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**Modeling and simulation of a green hydrogen
production using photovoltaic system in algeria**

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Dedication

To my beloved mother and father, whose unconditional love, endless sacrifices, and unwavering support have been the foundation of my success. Your encouragement and faith in me have given me the strength to overcome every challenge and pursue my dreams.

To my dear grandfather and grandmother, whose prayers, wisdom, and affection have always guided my path and filled my life with comfort and inspiration.

To my beloved brothers and sisters, for your constant support, understanding, and encouragement. Your presence has made this journey easier and more meaningful.

To my loyal friends, thank you for your friendship, motivation, and the memorable moments we shared throughout this academic journey.

*To everyone who has supported, encouraged, and believed in me, directly or indirectly, I express my deepest gratitude and dedicate this work as a token of my sincere appreciation. **With love, respect, and gratitude,***

Rafik Bourenane

Ahmed Cherchar

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Liste of abbreviations and nomenclature

Abbreviation	Full Meaning
AEL	Alkaline Water Electrolysis
PEM	Proton Exchange Membrane
SOE / SOEC	Solid Oxide Electrolysis (Cell)
AEM	Alkaline Anion Exchange Membrane
AAEMWE	Alkaline Anion Exchange Membrane Water Electrolysers
AWE	Alkaline Water Electrolysis
PV	Photovoltaic
GW	Gigawatt
TWh	Terawatt-hour
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture and Storage
KOH	Potassium Hydroxide
YSZ	Yttria-Stabilized Zirconia
STP	Standard Temperature and Pressure
BOG	Boil-Off Gas
CAPEX	Capital Expenditure (Initial Investment)

Abbreviation	Full Meaning
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
DI	Direct Injection
ICE	Internal Combustion Engine
SAF	Sustainable Aviation Fuel
RSM	Response Surface Method
I _{PV}	Photovoltaic Array Output Current
V _{PV}	Photovoltaic Array Output Voltage
SKA3	Terga Thermal Power Plant Identifier

General Introduction

General Introduction

The global energy sector currently faces a dual challenge: the rapid depletion of fossil fuel reserves and the escalating threat of climate change caused by greenhouse gas emissions [1]. In response, the world is moving towards a sustainable energy transition, with renewable energy sources such as solar and wind power playing a pivotal role [2]. However, the inherent intermittency of these resources remains a significant obstacle to their widespread integration into the electricity grid [3].

Green hydrogen has emerged as a revolutionary solution to this challenge. It is a versatile, carbon-free energy carrier, enabling the storage and transmission of renewable energy across diverse sectors, including industry, transportation, and power generation [4]. Unlike gray or blue hydrogen, green hydrogen is produced through the electrolysis of water using only renewable electricity, resulting in zero carbon emissions [5].

With its vast geographical area and exceptional levels of solar radiation, particularly in the High Plateaus and the Sahara Desert, Algeria is uniquely positioned to become a global hub for green hydrogen production [6]. Recognizing this potential, the Algerian government launched a national strategy aiming to integrate 27% renewable energy into the national energy mix by 2030, positioning Algeria as a major supplier of clean energy to the international market, particularly Europe [7].

Despite the promising potential of this technology, the design and implementation of hydrogen-powered photovoltaic solar energy systems require rigorous technical and economic assessments. The complexity of these systems, including fluctuations in solar radiation and the non-linear behavior of electrolyzers, necessitates the use of advanced modeling and simulation tools to optimize performance and ensure reliability [8].

This study is structured around a comprehensive methodology divided into several key components, which are presented in this manuscript in three main chapters:

- Chapter I: This chapter provides an overview of renewable energy systems and green hydrogen, covering hydrogen properties and different electrolysis techniques (Alkaline, PEM, SOE, AEM). It also reviews the status of renewable energy in Algeria and the world, and presents the Terga thermal power plant and its technical specifications.
- Chapter II: This chapter begins by providing a comprehensive literature review

outlining available options, known failure patterns, performance limits, and experimental data, thus transforming guesswork into informed component selection and sound assumptions.

- Chapter III: In this chapter presented the MATLAB/Simulink simulation of a green hydrogen production system for the Terga power plant, using a 1 MW PV array directly coupled to a PEM electrolyzer.

