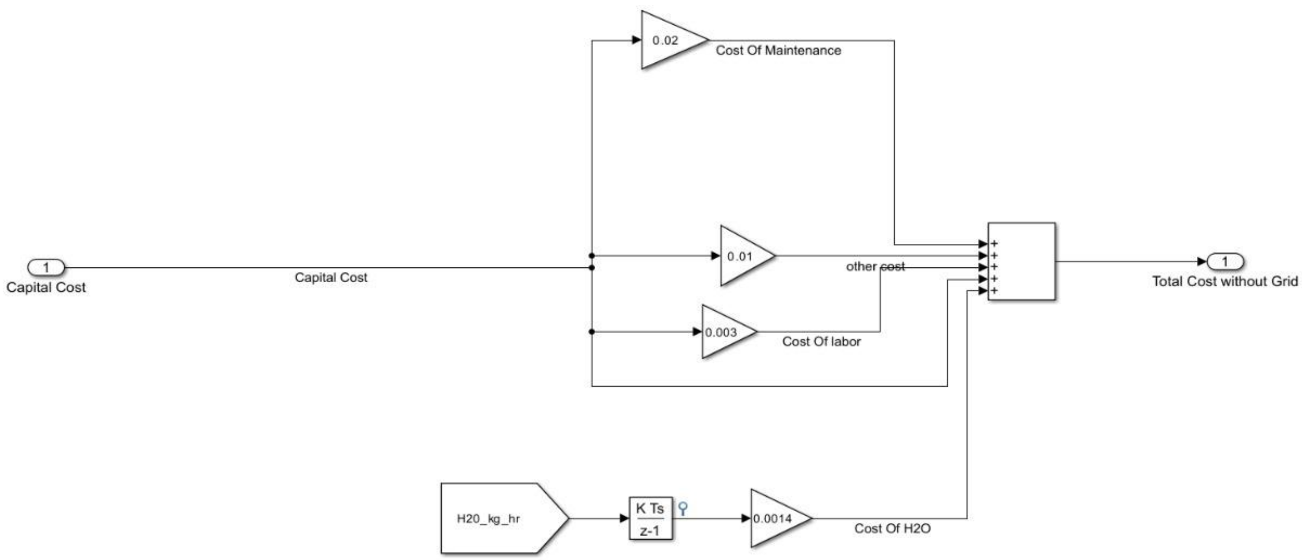


Figure 30: Total cost subsystem

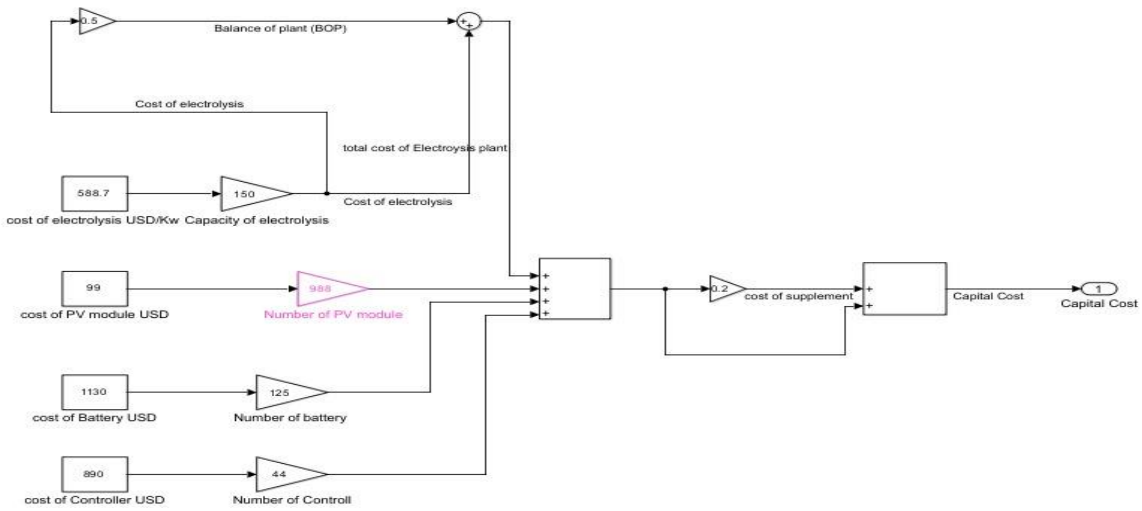


Figure 32: Capital Cost Subsystem

- 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:

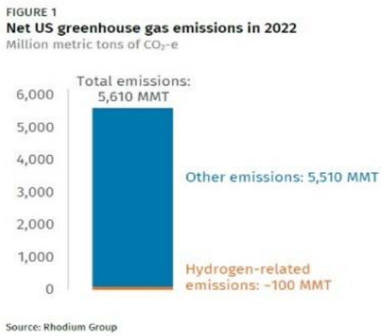


Figure 33: Environmental Impact of hydrogen (40)

- Reduction in greenhouse gases

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:

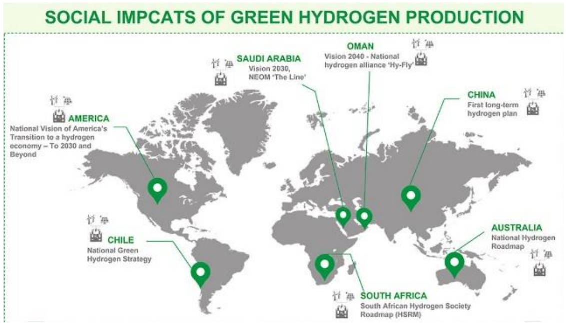


Figure 34: Social Impact of Hydrogen (41)

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.

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

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

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

$$Area = \frac{I\ (amp)}{Current\ density\ (\frac{amp}{cm2})}$$

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

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

$$Pohmic = I\text{^}2 * Rohmic * no.\ of\ cells$$

$$P\_Electrolysis = P\_total - 1.5 * P\_ohmic$$

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

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

PV system

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

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

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

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

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

$$N_{pvs} = \frac{V_{DC}}{V_{pv}}$$

- Batteries

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

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

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

Charge controller

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

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

Compound Annual Growth Rate

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

$EV = Ending\ Value$
$BV = Beginning\ Value$

$n = Number\ of\ years$

Cost

AWE Cost = AWE capacity×588.7 USD/kW

BOP Cost=50% of AWE capital cost

PVCost=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

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