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Theme

Techno-economic estimation of hydrogen production from renewable sources in Ouargla Region – Algeria

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الإهداء

بسم الله الرحمن الرحيم

الحمد لله تعظيما وإجلالا ما أقبل اليسر بعد العسر إقبالا وما أتت نفحات اليسر ناسخة من المتاعب والمكاره ألوانا و أشكالا

ونصلي ونسلم على خير الخلق وخلاصة الأنبياء سيدنا ومولانا محمد وعلى أله وصحبه وسلم تسليما

الى جنتي أمي أهديك نجاحي وتخرجي فما كان ليتحقق لولا توفيق الله ثم رفعت كفيك بعد الصلاة

والى قدوتي أبي رحمة الله عليه هأنا اليوم أمشي بمقولتك التي أوصيتني بها أنه

' إذا ذكرت لك الرجولة والمواقف والعلم فقل هأنا هنا وليس كان أبي '

الله يشهد أن الطريق لم تكن سهلة وانا لم أكن بذات الصبر كل مرة ولم تقف الظروف معي في طريقي ولكني أكملت المسير وصبرت ومشيت الطرق رغم صعوبتها و وعورتها لأني أثق بالله عز وجل وبقدرتي على ذلك

وأخر كلامي أن الحمدلله رب العالمين

Trabelsi Ayoub Abdelhai

الإهداء

بسم الله الرحمن الرحيم

أحمد الله تعالى حمدا كثيرا مباركا فيه و أشكره شكرا لا ينقطع على ما من به علي من فضل وتوفيق

وتيسير في إنجازه هاته المذكرة والصلاة والسلام على نبينا وحبيبنا محمد عليه أفضل الصلاة والسلام

لم تكن الرحلة قصيرة ولا سهلة فالحمد لله الذي يسر البدايات وبلغنا النهايات بفضله وكرمه

أهدي هاته المذكرة الى والدي وأخوتي وأخصصها الى والدتي التي لولا دعائها لما وصلت لمقامي هذا

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Greek Symbols

$\boldsymbol{I}$: Output current from the PV array(A).

$\boldsymbol{V}$:Voltage across the PV array(V).

$\boldsymbol{P}$: Electrical power output(W).

$\boldsymbol{I_{ph}}$:Photocurrent (A).

$\boldsymbol{I_s}$:Diode saturation current (A).

$\boldsymbol{I_{rs}}$:Reverse saturation current at reference temp (A).

$\boldsymbol{I_{sc}}$: Short-circuit current (A).

$\boldsymbol{V_{oc}}$: Open-circuit voltage (V).

$\boldsymbol{R_S}$: Series resistance (Ω).

$\boldsymbol{q}$: Electron charge (c).

$\boldsymbol{k}$: Boltzmann's constant (J/K).

$\boldsymbol{A}$: Diode ideality factor.

$\boldsymbol{E_g}$: Bandgap energy of the semiconductor (Ev).

$\boldsymbol{T_r}$: Operating temperature of the cell (actual)(K).

$\boldsymbol{T_0}$: Reference temperature (25°C 298.15K).

$\boldsymbol{T}$: Cell temperature (K).

$\boldsymbol{G}$: Solar irradiance (actual)(W/m^2).

$\boldsymbol{G_{ref}}$: Reference irradiance)(W/m^2).

$\boldsymbol{N_S}$: Number of cells in series.

$\boldsymbol{N_p}$: Number of cells in parallel.

$\boldsymbol{K_i}$: Temperature coefficient of Isc (A/K).

$\boldsymbol{U_{th}}$: Tension théorique

$\boldsymbol{U_{anode}}$: Surtension anodique (V)

$\boldsymbol{U_{cathode}}$: Surtension cathodique (V)

$\boldsymbol{U_{ohm}}$: Chute de tension dans la résistance interne d’électrolyseur

$\boldsymbol{P_{el}}$: Electrical power of electrolyser (W).

$\boldsymbol{\eta_{CONV}}$:Efficency of converter.

P_{pv}: Electrical power of solar panel (W).

m_{H_2}:Hydrogen mass (kg)

HHV_{H_2}:Higher heating value (kwh/kg)

$M_{H_{2,year}}$: Hydrogen mass in a year (kg)

V_{H_2}: Hydrogen volume (L)

$CAPEX$: Initial investment cost of the system.

C_{pv}: Investment cost of solar panels.

C_{conv}: Investment cost of converter

C_{el}: Investment cost of electrolyser

C_{Tn}: Investment cost of tank

Cap_{pv}: capital investment of Pv ($/KW).

Cap_{el}: capital investment of PEM Electrolyser ($/KW).

Cap_{conv}: capital investment of converter ($/KW)

Cap_{Tn}: capital investment of Tank($/Kg)

S_{Tn}: ***sizetank (Kg).***

$OPEX$: Cost of maintenance and exploitation.

Ma: Equipment maintenance cost.

Rep : Cost of replacing equipment .

£ : Maintenance cost of factor .

General Introduction

General Introduction:

The world today faces increasing environmental and economic challenges due to its heavy reliance on fossil energy sources such as natural gas, oil, and coal. This dependency threatens the long-term sustainability of human development and calls for urgent and radical transformations in how energy is produced and consumed globally. Among the most promising alternatives is green hydrogen, a clean fuel that emits no CO_2 when used and can be generated through water electrolysis powered by renewable energy sources, particularly solar energy. Algeria, and especially the Ouargla region, possesses one of the highest solar potentials in the world, making it a prime candidate for developing solar-powered hydrogen production systems.

In this context, this study explores the techno-economic feasibility of green hydrogen production using solar photovoltaic energy in the Saharan climate of Ouargla. The study aims to evaluate the performance, efficiency, and cost of a system composed of solar panels, converters, and an electrolyzer. To guide this research, the following key questions are raised: how does the quality of solar energy affect hydrogen production performance? What are the technical and economic factors influencing the selling price of hydrogen? And how do different climatic conditions impact system efficiency?

The main objectives of this work are to assess the technical viability of producing hydrogen from solar energy under desert conditions, to determine the production cost and analyze the economic return, and to compare the system’s performance across different high-solar-potential regions.

The content of the study is structured as follows

The first chapter presents a theoretical background on hydrogen, including its types, properties, production through electrolysis, storage, transportation, and applications, along with a comparison of economic and environmental aspects of different production methods.

The second chapter provides a techno-economic analysis of the hydrogen production system, including mathematical modeling to estimate output, efficiency, costs, and potential profitability.

The third chapter consists of a practical simulation conducted over one year, using real climatic data from Ouargla, Hassi R'Mel, and Tamanrasset to determine the most suitable region for implementation based on technical and economic performance.

This study contributes to a better understanding of the potential for solar-powered hydrogen production in Algeria and supports national efforts toward energy transition, sustainability, and low-carbon development.

Chapter I

Generalities on Green Hydrogen

I.1. Introduction:

Currently, 80% of the energy consumed by societies comes from fossil fuels (natural gas, oil, coal), while 20% is derived from renewable sources (biomass, nuclear, hydroelectric, and to a lesser extent, solar and wind energy). Unless there is a shift in energy production and consumption practices, the long-term development and sustainability of human societies will be at risk.[1]

In this chapter, we will explore green hydrogen and other types of hydrogen, as well as the different types of electrolyzers, hydrogen storage methods, and the logistics of transport and distribution.

I.2. Definition of Hydrogen:

Hydrogen, which means "water generator" (hydro = water, gene = generator), is the simplest and most abundant chemical element in the universe. It occupies the first place in Mendeleev's periodic table and consists of a single proton nucleus around which an electron gravitates. In the natural state, hydrogen does not exist in its pure form but is always bound to other elements such as water (H_2O) or hydrocarbons (for example, methane CH_4). The dihydrogen molecule (H_2) is formed by two atoms of hydrogen and is the form in which hydrogen is often used.[1]

I.3. Different Types of Hydrogen:

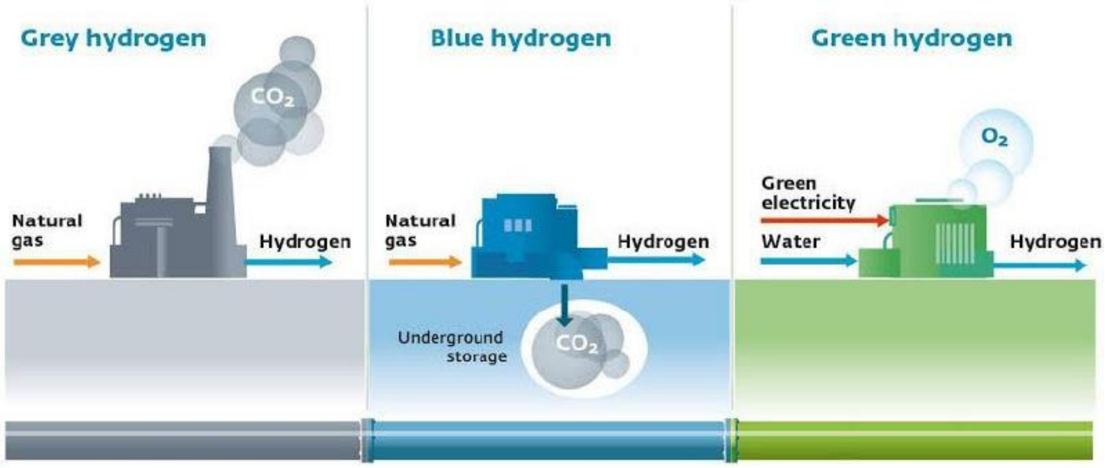


Figure I.1: Types of Hydrogen [2].

A- Grey hydrogen:

Grey hydrogen is produced from fossil fuels and generally uses the steam reforming method (SMR). During this process, CO2 is produced and ultimately released into the atmosphere. It accounts for about 95% of the hydrogen produced in the world today[2]. As shown in **Figure I.2**, this process relies on natural gas without capturing carbon emissions

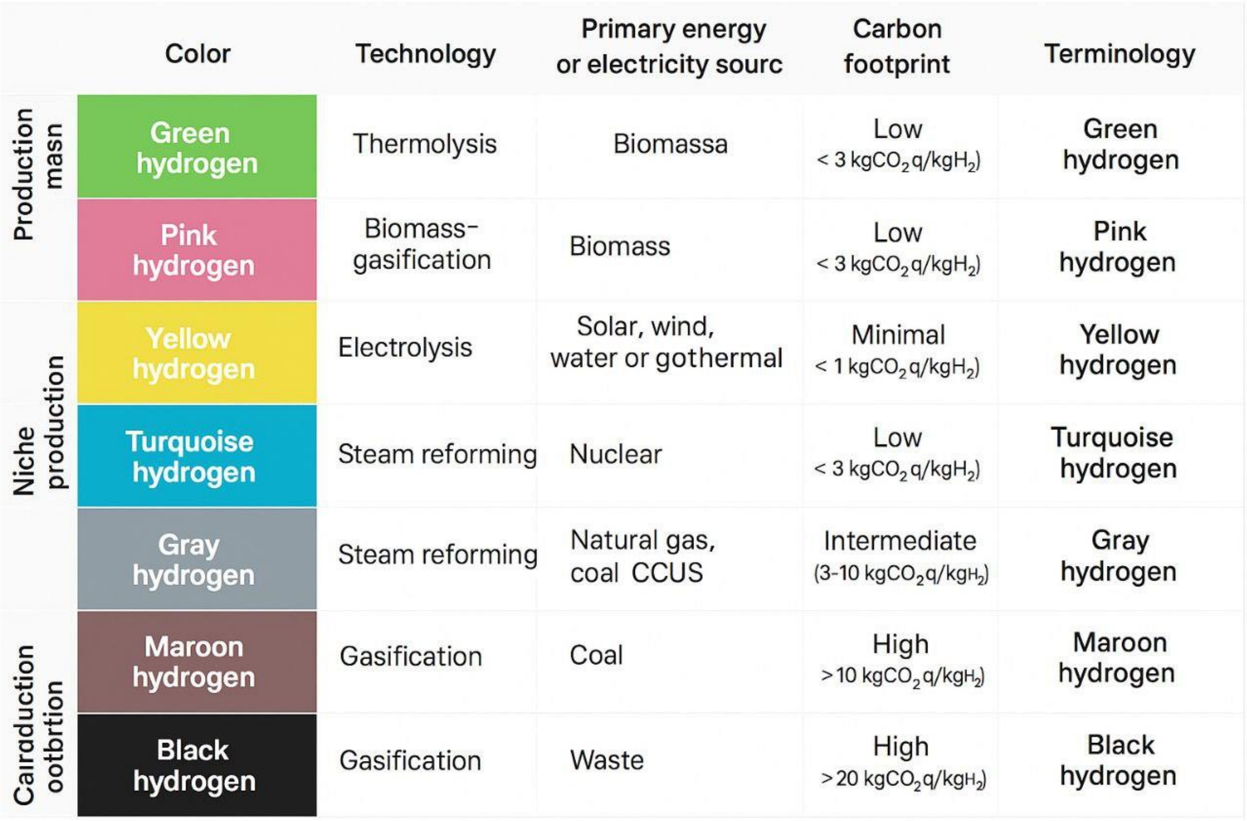
B- Blue hydrogen:

Blue hydrogen refers to hydrogen derived from natural gas, which is a fossil fuel. However, most (but not all) of the CO2 emitted during the process would be captured and stored underground (carbon sequestration) or linked to a solid product (such as bricks) and used. This is known as carbon capture, storage and use (CCSU).

As the CO2 emission is limited, the production process of blue hydrogen is considered low in carbon [2]. as illustrated in **Figure I.3*.***

C- Green hydrogen:

Green hydrogen is mainly produced by fractionating water using electricity from renewable energy sources. The reason it is called green is that there is no CO2 emission associated with hydrogen production and use[2]. **Figure I.4** demonstrates this process, which uses green electricity to split water into hydrogen and oxygen with no emissions.



	Color	Technology	Primary energy or electricity sourc	Carbon footprint	Terminology
Production masn	Green hydrogen	Thermolysis	Biomassa	Low $< 3\ kgCO_2q/kgH_2)$	Green hydrogen
	Pink hydrogen	Biomass-gasification	Biomass	Low $< 3\ kgCO_2q/kgH_2)$	Pink hydrogen
Niche production	Yellow hydrogen	Electrolysis	Solar, wind, water or gothermal	Minimal $< 1\ kgCO_2q/kgH_2)$	Yellow hydrogen
	Turquoise hydrogen	Steam reforming	Nuclear	Low $< 3\ kgCO_2q/kgH_2)$	Turquoise hydrogen
	Gray hydrogen	Steam reforming	Natural gas, coal CCUS	Intermediate $(3\text{-}10\ kgCO_2q/kgH_2)$	Gray hydrogen
Cairaduction otbrtion	Maroon hydrogen	Gasification	Coal	High $> 10\ kgCO_2q/kgH_2)$	Maroon hydrogen
	Black hydrogen	Gasification	Waste	High $> 20\ kgCO_2q/kgH_2)$	Black hydrogen

Figure I.2: Summary of hydrogen production pathways and colors[3].