Chapter I: Overview on renewable system and green hydrogen

I.1. Introduction

The global economy's heavy reliance upon fossil fuels is under increasing threat by the dual challenges of supply security and climate change

Renewable energy systems such as solar photovoltaic, wind, hydropower, geothermal energy, and biomass are a cornerstone of the global transition to a sustainable future, contributing to reducing dependence on fossil fuels and lowering carbon emissions.

Green hydrogen is a fundamental pillar of climate balance plans, as it provides the effective possibility of storing, transporting and using clean energy efficiently. It is produced by electrolysis of water using renewable energy sources, making it a sustainable option that supports the energy transition process.

I.2. Generality on hydrogen and renewable energy

I.2.1. renewable energy system

Renewable energy systems are technologies that harness energy from naturally occurring, renewable sources such as sunlight, wind, hydropower, geothermal energy, and biomass, which are replenished year-round. These systems convert most forms of renewable energy relatively easily into electricity, and solar, geothermal, and biomass energy can also provide heating and cooling. In principle, they can provide all traditional energy services (electricity, heating, cooling, and transportation fuel). Their naturally distributed nature allows them to provide power to remote areas without requiring extensive transmission networks [9].

I.2.2. Different type of renewable energy

Renewable energy sources offer sustainable alternatives to traditional fossil fuels, exploit natural processes to generate power. Solar energy captures the sun's electromagnetic waves, converting them into heat or electricity through technologies like photovoltaic systems [10]. Wind energy transforms the kinetic energy of moving air into electrical or mechanical power, typically utilizing large wind turbines. Hydropower generates electricity by harnessing the energy of moving water, often employing dams to create reservoirs and using turbines, generators, and transformers to convert kinetic energy into electricity [11]. Biomass utilizes organic matter such as crops, residues, and animal manure, which can be stored as fuel to produce electricity, offering a readily available and inexpensive option with potentially fewer greenhouse gas emissions than fossil fuels [9]. Lastly, Geothermal energy provides a constant,

Weather-independent source of thermal and electrical energy from the Earth's interior, ensuring a reliable and environmentally friendly base-load power supply 24/7 [11].

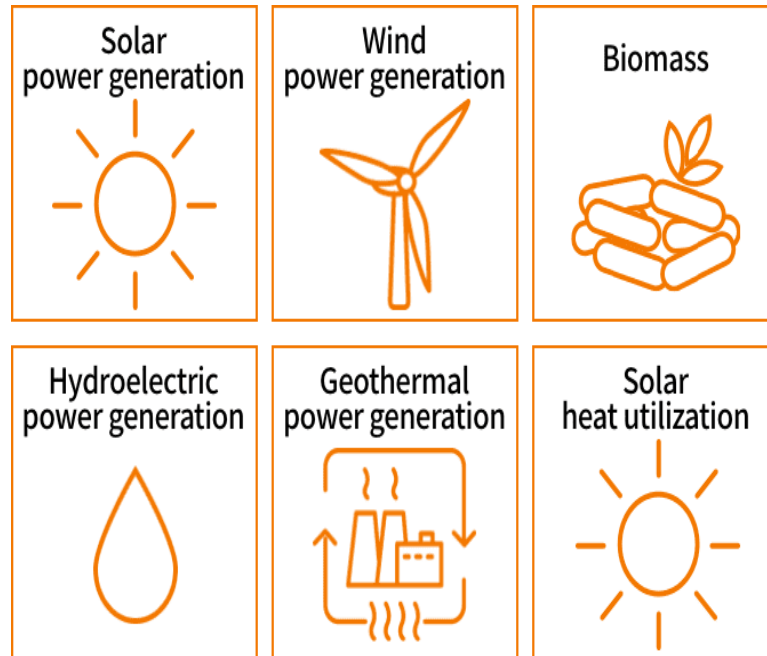


Figure I. 1: Different type of renewable energy [12].

I.2.3. Hydrogen Properties

Hydrogen (H_2) is the most common element in the universe, but it never occurs by itself on earth, as it always combines with other elements such as oxygen (to form water as molecule) or carbon (to form hydrocarbons and coal). Thus, it needs to be produced and for this reason it is not a primary source, but only an energy carrier, which could be used in combination with electricity in an innovative overall energy system [13].