I.4. Physicochemical proprieties of hydrogen :

First element in the periodic table. In the normal condition it is a colorless, odorless and tasteless gas, made up of diatomic molecules, H2. The hydrogen atom, symbol H, is made up of a nucleus with a positive charge unit and an electron. Its atomic number is 1 and its atomic weight is 1,00797. There are three hydrogen isotopes: protium, mass 1, found in more than 99.98% of the normal element; deuterium, mass 2, found in nature at approximately 2%, and tritium, mass 3, which appears in small quantities in nature. It can also be artificially produced by various nuclear reactions, in the table below we will discover physicochemical properties of hydrogen.[4]

Table I.1:property of Hydrogen [4].

property	numerical value
atomic number	1
atomic mass	1.0079 g/mol
solidification temperature	14 K
melting temperature	-259,14 °C
boiling temperature	-252,87 °C
mass density	0,00838 kg/m3
liquid density	70.79 kg/m3
Electronegativity	2.1
net calorific value (NCV)	120 MJ/kg
Gross Calorific Value (GCV)	142 MJ/kg
Heat specific Cp	14.3 kJ/kg K
Heat specific Cv	10,3 kJ/kg K
Ignition energy	0.020 mJ
Diffusion coefficient in air	0,61 cm/s
critical pressure	12.8 atm

I.5. Logistics Chain of Green Hydrogen:

Hydrogen can be produced without the production of greenhouse gases, which the clean energy supply chain allows following the following steps:

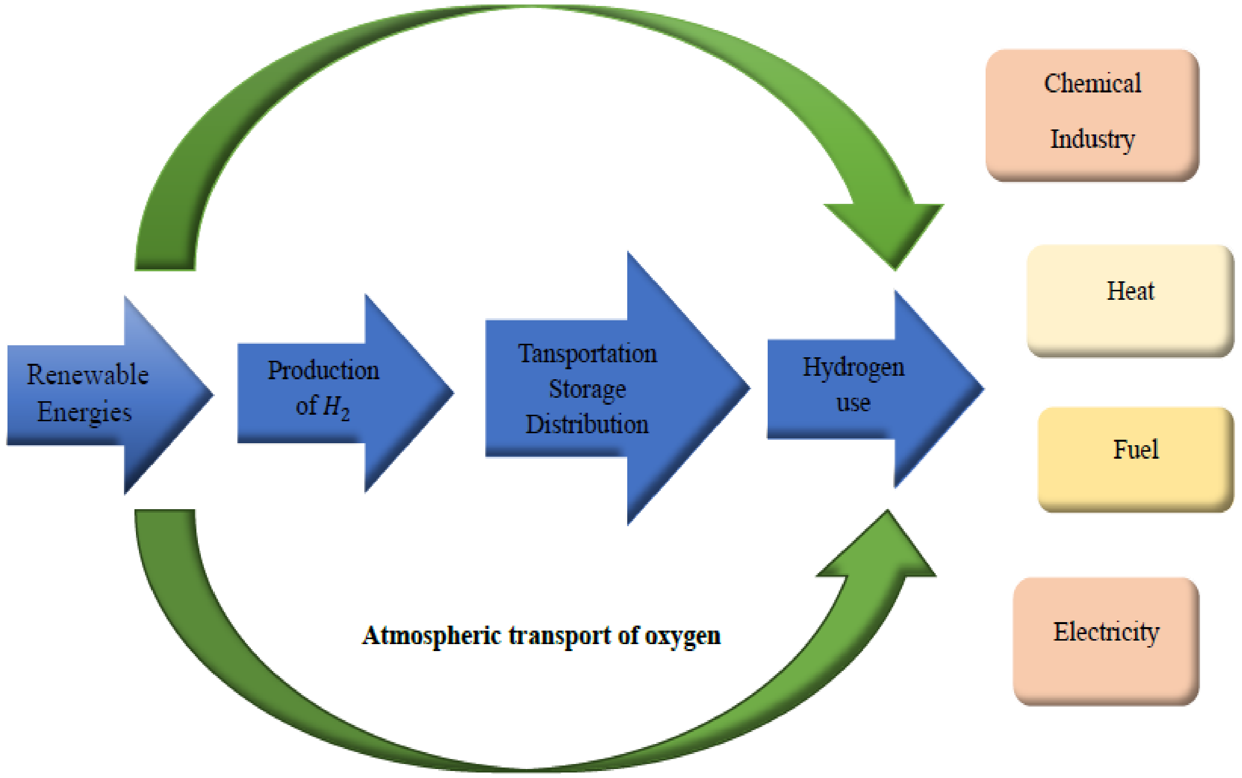


Figure I.3: Hydrogen cycle**.**

I.5.1. Renewable Energies :

An energy is called renewable when it is produced by a source that nature is built or reconstituted faster than human use. They can be considered inexhaustible in human time, they do not cause any direct pollution, they are not yet able to replace other energy sources and offers the potential to significantly reduce fossil fuel use. Renewable energy is very diverse[5]

I.5.1.1.Solar Energy :

The Sun is an almost inexhaustible energy source that sends radiation to the Earth's surface, which represents about 8,400 times annual energy consumption. This corresponds to an immediate capacity received of 1 kW peak per square meter (KWc/m^2) spread across the entire spectrum, from UV to IR. Solar energy is produced and used in several ways:

- **Thermal solar power :**It is simply heat production through dark panels. Steam can also be produced from the sun's heat and then converted into electricity.

- **Solar photovoltaic power:** which consists of producing electricity directly from light using solar panels. This form of energy is already being exploited in many countries, particularly in countries or regions without traditional energy resources such as hydrocarbons or coal[6]

.

I.5.1.2.Hydroelectric Energy :

Hydropower is currently the world's main source of renewable electricity. In 2023, hydropower installed capacity was about 1,360 GW, accounting for about 17% of the world's total electrical capacity. In Africa, hydropower accounts for about 12% of total electricity generated. The process of producing hydroelectric electricity depends on the exploitation of mechanical (motor and positional) energy for water.

The principle used to generate electricity from water power is similar to that used in old water mills. Instead of moving a wheel, the water force rotates a turbine, which in turn moves an electric generator (alternator) to produce electricity.[1]

I.5.1.3.Wind Energy :

Wind energy is part of renewable energies. Wind generator uses wind kinetic energy to drive the rotor shaft this is then converted into mechanical energy itself transformed into electrical energy by an electromagnetic generator paired with wind turbines.[1]

I.5.1.4.Geothermal Energy :

Geothermal energy is the energy generated by the heat found beneath the Earth's surface, which increases with depth at an average rate of 3°C per 100 meters. This energy is harnessed either for electricity generation or for heating purposes.It is classified into two main types based on temperature and depth:

Low-temperature geothermal energy: used for heating, extracted from medium depths with temperatures ranging from 30°C to 150°C.

High-temperature geothermal energy: used to generate electricity, extracted from deeper layers where temperatures exceed 150°C..[18]

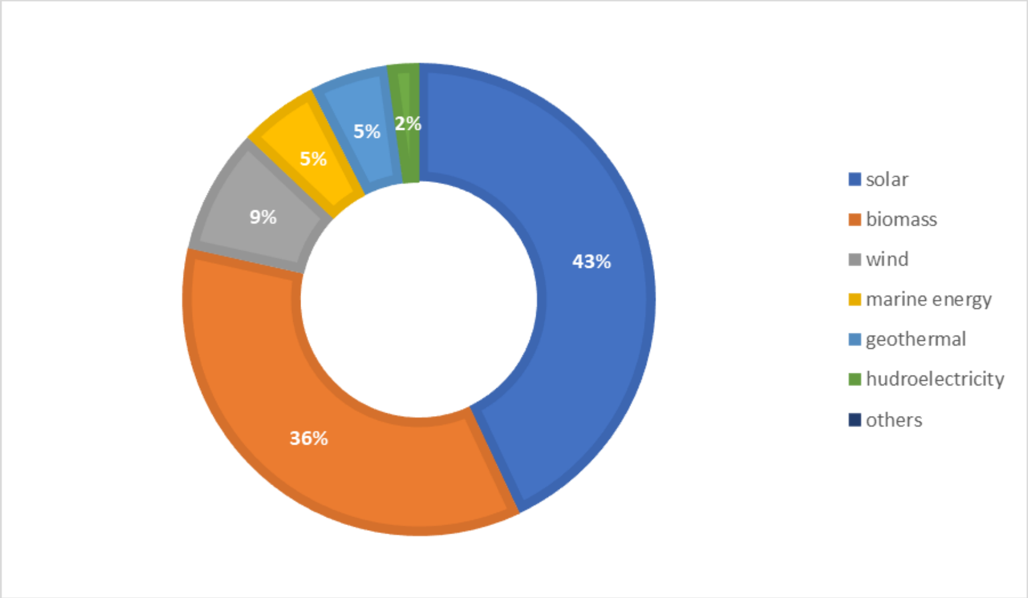


Figure I.4: Distribution of renewable energy sources by global production share[1].

I.5.2. Hydrogen Production via Water Electrolysis:

Electrolysis is currently the most effective technology to produce and store hydrogen with a low carbon footprint.

I.5.2.1. Definition of Electrolyzer :

An electrolyser consists in passing a electric current in the water to separate the molecules and form dihydrogen and oxygen.[7]

I.5.2.2. Operating Principle :

Water electrolysis is a process by which the water molecule will be dissociated for to produce the elements, hydrogen and oxygen, gaseous in ambient state.

The overall reaction is:

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (I.1)$$

This reaction is not spontaneous; it will be produced by applying a difference of potential (electrical voltage) between two electrodes.

The process occurring at the negative electrode, the cathode, is reduction. This is the process by which the molecule undergoes an electron(s) gain and divides into hydrogen (H_2), by producing a hydroxide anion

(OH^-) as follows:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad (I.2)$$

The process occurring at the positive electrode, the anode, is oxidation. This is the process by which the molecule undergoes a loss in electron(s). Each water molecule then divides into oxygen (O_2) and produces a hydrogen cation (H^+) by releasing electrons that move in the circuit to the cathode. The reaction is:

$$2H_2O \rightarrow O_2 + 4H^- + 4e^- \qquad (I.3)$$

The sum of the two reactions in the circuit gives the reaction the electrolysis of water; to balance the exchanged electrons, one must multiply the equation of the cathode reduction reaction by 2. Ions and is combine to form water molecules. After addition and simplification[7] we get:

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (I.4)$$

I.5.2.3. Types of Electrolyzers :

- **Alkaline electrolysers:**

The alkaline electrolyser is the most mature and commonly used electrolyser technology, especially at large scale.

An alkali solution which normally is 20% - 40% potassium hydroxide (KOH), is used as electrolyte to raise the ionic conductivity in the cell stack. Other electrolytes like sodium hydroxide (NaOH), sodium chloride (NaCl) have also been used . The use of liquid and corrosive alkali solution is one of the major drawbacks of alkaline electrolyser.

In alkaline electrolyser. , the poles are separated by a membrane.where Previously, asbestos was used as diaphragm with a thickness in the range of 3mm . The operation temperature of the electrolyser is hence limited to 80◦C due to the use the asbestos. The water is reduced at cathode to generate hydrogen and hydroxide. The hydroxide will be circulated through the diaphragm to the anode and recombined to generate oxygen[8]. The reaction is expressed in equation :

$$Anode{:}\ \ 2OH^- \rightarrow {}^1\!/_2\, O_2 + H_2O + 2e^- \qquad (I.5)$$

$$Cathode{:}\ 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad (I.6)$$

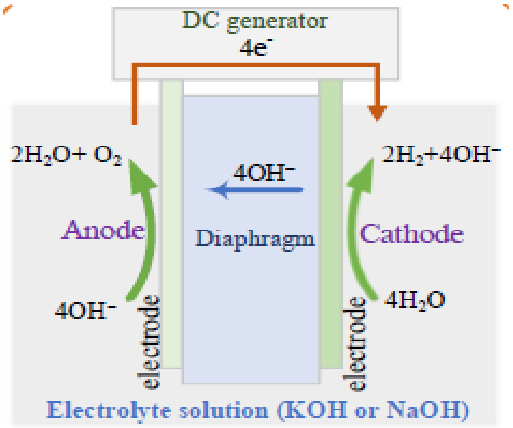


Figure I.5: Alkaline electrolysers [9].

- **PEM electrolyser:**

The main characteristic of this type of electrolyser is its solid electrolyte, consisting of of a polymer membrane. This ensures the conduction of hydronium ions produced at the anode and allows separation of hydrogen and oxygen produced.

The advantages of this technology are compactness, simplicity of design of operation, limiting corrosion problems, and performance substantially. The electrolyte is not liquid, so they can be used to a higher current density than the alkaline type (1 to 2 A)[7].

In PEM electrolyzers, at the anode, water is oxidized to produce oxygen, electrons, and protons. The protons travel through the proton exchange membrane to the cathode side, while the electrons reach the cathode via an external circuit. At the cathode, protons are reduced to generate hydrogen gas[8]. The following reactions occur in a PEM electrolyzer:

$$Anode:\ H_2O \rightarrow {}^{1}\!/_{2}\, O_2 + 2H^+ + 2e^- \tag{I.7}$$

$$Cathode:\ 2H^+ + 2e^- \rightarrow H_2 \tag{I.8}$$

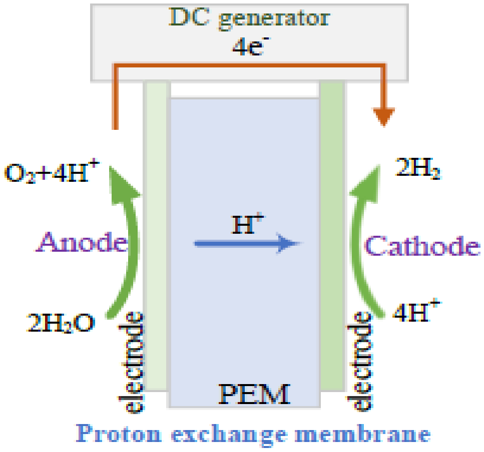


Figure I.6:PEM electrolyser [9].

- **Solid oxide electrolyser:**

The above two electrolyser technologies are all operated under low temperature (less than 100∘*C*), wheres SOE operates at high temperature (up to 1000∘*C*). This results in high efficiency compared with alkaline and PEM technology.At the cathode side, water, or rather steam is reduced to produce hydrogen. The generated oxide anions will pass through the solid electrolyte to the anode where they form oxygen [8]. The following reactions take place in a SOE:

$$Anode:\ O^{2-} \rightarrow {}^{1}/_{2}\, O_2 + 2e^- \tag{I.9}$$

$$Cathode:\ 2H_2O + 2e^- \rightarrow H_2 + O^{2-} \tag{I.10}$$

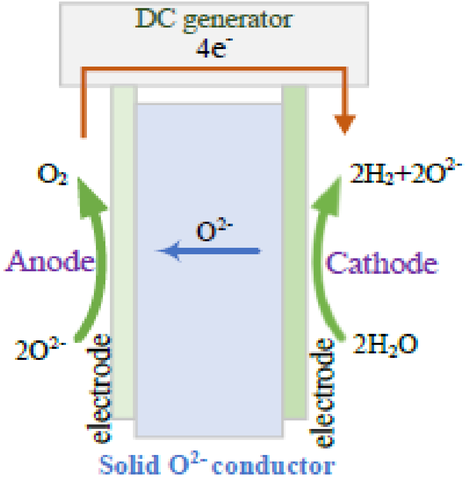


Figure I.7: Solid oxide electrolyser [9].

- **Comparison of electrolyser types:**

Table I 2*:*Comparison of electrolyser types[8].