Several numerical data points representing the properties of hydrogen have been compiled in the table (I.1) below.

Table I. 1: the properties of hydrogen [14; 15].

Proprieties	Numerical value
Phase at STP	Gas
Color	Colorless
Density	0.08988 g/L (0 C, 101.325 kPa)
Melting point	14.01 K, 259.14 C
Boiling point	20.28 K, 252.87 C
Molar heat capacity	(H ₂) 28.836 J.mol ⁻¹ K ⁻¹
Thermal conductivity	0.1805 W.m ⁻¹ .K ⁻¹
Flame speed in air	260 cm/s (7 times that of natural gas)
Air diffusion coefficient	0.61 cm ² /s (natural gas 0.16)
Detonation velocity in air	2.0 km/s (natural gas 1.8 km/s)

STP: standard temperature and pressure.

I.2.4. Different type of hydrogen

Hydrogen can be produced in several ways and is typically classified by color based on the energy sources used and their environmental impact. Gray hydrogen is produced from fossil fuels such as coal or natural gas through steam reforming without carbon capture, making it the most widely used but also the most polluting method [16]. Blue hydrogen is generated using a similar process, but with carbon capture and storage (CCS) to reduce carbon dioxide emissions, making it a cleaner alternative [17]. Green hydrogen is the most sustainable type and is produced via water electrolysis technologies (AEL, PEM, SOE, AEM) powered by renewable energy sources such as solar, wind, hydro, geothermal, and biomass, resulting in near-zero emissions [17].

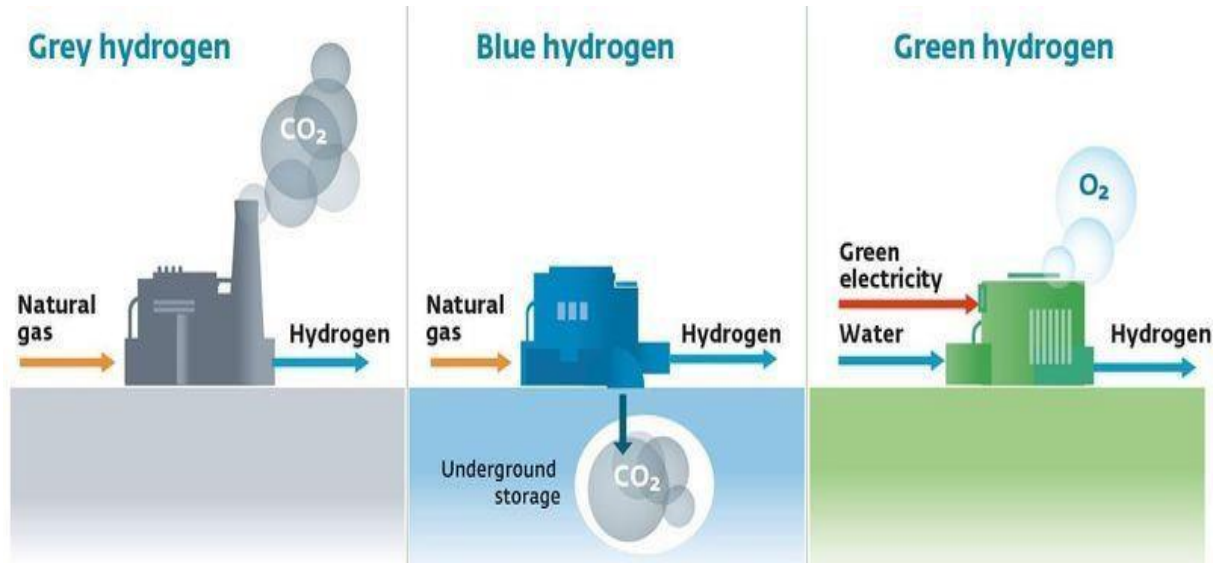


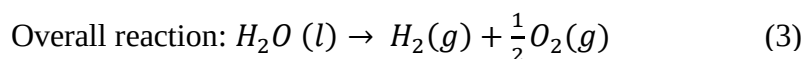
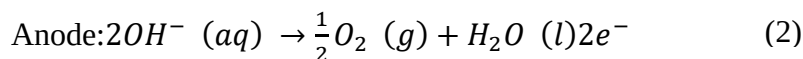
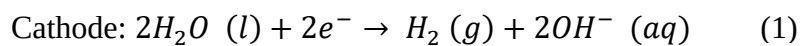
Figure I. 2: Different type of hydrogen. [18]