Specification	Alkaline	PEM	SOE
Technology maturity	State of the art	Demonstration	R&D
Cell temperature (◦c)	60-80	50-80	900-1000
Cell pressure (bar)	< 30	< 30	< 30
Current density (A/$\boldsymbol{Cm^2}$)	0.2-0.4	0.6-2.0	0.3-1.0
Cell voltage (V)	1.8-2.4	1.8-2.2	0.95-1.3
Efficiency (%)	62-82	67-82	81-86
System lifetime (year)	20-30	10-20	--
Cold start up time (min)	15	< 15	> 60

I.5.3. Hydrogen Storage :

Hydrogen is an ultralight gas that occupies a substantial volume under standard pressure conditions, that is to say atmospheric pressure. A litre of this gas weighs only 90 mg under normal atmospheric pressure, which means it is 11 times lighter than the air we breathe. In order to store and transport hydrogen efficiently, this volume must be significantly reduced.[6]

where Hydrogen storage is an important component in hydrogen economy, and one of the most urgent and challenging applications is to develop safe, reliable, efficient and effective storage mechanisms. In its natural form, hydrogen has a high gravimetric energy density while the volumetric energy density is low. It is known that under ambient temperature and pressure, 5kg of H2 would fill a ball of 5m in diameter which is similar to an inflated hot-air balloon in volume[8].

There are three typical approaches to store hydrogen:

- Physical storage as compressed gas
- Physical storage as cryogenic liquid hydrogen
- Materials-based storage or solid state storage

A. High-Pressure Gas Storage :

Current developments in hydrogen storage are focused on designing reservoirs capable of withstanding high pressures of up to 700 bars. Because hydrogen is the smallest element in the universe, preventing its leakage requires the use of advanced and specialized materials. One of the basic ways to reduce the volume of gas, while maintaining a constant temperature, is to increase its pressure.[10]

For example, at 700 bar.Hydrogen density reaches 42 kg/m3, compared to 0.090 kg/m3 under normal conditions of pressure and temperature. At this high pressure, 5kg of hydrogen can be stored in a 125L tank.[6]

B. Low-Temperature Liquid Hydrogen Storage:

Sophisticated technology for storing a large amount of hydrogen in limited size is to convert gas hydrogen into liquid hydrogen by cooling it to a very low temperature. Hydrogen turns into liquid state when cooled below -252.87 ° C. At this degree and 1.013 bar pressure, the liquid hydrogen density is about 71 kg/m3. At this pressure, 5kg of hydrogen can be stored in a 75 litre tank.[6]

To maintain hydrogen in liquid condition at this low grade, tanks must be perfectly insulated. However, using liquid hydrogen as a method of storage is very expensive, making its application impractical for individuals right now. In addition, about 3 to 4% of hydrogen is lost due to evaporation daily.[10]

C. Hydrogen Storage in Hydrides:

When hydrogen reacts with certain metals or alloys, it can combine with them to form compounds called metal hydrides. During this process, hydrogen molecules are separated and hydrogen atoms are inserted into spaces within lattice of the metal or alloy. This creates efficient storage comparable to the density of liquid hydrogen. However, when the mass of metal or alloy is taken into account, the gravimetric storage density of metal hydride would then become comparable to the storage of hydrogen under pressure. The best achievable gravimetric storage density is about 0.07 kg H_2/kg metal,

for a high temperature hydride such as MgH_2. During the storage process (charge or absorption), heat is released, which must be removed in order to achieve reaction continuity. During the hydrogen release process (discharge or desorption), heat must be supplied to the storage tank. .[5]

I.5.4. Transport and Distribution :

Hydrogen is transported between the production centre and the place of use and distributed in different ways depending on the desired duration of such transport, the hydrogen mass concerned, the geography of the places studied and the technical and economic factors.[5]

A. Pipeline Transport :

This type of transport can provide hydrogen through a distribution network with pipes connected to several consumers, both for hydrogen in its liquid and gas state. However, the gas hydrogen pipe system requires less investment compared to liquid hydrogen pipe systems.[11]

B. Maritime Transport :

The fact that liquid hydrogen is dense and that the refrigerated reservoirs it contains may have very large capacities naturally indicates transport by sea from places with high production capacity to those with high consumption. It is possible to contain liquid hydrogen in large spherical cooling tanks in double wall 3000 cubic meters.[10]

C. Road Transport :

Hydrogen transport shall be by road or rail, either in the form of Steel cylinders containing hydrogen under pressure, either in coolant form. Storage and distribution of compressed hydrogen has been standard practice for many years with cylindrical cylinders or assemblies, made of steel, swollen to 20 or 25 megapascals (200 or 250 bar). The defects of this storage method are only 14 kg/m3 at 20 Mpa and normal temperature (21 ° C). Hence the development of a new storage technology based on developments in composite reservoirs that can store hydrogen up to 700 bars.[5]

I.6. Applications of Hydrogen :

Hydrogen is versatile and can be utilized in various ways. These multiple uses can be grouped into two large categories:

- **Hydrogen as a feedstock:**

  hydrogen is used in several industrial processes. Among other applications, it is important to point its use as raw material in the chemical industry, and also as a reductor agent in the metallurgic industry. Hydrogen is a fundamental building block for the manufacture of ammonia, and hence fertilizers, and of methanol, used in the manufacture of many polymers. Refineries, where hydrogen is used for the processing of intermediate oil products, are another area of use. Thus, about 55 % of the hydrogen produced around the world is used for ammonia synthesis, 25% in refineries and about 10 % for methanol production. The other applications worldwide account for only about 10 % of global hydrogen production. [12]

- **Hydrogen as an energy vector enabling the energy transition:**

Hydrogen is emerging as a key energy vector enabling the energy transition. Its use in this context has already begun and is gradually increasing. In the coming years, this field is expected to grow dramatically. The versatility of hydrogen and its wide range of applications make it a strong candidate for decarbonizing existing economies. .[12]

The role of hydrogen in the decarbonization process is summarized in the graph below:

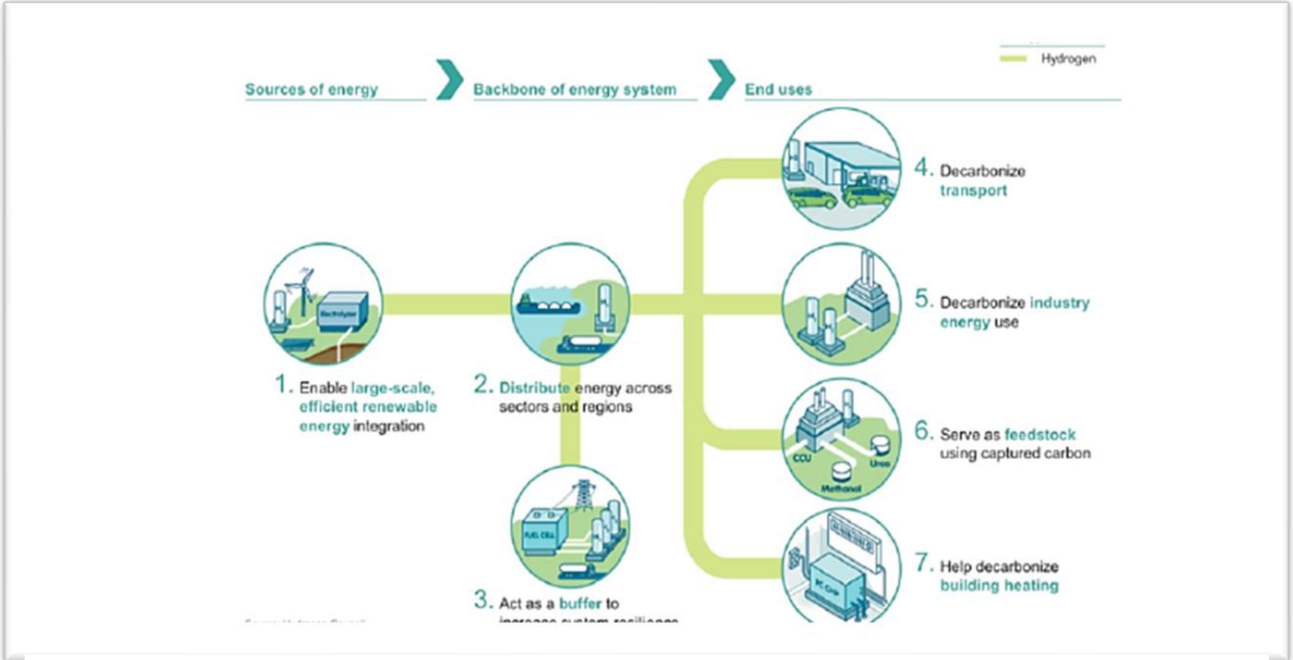


Figure I.8: The seven roles of hydrogen in decarbonizing major sectors of the economy[12].

- **Hydrogen Energy Storage:**

Hydrogen energy storage is one of the most popular chemical energy storage . Hydrogen is storable, transportable, highly versatile, efficient, and clean energy carrier . It also has a high energy density. As shown in Fig. 15, for energy storage application, off peak electricity is used to electrolyse water to produce hydrogen. The hydrogen can be stored either as compressed gas, liquefied gas, metal hydrides or carbon nanostructures . The choice of the storage technology depends on the characteristics of available technologies in terms of technical, economical or environmental performance . During the discharge phase, the stored hydrogen is either used in fuel cell or burnt directly to produce electricity. One major drawback in using hydrogen for electricity storage is the substantial energy losses during a single cycle . For example, electrolysis currently have an efficiency of 60%, transport and compression for storage may lead to another 10% efficiency loss (although this can be lower) while reconversion to electricity has a efficiency of about 50% for fuel cell application (higher efficiency is anticipated for combustion based power generation if cogeneration of heat is integrated). Thus, the overall round trip efficiency may be in the neighbourhood of 30%. This is partially compensated by the high storagedensity.[22]

I.7.Comparaision between different hydrogen production methods:

➢ The economic comparaision:

Depending on the hydrogen production method and kind of energy used final hydrogen costs could be very different. The costs of the grey hydrogen are the lowest, mostly between 0.8 and 2.1 € per kg of hydrogen. The blue hydrogen could be significantly higher in comparison to grey hydrogen due to additional costs for carbon capture and storage. However, currently the highest hydrogen costs are in the case that hydrogen is produced in an electrolyzer using electricity from RES,. The cost range of green hydrogen is mostly between 2.2 and 8.2 € per kg of hydrogen [13].

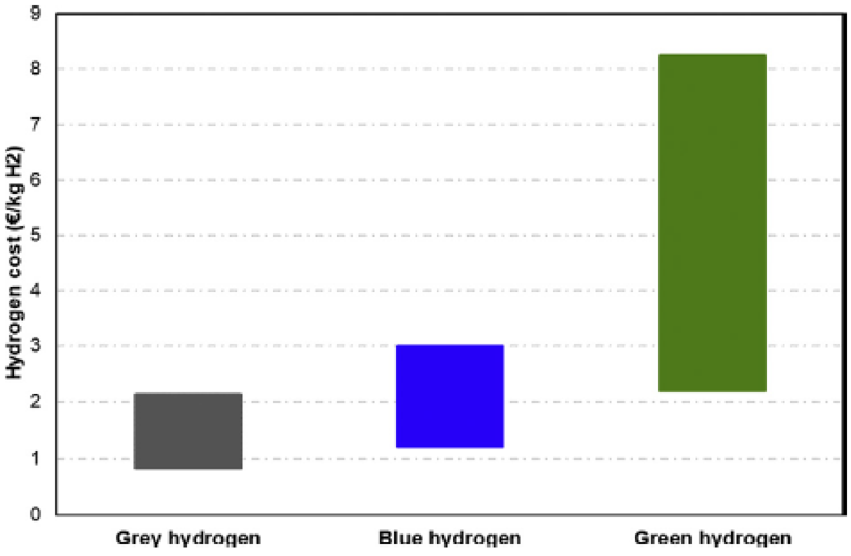


Figure I.9: Reported cost of hydrogen production for different production pathways [13].

- **The enviromental comparaision :**

As shown in Fig. 12, only hydrogen produced using renewable electricity sources—such as hydro, wind, and photovoltaic (PV)—exhibits very low greenhouse gas emissions and therefore offers a positive ecological performance. When fugitive methane emissions are also included in the calculation, the greenhouse gas emissions associated with grey and even blue hydrogen become significantly higher. According to the IEA , upstream methane emissions can contribute up to 5.2 kg CO_2-equivalent per kg of hydrogen in grey or blue hydrogen production processes[13].

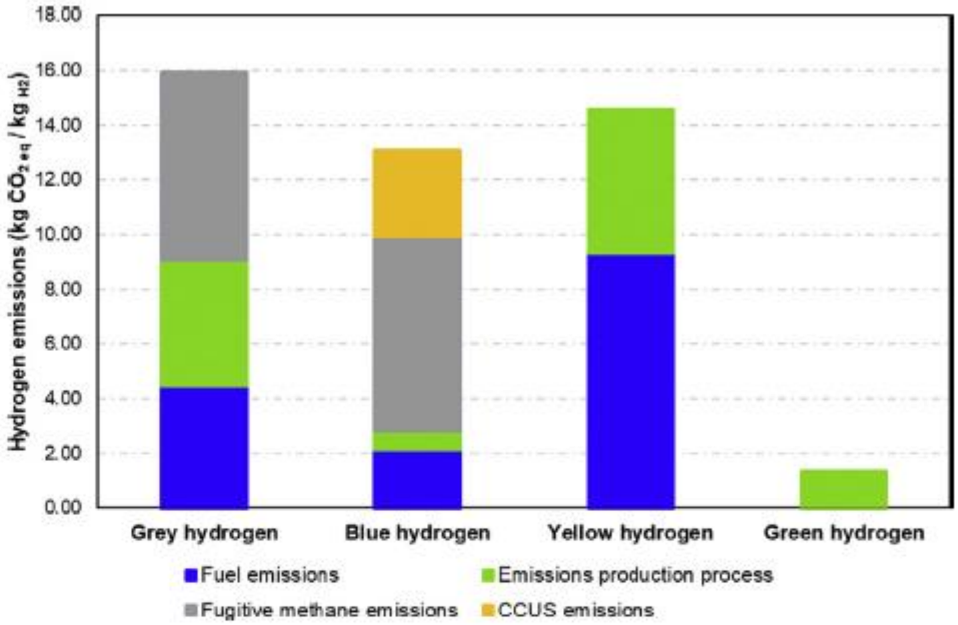


Figure I.10: Hydrogen emissions for various production methods [13].

I.8. Conclusion:

In this chapter, we explored the fundamental concepts related to hydrogen, with a particular focus on green hydrogen. We defined hydrogen, discussed its various types, and outlined its physicochemical properties. The chapter then detailed the green hydrogen logistics chain, including renewable energy sources, electrolysis technologies, storage methods, and transport systems. Finally, an economic and environmental comparison of production methods was presented, showing the potential of green hydrogen as a clean and sustainable energy vector. This chapter lays the essential theoretical groundwork for the technical and experimental aspects developed in the following sections.

ChapterII

techno-economic study of hydrogen production in the Ouargla region

II.1.Introduction:

This chapter focuses on the technical and economic assessment of hydrogen production from solar energy, through the study of the performance of the system's components and analysis of its feasibility. Mathematical relations and equations were used to calculate the amount of hydrogen produced, the power capacity of the solar panels, and the efficiency of both the converter and the electrolyzer. In addition, estimation relations were adopted to determine the investment cost of the system, with the aim of evaluating it from both technical and economic perspectives.

II.2.Previous studies:

In this section, we present the previous research work closest to our case study:

- **Djanila Ghribi 2012**

This study analyzes the performance of a hydrogen production system powered by solar energy, using a 60 W photovoltaic panel and a 50 W PEM electrolyser. Hydrogen production was evaluated at seven different locations in Algeria based on solar radiation and temperature data. The results showed that southern regions such as Tamanrasset and Adrar have the highest annual hydrogen production (up to 29 m³/year), due to higher solar irradiance and the availability of underground water, making them promising areas for green hydrogen production[14].