I.2.5. Electrolysis Technologies

Electrolysis is the central production technology of the hydrogen system. Electrolysis uses electrical energy to force a non-spontaneous reaction to dissociate water molecules. There are various technologies depending on the electrolyte and operating conditions.

❖ Alkaline water electrolysis (AEL)

Alkaline water electrolysis is used to split water into the gases hydrogen and oxygen using electric energy. The chemical reactions are given in the Equations (1)-(3). At the cathode, water molecules are reduced by electrons to hydrogen and negatively charged hydroxide ions. At the anode, hydroxide ions are oxidized to oxygen and water while releasing electrons. Overall, a water molecule reacts to hydrogen and oxygen in the ratio of 2:1. [19]



A schematic flow diagram of alkaline water electrolysis is shown in **Figure I.4**.

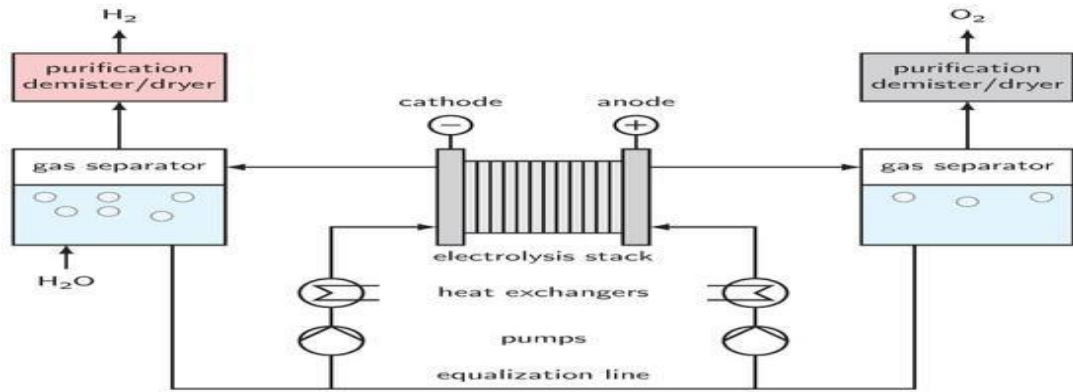
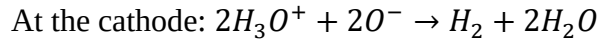
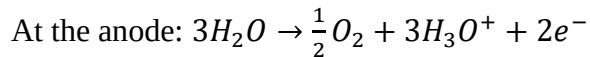


Figure I. 3: A schematic flow diagram of alkaline water electrolysis [20]

❖ Proton exchange membrane (PEM)

The operating principle of a PEM (proton exchange membrane) electrolyzer is based on the same concept as a PEM fuel cell. The main characteristic of the PEM electrolyzer is its solid electrolyte, consisting of a polymer membrane. This ensures the conduction of hydronium ions (H_3O^+) produced at the anode and allows the separation of the gases produced (H_2 and O_2), according to the reactions below [21]:



The principle of PEM electrolysis is schematically described by the following **figureI.5:**