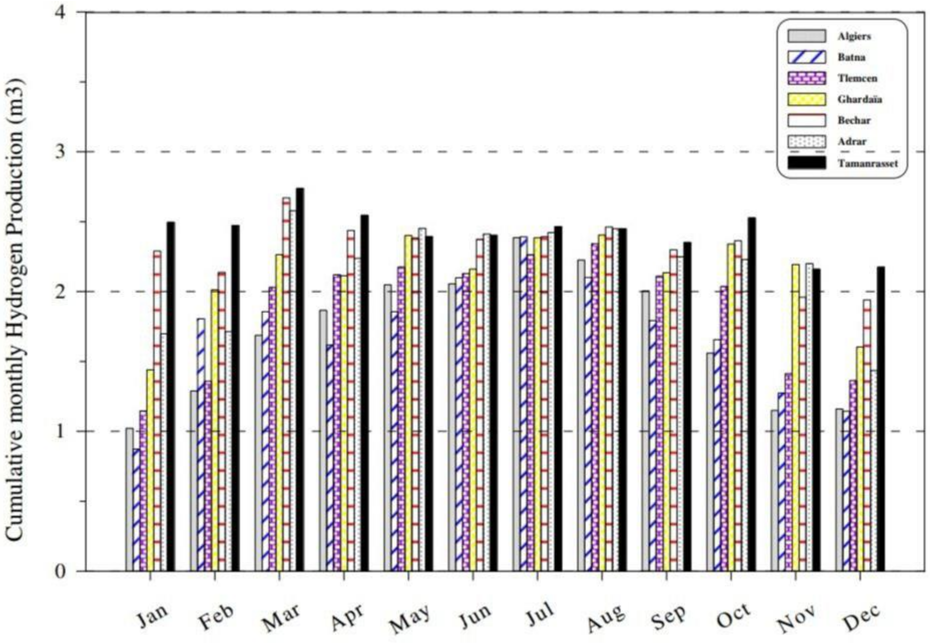


Figure II.1: Cumulative monthly Hydrogen production for different states [14].

- **Mohammed Douak et all 2015**

In this study, researchers proposed the production of hydrogen from wind energy in some locations in Algeria (Adrar, hassi-R'mel, Tindouf) through analysis of water electrolyte as an alternative solution to greenhouse gases since it is storable, transported and environmentally acceptable and the aim is to achieve a technology platform that allows the assessment of emerging techniques for the production of hydrogen from the wind.

Using four wind power conversion systems of 600, 1250, 1500 and 2,000 kW by De winf D6 and D7 machines, the data obtained from the production sites were analyzed using weibull protection distribution function.

Hydrogen was obtained in the amount of 76.12 tons/year in Adrar by De wind D6, 95.12 and 84.48 tons/year in the hassi-R'mel and Tindouf on a succession by De wind D7.

The results show that the electrical cost has a strong impact, followed by the influence of electrical analyzer expenditures and investment[15].

- **Rahmouni et all 2016**

This study suggested an assessment of the potential of hydrogen production from renewable resources (solar photovoltaic and wind) in Algeria. To this end, they analyzed statistically and graphically renewable resources data using the Geographic Information System (GIS).

There were two locations with high wind power potential: submarine (hassi-R'mel) and Idrar with production values of 1077 .88 and 915.09 GWh/km2/year on succession, as well as producing hydrogen at a rate of 18447 .6 and 15705.3 tons/km2/year on succession.

For solar energy, it has an annual value of 368.7 and 258.5 GWh/km2 in Tamanrast and Tarf, respectively, offset by hydrogen production potential of 6327.19 and 4437.14 tons/km2 per year respectively.

The study concludes that Algeria's desert is ideal for large-scale solar or wind hydrogen production projects[16].

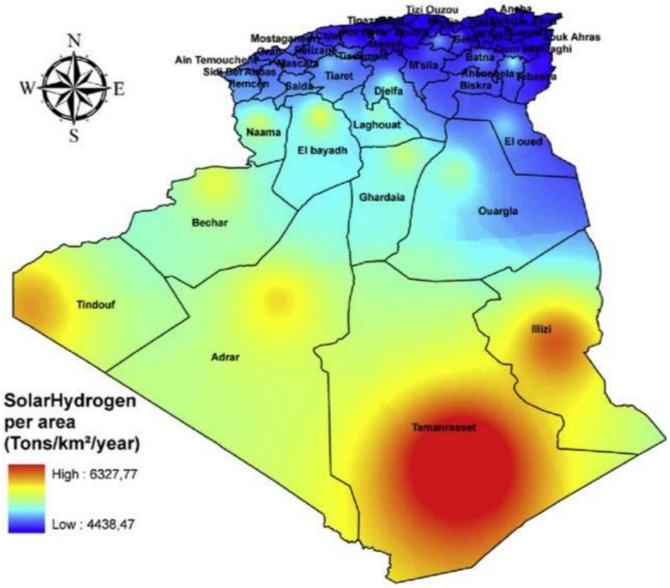


Figure II.2: Hydrogen potential from solar energy [16].

- **Gianpiro et al 2024**

This study demonstrates the feasibility of producing green hydrogen in the Province of Brindisi, Apulia, Italy, by relying on renewable energy sources, particularly wind and solar energy using photovoltaic technology. It analyzes climate data, the chosen technologies, land consumption, and the economic aspects of the project. The findings reveal that 200 MW wind farms offer the best economic performance, achieving the lowest hydrogen production cost of €191.2/MWh when accounting for CO_2 emission reductions. The study also highlights that expanding renewable energy projects requires solutions that minimize agricultural land use, such as utilizing rooftops, water surfaces, and infrastructure. The results conclude that transitioning to a green hydrogen-based economy is achievable, but it requires continued governmental and regulatory support, along with technological innovation to reduce costs and ensure environmental sustainability[17].

II.3. Description of Ouargla region:

Ouargla is located in southeastern Algeria and covers an area of 163,233 km². It has a population of approximately 626,798 people. It is bordered to the north by the wilayas of Touggourt and El Oued, to the east by Tunis, to the south by Tamanrasset and Illizi, and to the west by Ghardaia. Its annual solar radiation averages more than 6,100 watt-hours per square meter, making it one of the richest regions in Algeria in solar energy. The Algerian government selected it to host one of the most important pilot projects within the National Renewable Energy Development Program, a solar plant aiming to produce 100 megawatt-hours to reduce energy consumption in the residential sector.

For comparison purposes, the study included two additional regions: Hassi R'Mel and Tamanrasset. Hassi R'Mel is located in the northern Algerian Sahara within the province of Laghouat, at an altitude of approximately 772 meters above sea level. It is characterized by a dry desert climate and significant solar radiation. Tamanrasset is located in the far south of Algeria and is one of the highest regions in the country, exceeding 1,300 meters above sea level. It enjoys a relatively mild desert climate and strong solar radiation, making it theoretically eligible for solar energy projects despite its geographical distance and limited infrastructure compared to Ouargla. [19].

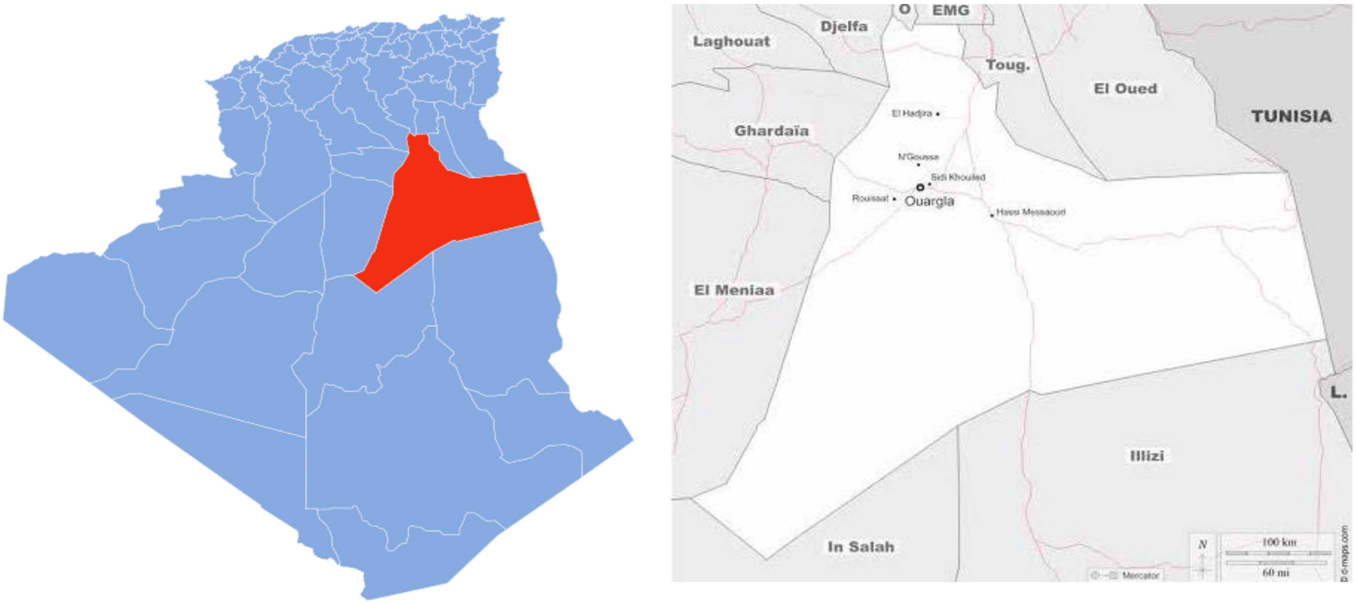


Figure II.3: Geographic data of Ouargla

II.4. System Modelling:

The sized system is considered to be a PV-EL-H2 tank (see Figure 1) of the city of Ouargla in southeast of Algeria. The region is known for its oil and gas industries in Algeria. In addition, it has great solar energy potential due to the high levels of solar radiation at this location, as the system consists of a single solar panel, a elctrolyzer PEM, a dc/dc converter and a hydrogen tank.

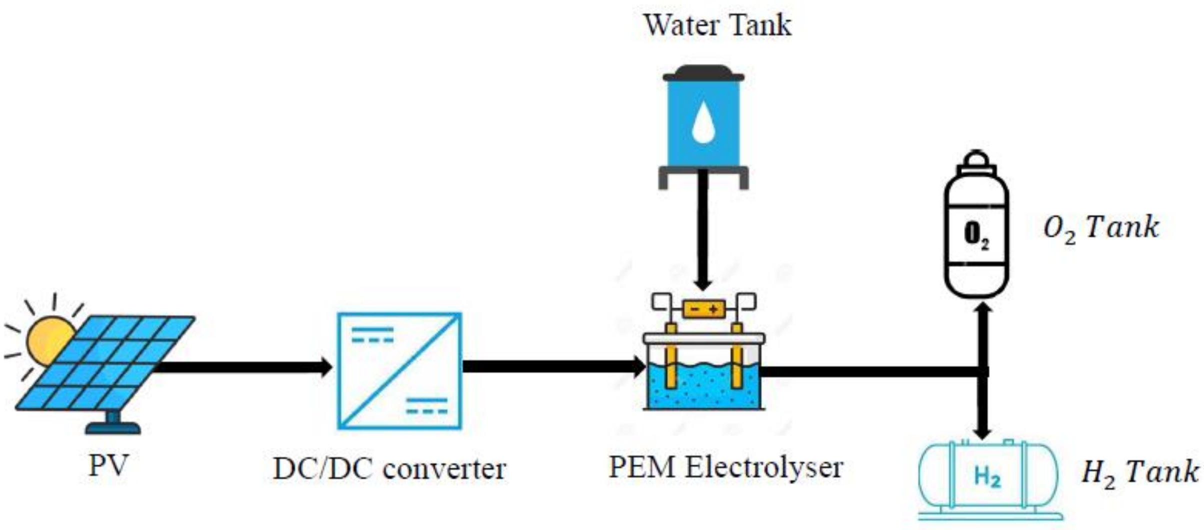


Figure II.4: Bloc diagram of hydrogen production system from PV module**.**

II.4.1.Modelling of PV module:

A photovoltaic module converts solar lighting directly into electricity, and its current and output voltage depend mainly on radiation and temperature.

A. Simulation models of the I-V characteristic:

We can represent our photovoltaic module by **Figure II.5*:***

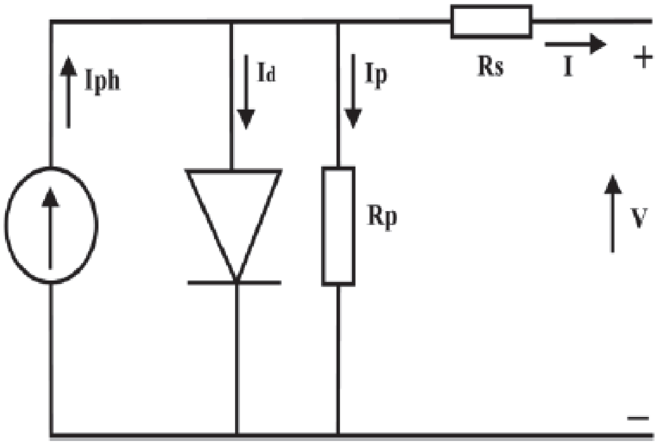


Figure II.6: Equivalent electrical diagram of a photovoltaic module [20].

According to the photovoltaic module circuit, the node law is applied to find the relationship between current and voltage[10]:

$$I = I_{ph} - I_D - I_{RSh} \tag{II.1}$$

$$I_D = I_s.[exp\left(\frac{q.V}{A.K.T_r}\right) - 1] \tag{II.2}$$

$$I_D = I_S\,.[\exp\left(\frac{q.(V+I.R_S)}{A.K.T_r}\right) - 1] \tag{II.3}$$

$$I_{RSh} = \frac{V+I.R_S}{R_{sh}} \tag{II.4}$$

$$I = I_{ph} - I_s.\left[\exp\left(\frac{q.(V+I.R_S)}{A.K.T_r}\right) - 1\right] - \frac{V+I.R_S}{R_{sh}} \tag{II.5}$$

For modules assumed to be leak-free (infinite R_{Sh} and $I_{Sh} \approx 0$) this relation is as a result

$$I = I_{ph} - I_s.\left[\exp\left(\frac{q.(V+I.R_S)}{A.K.T_r}\right) - 1\right] \tag{II.6}$$

$$I_{ph} = [I_{sc} + K_i.(T_r - T_0)].\frac{G}{G_{ref}} \tag{II.7}$$

$$I_s = I_{rs}.\left(\frac{T_r}{T_0}\right)^3.\exp\,[\left(\frac{q.E_g}{A.K}\right).\left(\frac{1}{T_0} - \frac{1}{T_r}\right)] \tag{II.8}$$

$$I_{rs} = \frac{I_{sc}}{\exp\left(\frac{q.V_{OC}}{N_S.K.A.T_0}\right) - 1} \tag{II.9}$$

$$I = N_p.I_{ph} - N_p.I_s.[\exp\left(\frac{q.(V+I.R_S}{N_S.K.A.T_r}\right) - 1] \tag{II.10}$$

B. The characteristic of Pv:

Table II 1:photovoltaic module characteristic.

P_{pv}(w)	485
V_{oc}(v)	46.22
I_{sc}(A)	9.06
V_m(v)	44.14
I_m(A)	8.72
N_s	72
N_p	1
K_i	5.258

II.4.2. Electrolyser model:

An electrolyser is a device that uses electrical energy to make chemical reactions. In our study, the electrolysers used perform water electrolysis to produce hydrogen.

PEM are made from pure polymer membranes or composite membranes where the materials form a polymer matrix. One of the most commonly used materials by proton exchange membrane builders is Nafion, Figure III.7 represents the structure of a PEM electrolyser[10].