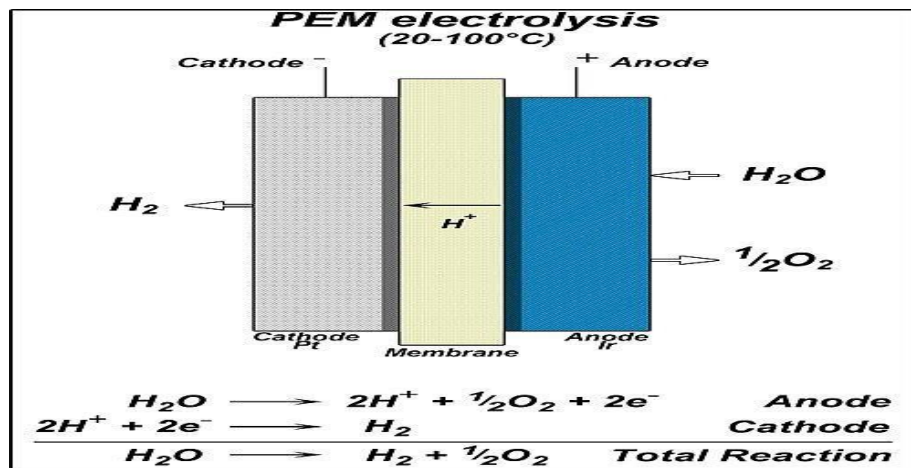


Figure I. 4: The principle of PEM electrolysis [22]

❖ Solid Oxide Electrolysis (SOE)

SOE cell is composed of two porous electrodes and a dense electrolyte layer generally made of zirconium (ZrO_2) doped with yttrium (Y_2O_3), called YSZ (yttria-stabilized zirconia). Water (steam) fed to the cathode side is reduced to produce H_2 and O^{2-} , and the O^{2-} ions migrate through the electrolyte (solid oxide) to the anode where are then oxidized to O_2 , Figure I.6 SOE operate at much higher temperatures, typically between 700°C and 850°C [23].

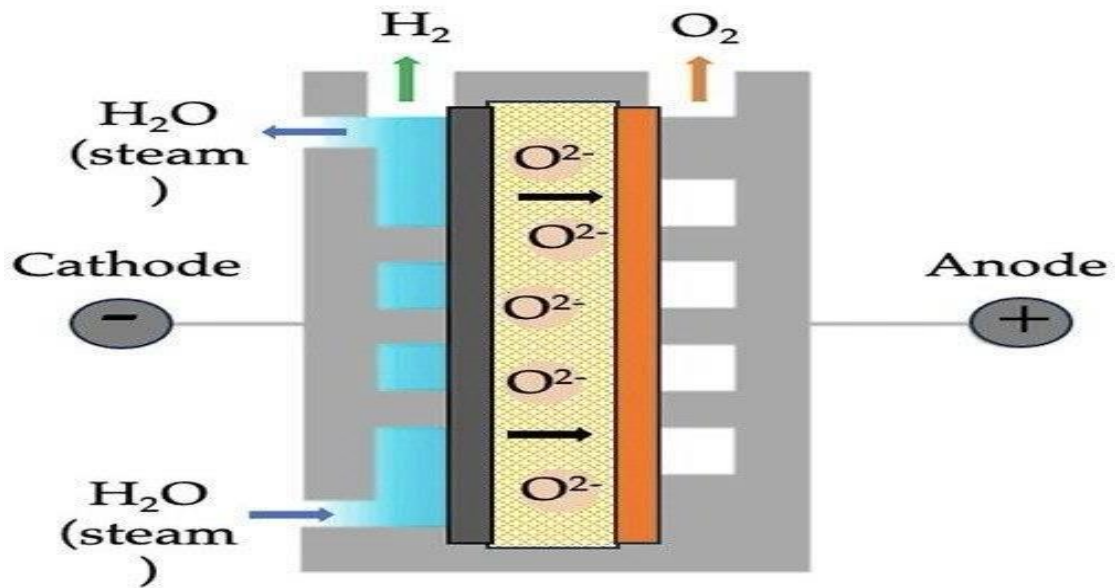


Figure I. 5: Solid oxide water electrolyzer (SOE) [23].

❖ Alkaline anion exchange membrane (AEM)

Alkaline anion exchange membrane water electrolyzers (AAEMWE) use electrical energy to split water into its elemental components, hydrogen (on the cathode) and oxygen (on the anode). The cell reactions in the AAEMWE are the same as in traditional alkaline electrolyzers using 30–35 wt% KOH liquid electrolyte. The essential difference between AAEMWE and Alkaline Water Electrolysis (AWE) is that the liquid electrolyte is replaced by a thin ion exchange membrane (solid electrolyte) to allow for OH^- anions transport [24].