In PEM electrolyzers, at the anode, water is oxidized to produce oxygen, electrons, and protons. The protons travel through the proton exchange membrane to the cathode side, while the electrons reach the cathode via an external circuit. At the cathode, protons are reduced to generate hydrogen gas[8].

The main inputs and outputs of an electrolyser are shown below:

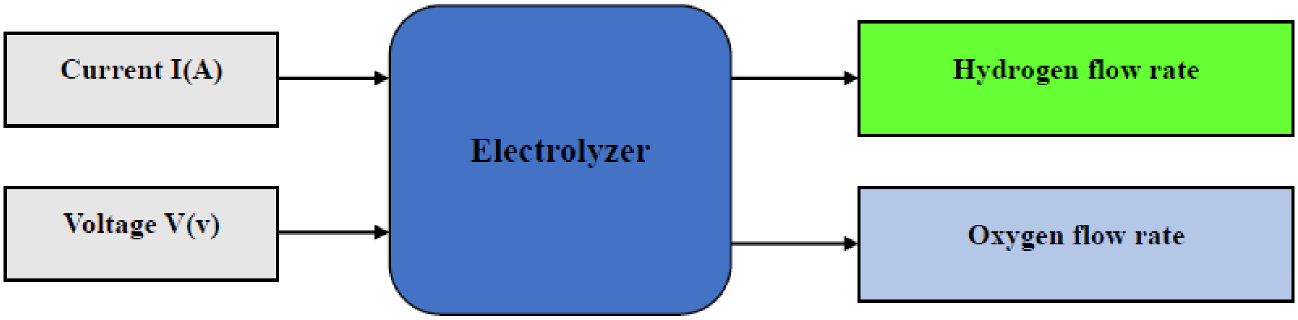


Figure II.7: Schema of electrolyzer inputs and gas outputs.

The following reactions occur in a PEM electrolyzer:

$$Anode:\ H_2O \rightarrow {}^1/_2\, O_2 + 2H^+ + 2e^- \tag{II.11}$$

$$Cathode:\ 2H^+ + 2e^- \rightarrow H_2 \tag{II.12}$$

II.4.2.1.The equivalent electrolyser scheme:

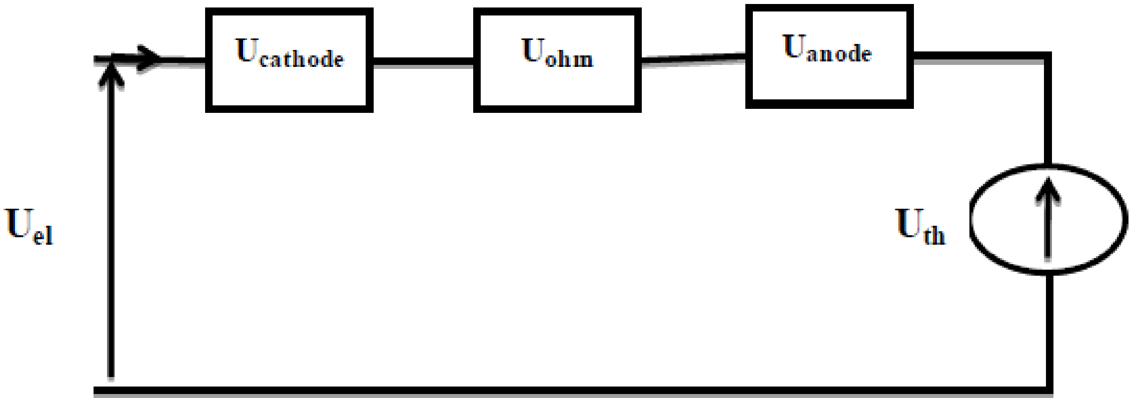


Figure II.8: Equivalent electrical diagram of the electrolyser [10].

$$\boldsymbol{U_{el} = U_{cathode} + U_{ohm} + U_{anode} + U_{th}} \tag{II.13}$$

$\boldsymbol{U_{th}}$: Tension théorique

$\boldsymbol{U_{anode}}$: Surtension anodique (V)

$\boldsymbol{U_{cathode}}$: Surtension cathodique (V)

$\boldsymbol{U_{ohm}}$: Chute de tension dans la résistance interne d'électrolyseur

C. The characteristic of electrolyser:

We used a PEM electrolyser.The following table represents the characteristics that we relied on in our study

Table II 2: Electrolyser characteristic**.**

P_{el}(W)	350
HHV_{H_2} (KWh/kg)	39.4
ρ_{H_2} (kg/m^3)	0.09
η_{el}	0.80

$$P_{el} = \eta_{CONV} . P_{pv} \tag{II.14}$$

$\boldsymbol{P_{el}}$: Electrical power of electrolyser (W).

$\boldsymbol{\eta_{CONV}}$:Efficency of converter.

$\boldsymbol{P_{pv}}$: Electrical power of solar panel (W).

Hydrogen mass produced :

First, we calculate the amount of hydrogen produced in one hour

$$m_{H_2} = \frac{\eta_{el}.P_{el}.1}{(HHV_{H_2}.1000)} \quad \text{(II.15)}$$

$\boldsymbol{m_{H_2}}$:Hydrogen mass (kg)

$\boldsymbol{HHV_{H_2}}$:Higher heating value (kwh/kg)

The annual hydrogen mass (kg/year) is calculated using the following formula:

$$M_{H_{2,year}} = \sum_{t=1}^{8760} m_{H_2}(t) \quad \text{(II.16)}$$

$\boldsymbol{M_{H_{2,year}}}$: Hydrogen mass in a year (kg)

Hydrogen production volume :

$$V_{H_2} = \frac{1000.M_{H_{2,year}}}{\rho_{H_2}} \quad \text{(II.17)}$$

$\boldsymbol{V_{H_2}}$: Hydrogen volume (L)

II.4.3.Chopper modeling:

The operating principle of a DC-DC converter is based on changing the DC voltage from one level to another using techniques such as chopping (switching). The DC voltage is converted into a pulsed form, then smoothed back using filters to obtain a DC current with a different voltage.

DC/DC converter plays a key role in this PV-EL adaptation, Converter control strategy makes both system works at their optimal working point and the power supplied to the electrolyser will be always the power produced by the PV
module after deducing the power losses from DC/DC controller/converter defined by ηconv[20].

A. The characteristic of converter DC/DC:

We connected the photovoltaic panel and the electrolyzer with a converter whose characteristics are shown in the following table**.**

Table II 3: Converter DC/DC characteristic.

η_{CONV}	0.95
P_{CONV}(W)	112

II.4.4.Storage of hydrogen:

Hydrogen produced from the pv-elctrolyzor system is stored in tanks that require certain conditions of high pressure and temperature to maintain the process safely and efficiently for later use.

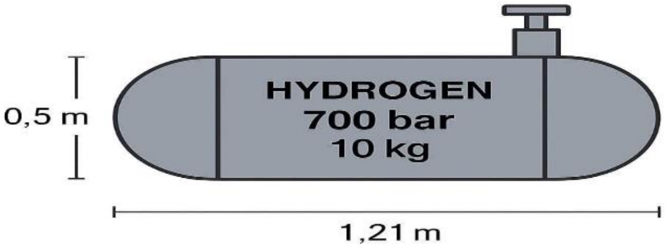


Figure II.9: Dimensions of the hydrogen tank.

A. Tank characteristics :

Dimensions and conditions required for storing the produced hydrogen.

Table II 4: Tank characteristics.

Volume (m^3)	0.238
Length (m)	1.21
Diameter (m)	0.5
Pressure (bar)	700
Mass (kg)	10

II.5.Economic study:

Hydrogen production costs are determined according to the price of energy Consumed by the process studied. Costs included Production itself (variable costs including consumption of raw materials, fixed costs). The cost price of hydrogen produced by water electrolysis is given by The following relation [21]:

$$LCOH = {}^{TC}/_{M_{H_{2,year}}} \tag{II.18}$$

It represents the minimum selling price.

II.5.1.Initial investment cost:

To find the initial investment cost, we collect the prices of the basic equipment that makes up the system, including the photovoltaic panel, electrolyser,converter, and tank[21].

$$CAPEX = C_{pv} + C_{conv} + C_{el} + C_{Tn} \tag{II.19}$$

$\boldsymbol{CAPEX}$**:** initial investment cost of the system.

$\boldsymbol{C_{pv}}$**:** Investment cost of solar panels.

$\boldsymbol{C_{conv}}$**:** Investment cost of converter

$\boldsymbol{C_{el}}$**:** Investment cost of electrolyser

$\boldsymbol{C_{Tn}}$**:** Investment cost of tank

- **Investment cost of solar panels:**

$$C_{pv} = Cap_{pv} \,.\, P_{pv} \tag{II.20}$$

$\boldsymbol{Cap_{pv}}$: capital investment of Pv ($/KW).

- **Investment cost of electrolyser:**

$$C_{el} = Cap_{el} \,.\, P_{el} \tag{II.21}$$

$\boldsymbol{Cap_{el}}$: capital investment of PEM Electrolyser ($/KW).

- **Investment cost of converter:**

$$C_{conv} = Cap_{conv} \,.\, P_{conv} \tag{II.22}$$

$\boldsymbol{Cap_{conv}}$: capital investment of converter ($/KW)

- **Investment cost of tank:**

$$C_{Tn} = Cap_{Tn} \,.\, S_{Tn} \tag{II.23}$$

$\boldsymbol{Cap_{Tn}}$: capital investment of Tank($/Kg)

$\boldsymbol{S_{Tn}}$: size tank (Kg).

II.5.2. Cost of maintenance and exploitation:

Any system requires consideration of the cost of maintenance and replacement of end-of-life equipment for the continued effectiveness of the system[21].

$$OPEX = Ma_{pv} + Rep_{pv} + Ma_{conv} + Rep_{conv} + Ma_{el} + Rep_{el} + Ma_{Tn} + Rep_{Tn} \quad (II.24)$$

$\boldsymbol{OPEX}$: Cost of maintenance and exploitation.

$\boldsymbol{Ma}$: Equipment maintenance cost.

$\boldsymbol{Rep}$: Cost of replacing equipment .

- **Maintenance solar panel**

$$Ma_{pv} = £ * P_{pv} \quad (II.25)$$

- **Maintenance converter**

$$Ma_{conv} = £ * C_{conv} \quad (II.26)$$

- **Maintenance electrolyser**

$$Ma_{el} = £ * C_{el} \quad (II.27)$$

£ : Maintenance cost of factor .

II.5.3.Total cost:

The total cost of installing and operating the system efficiently represents both the initial cost and the maintenance and exploitation cost[21].

$$TC = CAPEX + OPEX \quad (II.28)$$

Table II 5: The economic data of the system components.

	Service life	Rated capacity	Capital	Replacement	O&M
PV	25 years	485W	350$/kw	100%	8$/kw
PEM EL	15 years	355W	100$/kw	100%	8%
Converter	15 years	355W	1000$/kw	100%	0.5%
Tank	25 years	10kg	1$/kg	100%	8$/kg

We relied on this information mentioned in the table to calculate the cost of hydrogen production through the following equation:

$$LCOH = {}^{TC}/_{M_{H_{2,year}}} \quad (II.29)$$

II.6.Concluson:

This chapter constitutes a fundamental step in establishing the theoretical framework for the technical and economic assessment of hydrogen production from solar energy. The focus was placed on defining the equations and relationships that describe the performance of the system's components and allow for the calculation of relevant technical and financial indicators. Key factors influencing investment costs were also addressed, providing a methodological basis for further evaluation in subsequent stages.

ChapterIII

simulation and results

III.1.Introduction:

In this chapter, we present a detailed analysis of the economic and technical results of a modeling system used for solar-powered hydrogen production. Using simulations within the student program, we focused on studying the system's performance over a full year, tracking production changes and how climatic conditions affect the efficiency of converting solar energy to electricity, which in turn affects the quantity of hydrogen produced. We also evaluated the economic feasibility, including initial investment costs, maintenance costs, and the cost of selling hydrogen. We applied this study to the Ouargla region and added two other regions, Hassi R'Mel and Tamanrasset, to compare the technical and economic results between the regions. This analysis aims to highlight the feasibility of adopting this type of system in various regions, especially desert regions, as an alternative and clean energy source.

III.2Technical Results:

In our study of hydrogen production, the technical aspect is of great importance These are the key points and technical findings.

III.2.1Temperature and solar radiation:

- **Temperature values in ouargla T (C°) :**

The Figure III.1 represents a change in temperature over the course of an entire year, as it is distributed over a period of 8760 hours, where winter temperatures appear low compared to the temperatures of the summer months in the middle of the year and then decrease again. The maximum temperature reaches 48 degrees on August 1, while it drops to below 0 C° in the winter on January 23.The oscillations appearing on the curve reflect the daily change in temperature. Understanding this change contributes to providing a more accurate estimate of hydrogen production capacity throughout the year.

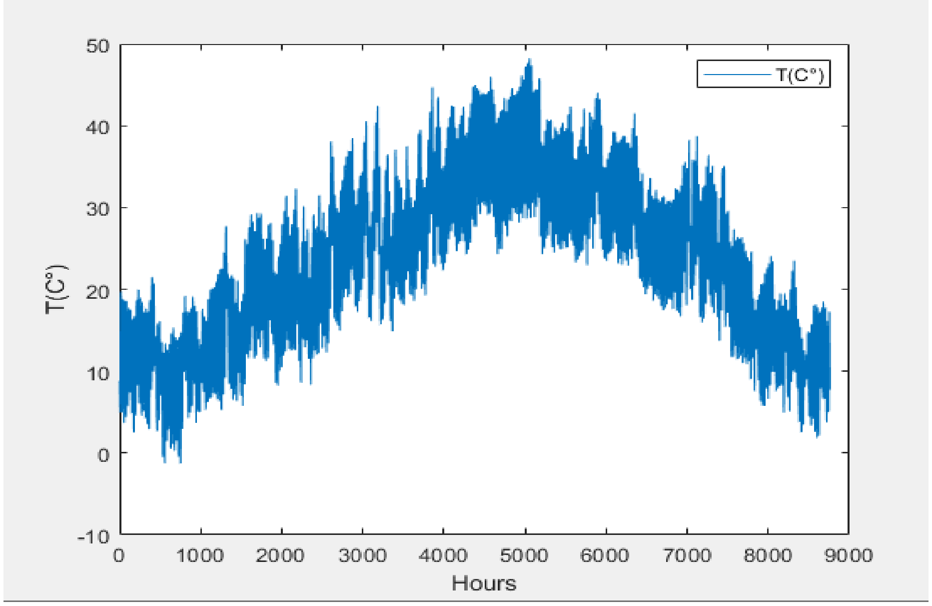


Figure III 1: Temperature graph for ouargla region (2023) [23].

- **Temperature values in hassi-rmel T (C°) :**

The figure III.*2* represents the temperature changes over a full year in the Hassi R'Mel region, where there is a gradual increase from the beginning of the year until the temperature reaches its highest level in late summer at 66 C° on August 29, and then the temperature values gradually decline until the end of the year.

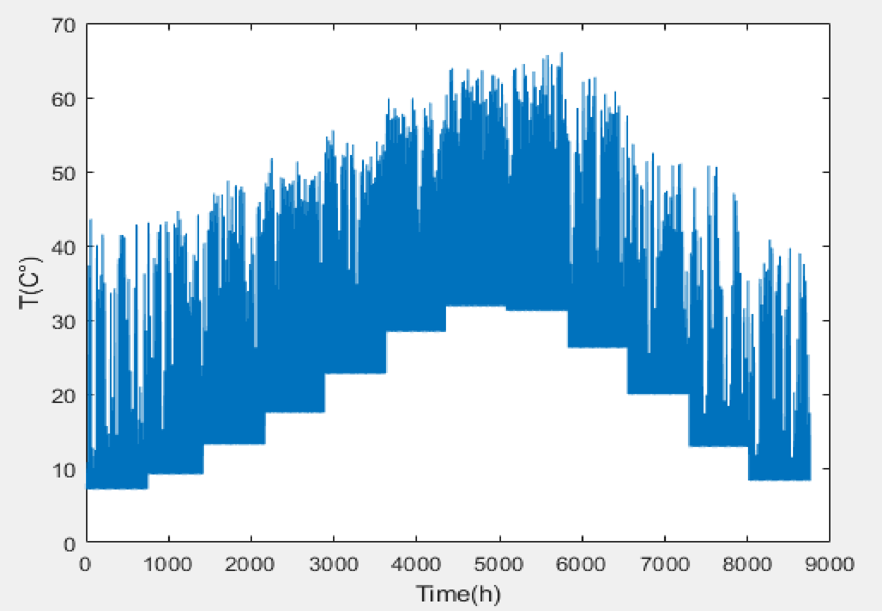


Figure III 2: Temperature graph for Hassi R'Mel region[23].

- **Temperature values in tamnraset T (C°)**

This figure shows the temperature changes in terms of hours over a full year in the Tamanrasset region, where we notice an approximate similarity with the data for Tamanrasset region, where the peak temperature was 62 C° in late summer, while at the end of the year the temperature is low, while the remaining seasons are variable, and this is due to the weather fluctuations during this period.

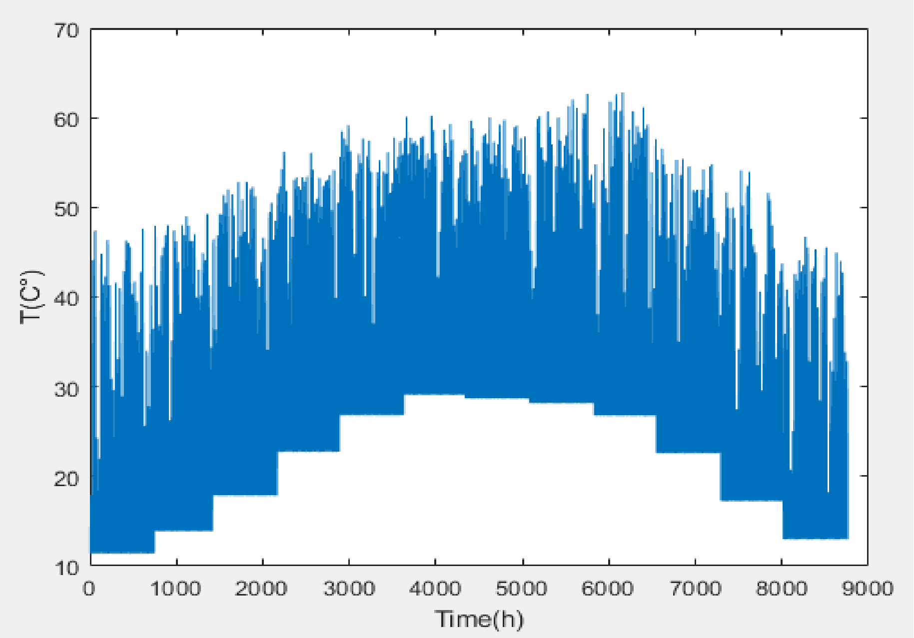


Figure III 3: Temperature graph for Tamanrasset region (2023) [23].

- **Solar radiation values G (W/m^2) Ouargla region :**

The figure III.*4* displays solar radiation(G in W/m²) during an entire year (8760 hours).We notice that the radiation follows an annual pattern similar to temperature, where it is high in summer and low in winter.The maximum value reaches 1024 W/m^2 and the minimum value reaches 251.3W /m^2 in winter. Oscillations appear as a result of weather conditions such as clouds and sandstorms that affect radiation reaching the Earth's surface.

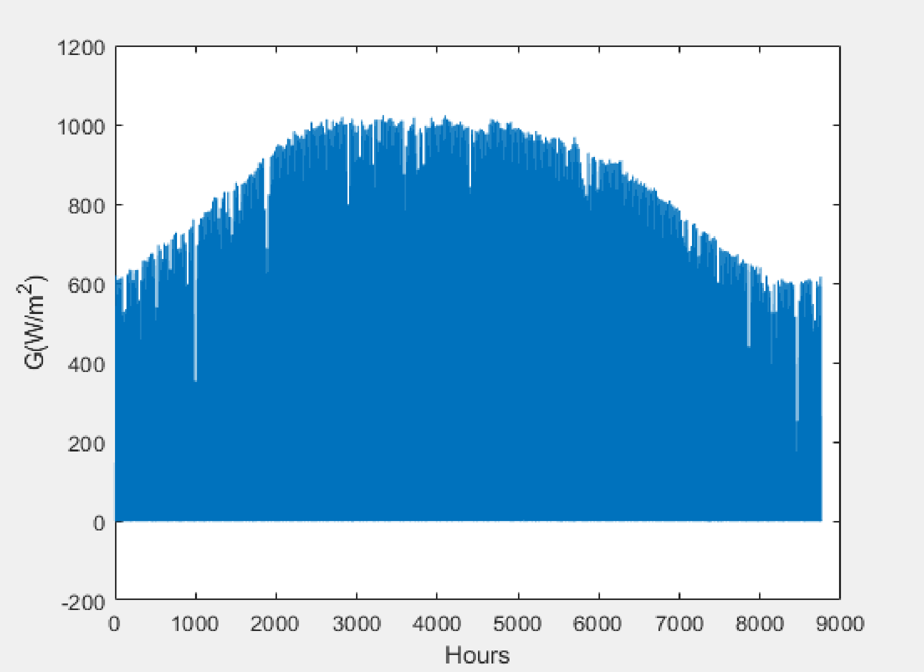


Figure III 4: Solar radiation graph for ouargla region(2023) [23].

- **Solar radiation values G (W/m^2) hassi-rmel region :**

This Figure III.5 represents the changes in solar radiation (G in W/m²) over a full year (8760 hours) in the Hassi R'Mel region. We notice that solar radiation follows a good pattern, gradually increasing from the beginning of the year to peak in the middle, with the highest value being 1130 on July 5, then gradually declining toward the end of the year.

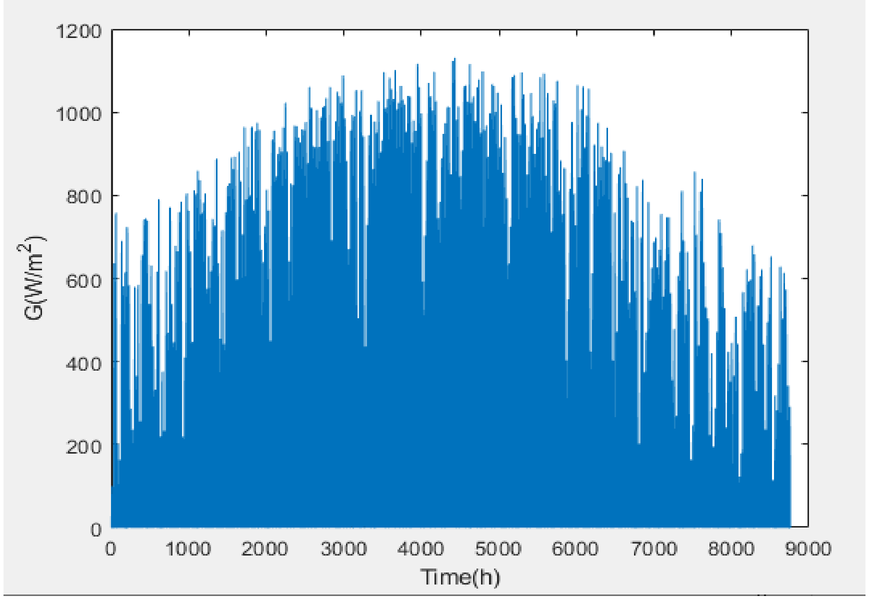


Figure III 5: Solar radiation graph for Hassi R'Mel region(2023) [23].

- **Solar radiation values G (W/m^2) Tamanrasset region**

This Figure III.*6* shows the variations in solar radiation (G in W/m²) throughout the year (8760 hours) in the Tamanrasset region. We notice a relative stability in solar radiation values throughout the year, with most values being high, often ranging between 800 and 1200 W/m², indicating strong and nearly constant solar radiation throughout the year. We also note that the lowest radiation values were recorded in the middle of the year, which is explained by the cold weather in Tamanrasset during the summer.

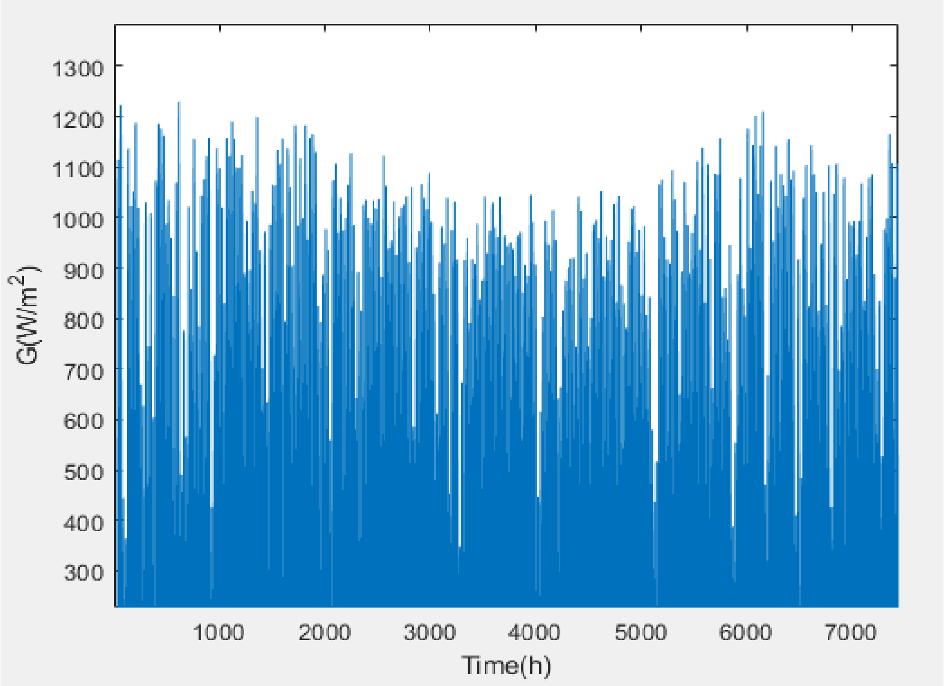


Figure III.6: Solar radiation graph for Tamanrasset region(2023) [23].

III.2.2. power production of solar panel and water electrolyzer:

- **power production of solar panel Ouargla region:**

The figure III.7 represents the development of the power production generated by the solar panel over a period of 8760 hours, as the power produced appears to gradually increase as we leave the winter season.This is due to the increase in solar radiation values, and the peak reaches 373.6 Won June 13, which indicates the optimal performance of the solar panel.On the other hand, the power decreases due to the decrease in radiation.Solar radiation reaches its lowest levels on December 22, which is estimated at 71 watts.

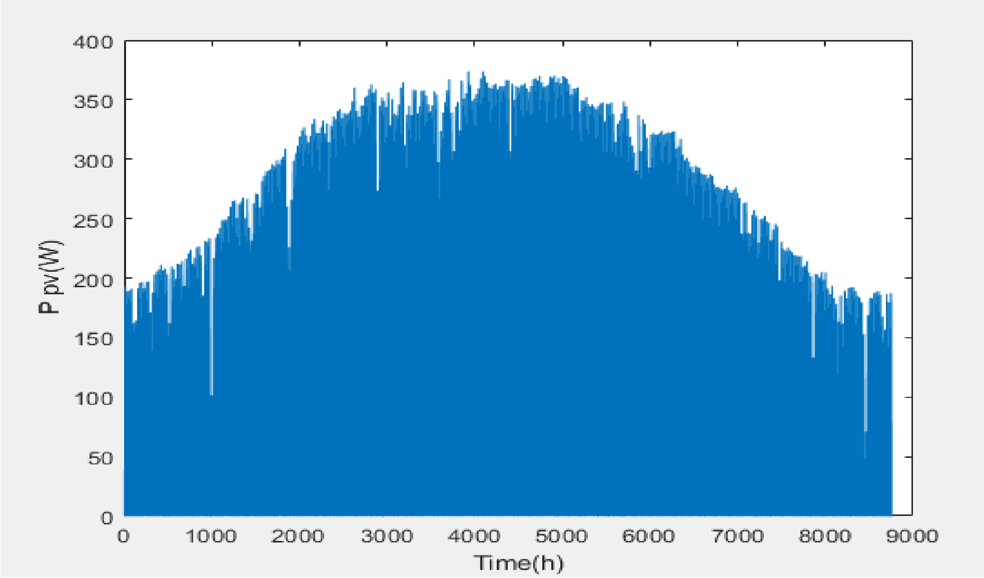


Figure III.7: power production graph for ouragla region**.**

- **power production of solar panel hassi-rmel region:**

The figure III.8 represents changes in the power production of a solar panel over an entire year (8760 hours). We note that changes in energy match changes in solar radiation, and this is due to the direct proportionality between them. Power values gradually increase at the beginning of the year reaching a peak in the summer, recording a peak value of 452.6 W. After that, energy begins to decrease until the end of the year.

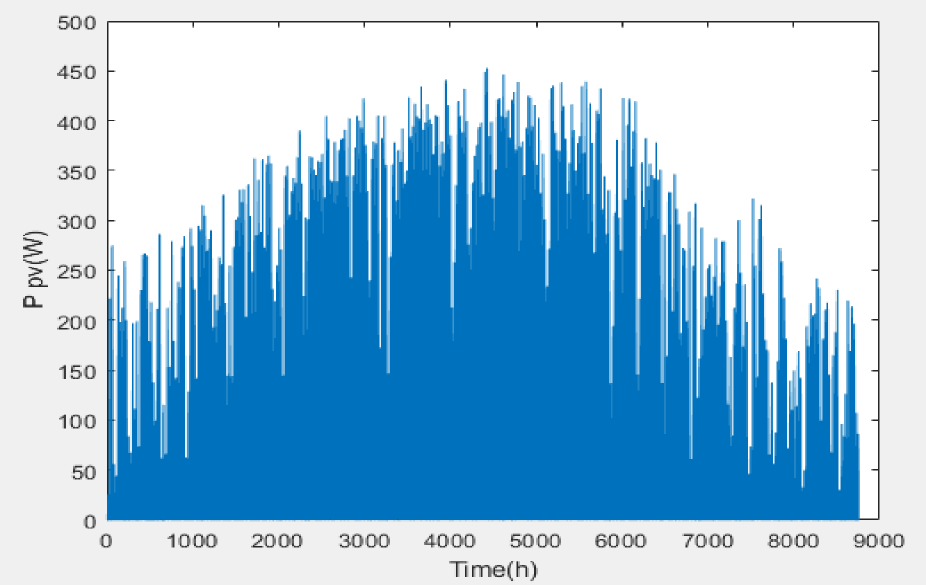


Figure III.8: power production graph for hassi-rmel region.

- **power production of solar panel Tamanrasset region**

The figure III.9 represents the changes in the power production of the solar panel during the hours of a full year(8760 hours), where we notice a relative stability in the capacity values that range between 430-470 W with a decrease for a certain period represented in the middle of the year and then a rise after that before the end of the year. This variation in capacities is caused by changes in the values of solar radiation.

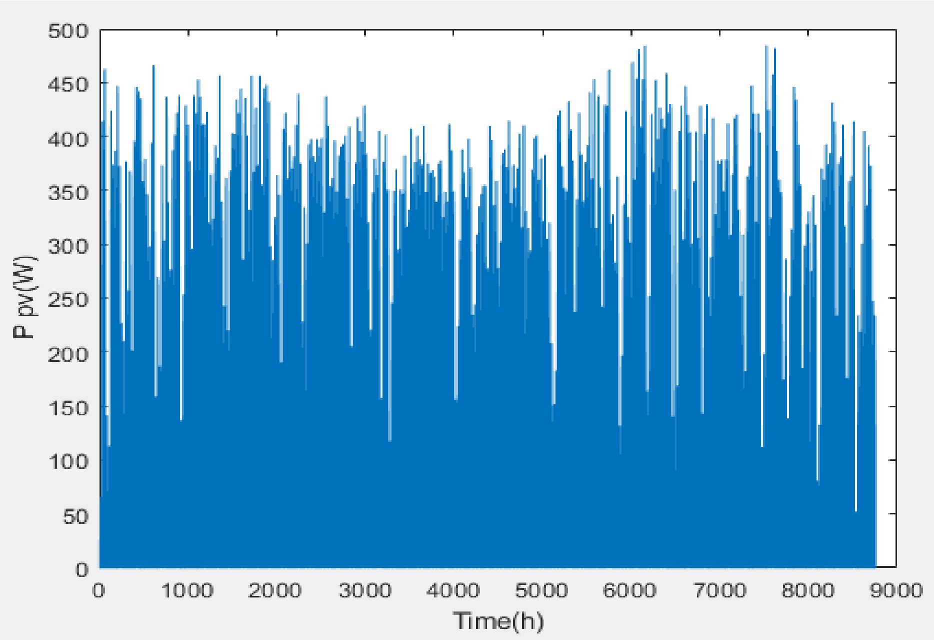


Figure III.9: power production graph for Tamanrasset region**.**

- **power production of water electrolyzer Ouargla region:**

The Figure III.*10* represents the changes in power production (Pel) consumed by a water electrolyzer over 8760 hours. The curve begins to gradually increase as we approach the middle of the year. This is due to the increase in the solar panel power associated with the increase in solar radiation. The peak value was recorded at 350.3 W on July 29 at noon, and then it begins to gradually decrease in the second half of the year. The analyzer power decreases to reach 66.8 W on December 22. It is also noted that there are momentary fluctuations in power due to sudden changes in weather conditions.

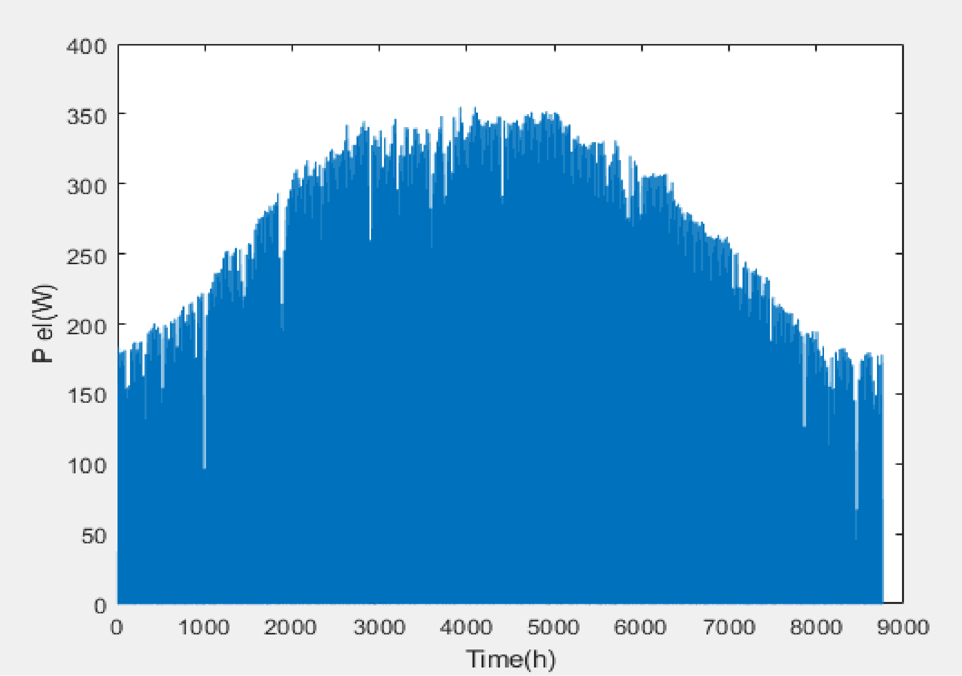


Figure III.10: power production graph of water electrolyzer for Ouargla region.

- **power production of water electrolyzer hassi-rmel region:**

The figure III.*11* represents the changes in the power production of the electrolyzer over the course of a full year(8760 hours). We notice a gradual increase in the capacity values at the beginning of the year until the middle of the summer, when the highest value is recorded, estimated at 430 W. The electrical capacity values then begin to decline until the end of the year, and this is a result of changes in the electrical capacity of the solar panel**.**

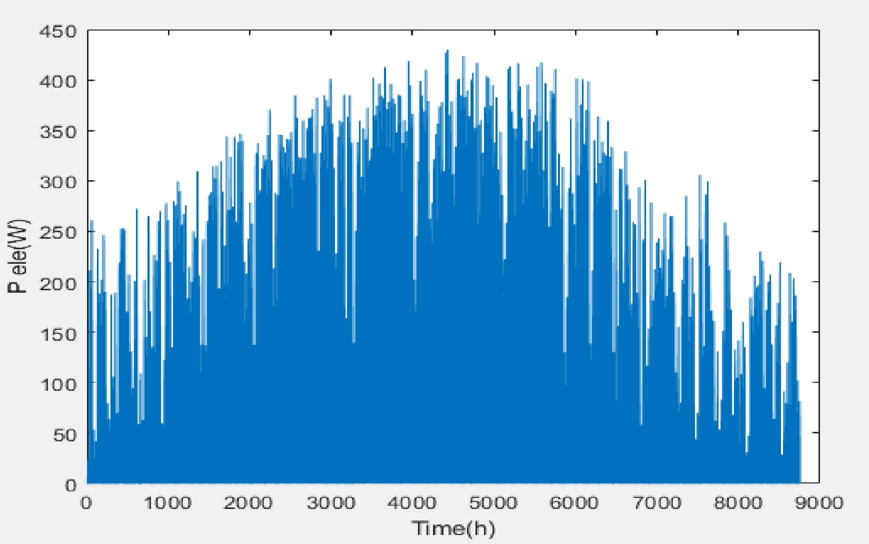


Figure III.11: power production graph of water electrolyzer for hassi-rmel region.

- **power production of water electrolyzer Tamanrasset region**

The figure III.*12* represents the changes in the power production of the electrolyzer over the course of a full year(8760 hours). We notice a relative stability in the electrical capacity values, which range between 400-450W at the beginning of the year, then decrease slightly in the summer, and then begin to increase in the late summer until the end of the year. This is a result of changes in the electrical capacity of the similar solar panel.

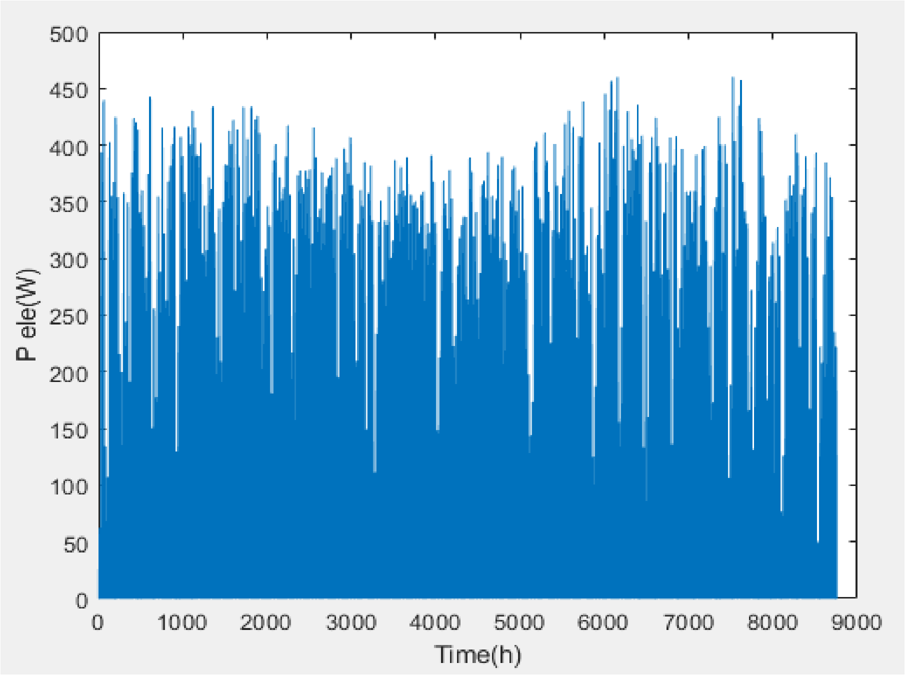


Figure III.12: Electrical power graph of water electrolyzer for Tamanrasset region**.**

III.2.3.The quantity of hydrogen produced by photovoltaics:

- **The quantity of hydrogen produced by photovoltaics Ouargla region:**

The figure III.*13* represents the changes in the mass of hydrogen produced in a full year(8760 hours). We notice a gradual and accelerated increase in the amount of hydrogen produced the closer we get to the middle of the year, where the peak production reached 0.007 kg. This increase is due to the abundance of solar radiation in the Ouargla region during this period, and thus high values for the electrical capacity of the analyzer. Then, the quantities produced decrease the closer we get to the end of the year, due to the decrease in solar radiation and temperatures.

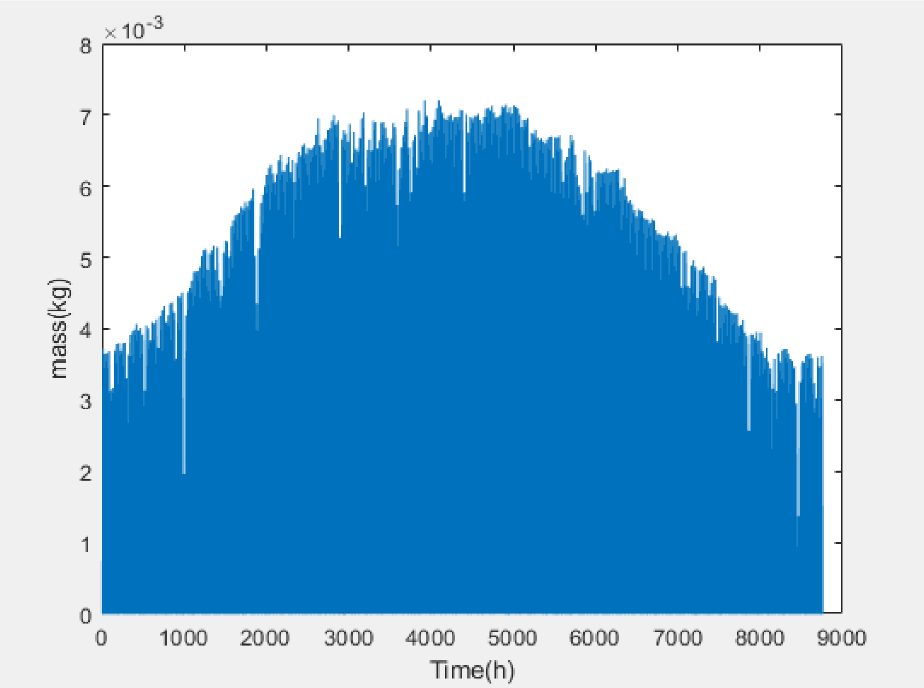


Figure III.13: hydrogen quantity produced for Ouargla region.

- **The quantity of hydrogen produced by photovoltaics hassi-rmel region:**

The figure III.*14* represents the changes in the mass of hydrogen produced over the course of a full year(8760 hours). We notice a gradual increase until we reach peak production in the middle of the year(0.0087kg). This is due to the abundance of solar radiation at that time and, consequently, high values for the electrical capacity of the analyzer. Then, the quantities produced decrease as we approach the end of the year due to the decrease in solar radiation and temperatures.

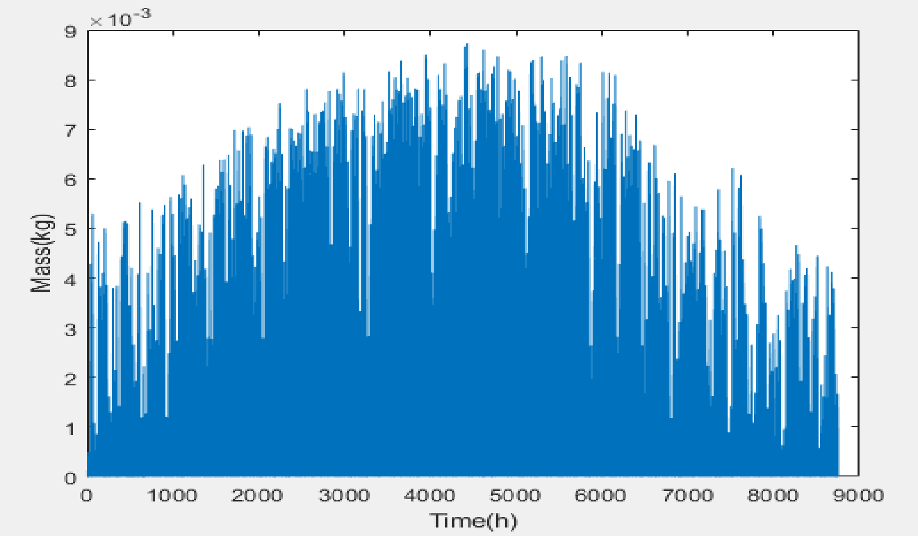


Figure III.14:hydrogen quantity produced for hassi-rmel region.

- **The quantity of hydrogen produced by photovoltaics Tamanrasset region:**

The figure III.*15* represents the changes in the mass of hydrogen produced in a full year(8760 hours). We notice a relative stability in the amount of hydrogen at the beginning of the year, where the amount of production ranges between 0.0075-0.008 kg, then decreases slightly in the middle of the year. This is due to changes in the electrical capacity of the analyzer associated with changes in solar radiation. Then the curve increases again until the end of the year, with disturbances in it, which explains the sudden changes in weather conditions.

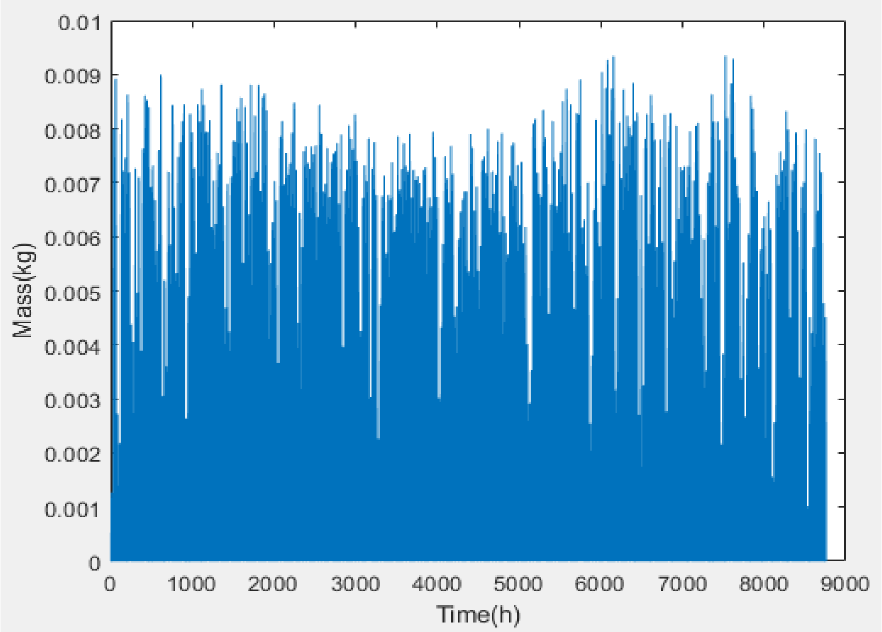


Figure III.15:hydrogen quantity produced for Tamanrasset region.

III.3.Economic results:

In this part, we will present the economic results of this investment, which determine the cost of producing and selling hydrogen, and to obtain it, we go through the stages presented in the following diagram:

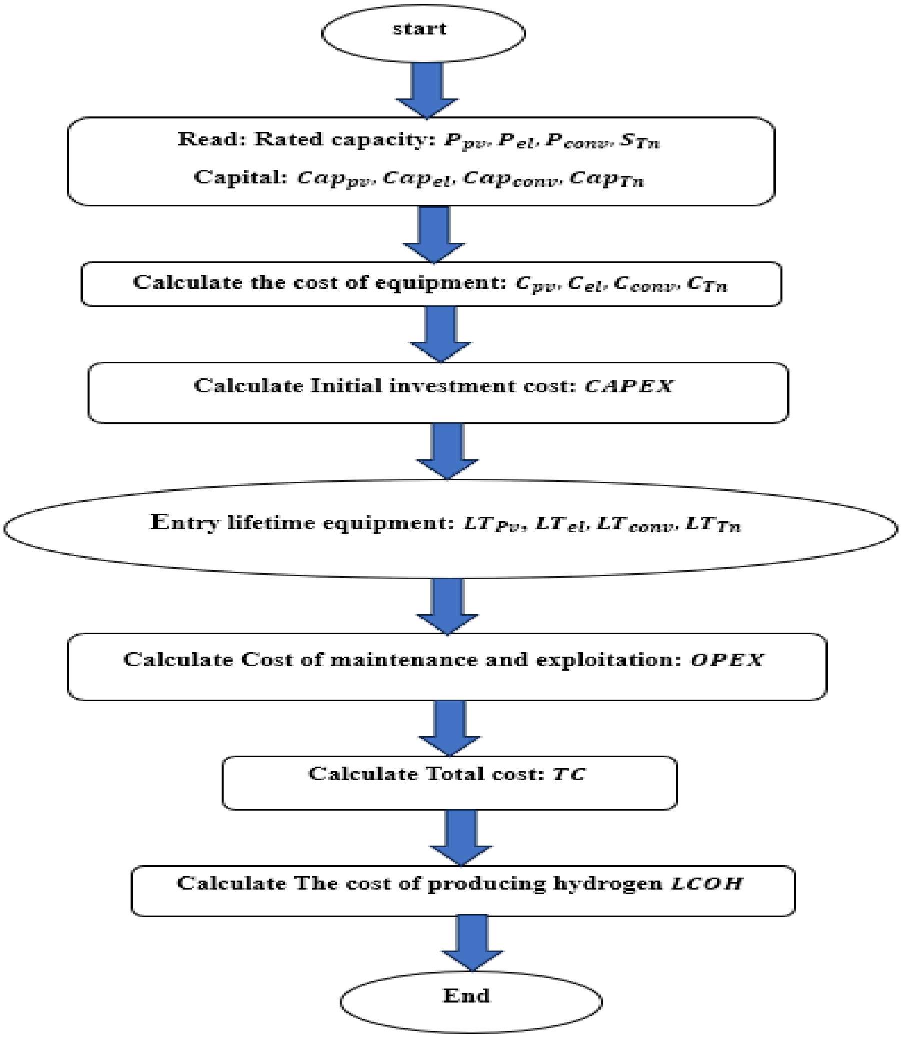
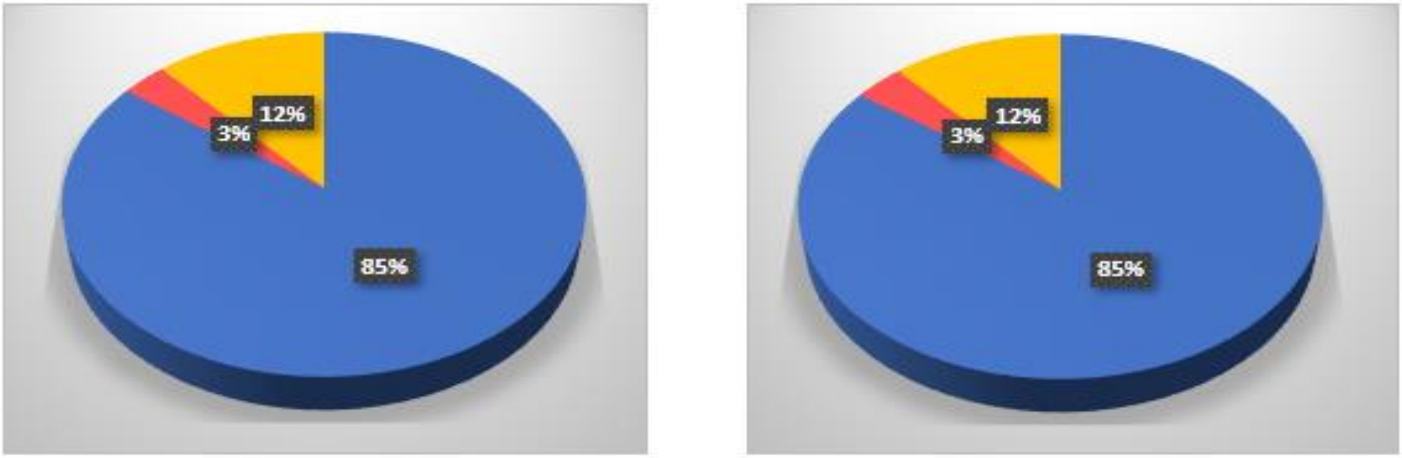


Figure III.16: The flow chart of the economic study.

III.3.1.The total cost of investment:

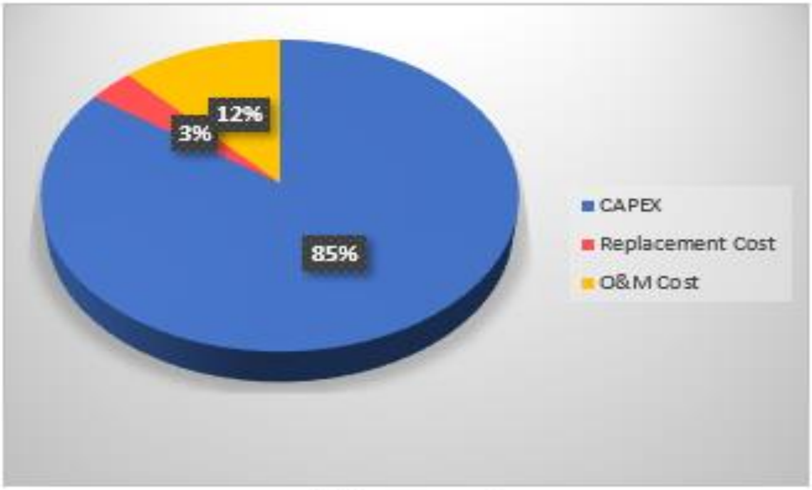
Table III 1:CAPEX, Replacement, and O&M Costs for Different Locations.

Location	CAPEX	Replacement Cost ($)	O&M Cost ($)	Total Cost ($)
Ouargla	46.9010	1.7337	6.3931	55.0278
Hassi R'mel	52.3509	2.0998	7.1390	61.5898
Tamanrasset	56.7010	2.2481	7.8697	66.8189



A.Ouragla.

B.Hassi R'mel.



C. Tamanrasset.

Figure III.17: Percentage Distribution of CAPEX, Replacement Cost, and O&M Cost in a Hydrogen Production System.

The results showed that the investment cost represented the largest proportion of total costs in all regions, at a roughly constant 85%, reflecting the importance of infrastructure and equipment in determining project feasibility. Ouargla recorded the lowest initial investment cost at $46,901, making it the most economical of the regions in terms of initial cost. Tamanrasset had the highest total cost ($66,819), followed by Hassi R'mel. This was due to the high replacement and maintenance costs, which reached $2,481 and $7,699, respectively, due to the high cost of some equipment. Ouargla maintained the lowest values across all aspects, with replacement costs reaching $1,737 and maintenance costs reaching $6,390, strengthening its economic position for project implementation. The relative pie charts support this analysis, clearly showing the dominance of the initial investment cost and the relative lowness of other costs, with slight differences between regions in replacement and maintenance rates.

III.3.2.The Levelised Cost of Hydrogen:

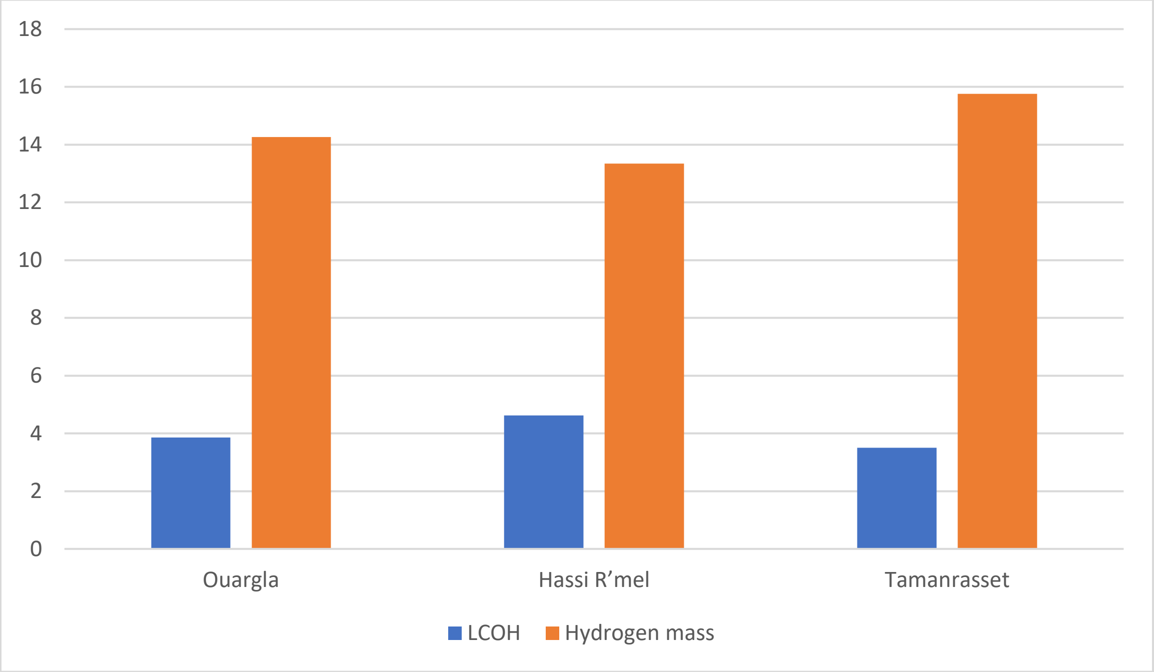


Figure III.18: Comparison of Levelized Cost of Hydrogen and Hydrogen Mass in Ouargla, Hassi R'mel, and Tamanrasset.

This chart compares the three regions (Ouargla, Hassi R'mel, and Tamanrasset) in terms of the total cost of hydrogen production (LCOH) and annual production quantities. The columns show that the cost of producing one kilogram of hydrogen in Ouargla is lower than in Hassi R'mel, which is consistent with the results of the previous economic analysis, which showed that Ouargla has the lowest total costs, both in terms of initial investment costs and replacement and maintenance costs. Despite the similar annual quantities of hydrogen produced in the three regions, the higher cost in Hassi R'mel reflects the impact of higher maintenance and replacement costs, making the project there less economically feasible. Despite the higher total costs, Tamanrasset has the lowest hydrogen production cost, due to a technical factor that contributed to improved production efficiency. Therefore, it can be said that Ouargla represents a good option in terms of economic return for solar-powered hydrogen production, combining low costs with good annual productivity.

III.4.Concluson:

In conclusion, this chapter analyzes the economic feasibility of solar-powered hydrogen production in three Algerian regions: Ouargla, Hassi R'Mel, and Tamanrasset. We find that investment costs represent the largest portion of the costs in all regions, accounting for approximately 85%, highlighting the importance of equipment in determining project efficiency. Ouargla boasts low total costs, making it the preferred choice in terms of economic feasibility, recording the lowest cost per kilogram of hydrogen production with good annual productivity. Conversely, Hassi R'Mel was less economically efficient due to high maintenance and replacement costs, despite its similar annual productivity. Despite recording the highest total cost, Tamanrasset's production costs were lower than Hassi R'Mel's, thanks to technical factors that improved production efficiency. Therefore, Ouargla is clearly the most economically suitable region for implementing a solar-powered hydrogen production project, given its balance between low costs and good production performance.

General conclusion

General conclusion:

This memoir onstitutes a scientific contribution to the search for alternative and clean energy solutions, through a study of the technical and economic feasibility of hydrogen production using solar energy in the Ouargla region, given its potential and favorable geographical location. The Hassi R'Mel and Tamanrasset regions were included in this study as a secondary component for comparison purposes, with the aim of observing regional differences in terms of technical performance and economic feasibility.

A comprehensive overview is provided of the importance of hydrogen as a promising future energy source, a practical solution to address the challenges of pollution and climate change, thanks to its pure properties and its ability to be stored, transported, and used in multiple fields. The technology of electrolysis of water using electricity generated from solar energy is also addressed, as one of the cleanest methods for producing green hydrogen, making it a subject of increasing global interest.

The theoretical foundation of the study was established by defining the physical and mathematical models and equations that govern the operation of a solar system consisting of a solar panel, a converter, and an electrolyzer. The technical and financial factors affecting project costs were also reviewed, enabling the development of a methodological framework that allows for accurate estimation of the indicators required for evaluation.

In the applied part of the study, a technical and economic simulation was conducted in the Ouargla region, including an analysis of annual solar radiation, photovoltaic system performance, and electricity generation capacity. This was then converted into an economic evaluation that included initial investment costs, replacement costs, and maintenance and operation costs. The results showed that Ouargla recorded the lowest total cost compared to the other two regions, reflecting its high economic feasibility. It also recorded the lowest cost per kilogram of hydrogen production, with good annual productivity, enhancing its competitiveness as a strategic location for such projects. Conversely, the results showed that Hassi R'Mel, despite similar annual production, suffers from high maintenance and replacement costs, which impacts its economic feasibility. Tamanrasset, while recording the highest total cost, had a lower hydrogen production cost than Hassi R'Mel, thanks to technical factors that improved operational efficiency. Based on these data, it can be argued that the Ouargla region is the ideal choice for a solar-powered hydrogen production project in Algeria, given its balance between low costs and high production levels, as well as its availability of strong solar radiation and acceptable infrastructure. The results of this study call for directing future investments toward regions with optimal qualifications, such as Ouargla, to support Algeria's energy transition and achieve sustainable development based on clean and renewable energy sources

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