❖ **Comparative Table of Electrolysis Technologies**

Table I. 2: Comparative Table of Electrolysis Technologies [19, 21, 23,24]

Parameter	Alkaline (AEL)	PEM	Solid Oxide (SOE)	AEM
Electrolyte	Liquid KOH	Solid Polymer	Ceramic (YSZ)	Anion Membrane
Charge Carrier	OH^-	(H_3O^+)	O^{2-}	OH^-
Operating Temp.	60–90°C	50–80°C	700–850°C	40–70°C
Catalyst	Non-precious metals	Precious metals (Ir, Pt)	Non-precious metals	Non-precious metals

I.3. Situation of renewable energy on the world and Algeria**I.3.1. World situation of renewable energy**❖ **Installed capacity and production**

The global energy transition to a low-carbon energy system is gaining speed to mitigate climate change and adapt to the fluctuations in fossil fuel prices. Clean power exceeded 40% of the world electricity generation by the end of 2024, with renewables comprising roughly 32%. [25, 26].

In 2025, global renewable power capacity reached a record 5,149 GW, equivalent to roughly 49% of the world's total installed power capacity. Solar photovoltaic (PV) has emerged as the primary driver of this growth, contributing over 600 GW of new capacity in 2024 alone. The following table illustrates the global distribution of renewable energy generation capacity as of the end of 2025 [27, 28, 29].

Table I. 3: Global Distribution of Renewable Energy Generation Capacity (End of 2025) [28, 29, 30]

Energy Source	Capacity (GW)	Share of Total Renewables (%)
Solar PV	2,391	46.4%
Hydropower	1,420	27.6%
Wind Energy	1,120	21.7%
Bioenergy	195	3.8%
Others (Geothermal, Marine)	23	0.5%

I.3.2. situation of renewable energy in Algeria

The government has launched a promising programmatic initiative (2030-2035), seeking to generate 22 gigawatts of renewable energy by 2030. The company plans to direct 12 gigawatts of it to cover local needs, and allocate the remaining 10 gigawatts for export. These targets are distributed between solar photovoltaic energy with a share (62%), wind energy with a share (23%), in addition to allocating 2 gigawatts for central solar energy (CSP)[31]

On the ground, Algeria is now halfway to achieving these ambitions, ranking 22nd among Africans in terms of total installed capacity, which reached 590 megawatts in 2023. Progress is clearly evident in the solar energy sector, which jumped to 451 megawatts in the same year, placing the country 12th on the continent, thanks to the launch of major projects aimed at effectively exploiting solar radiation. On the other hand, although wind energy is still in its early stages with a modest capacity not exceeding 10 megawatts in 2023, efforts are continuing to explore new areas and establish wind farms that allow maximum benefit from the country's natural [31].

Table I. 4: Renewable Energy Infrastructure in Algeria: Operational Project [32, 33, 34, 35, 36]

Project Name / Location	Technology Type	Installed Capacity (MW)
Hassi Rmel (Tilghemt)	Integrated Solar Combined Cycle (ISCC) / Hybrid	150 MW total (25 MW Solar + 125 MW Gas)
El Kheneg (Laghouat)	Solar Photovoltaic (PV)	60 MW
Djelfa Solar Plant	Solar Photovoltaic (PV)	40 MW
Adrar (Kaberten)	Onshore Wind Power	10.2 MW
Ghardaïa Pilot Plant	Solar Photovoltaic (PV)	1.1 MW
High Plateaus & South PV Fleet (Batna, M'Sila, In Salah, Timimoun, etc.)	Solar Photovoltaic (PV)	Approx. 340 MW (Combined total)
Solar 1,000 MW & 2,000 MW Batches (El Oued, Khenchela, Kenadsa, etc.)	Solar Photovoltaic (PV)	Multiple lots (Hundreds of MWs)

I.4. Situation of hydrogen in Algeria and the world

The global green hydrogen market is experiencing rapid growth as economies worldwide strive to reduce their carbon emissions. While this market currently accounts for less than 1% of total hydrogen production Which reached 97 million tons in 2023, it is projected to exhibit exceptional compound annual growth rates (CAGR) exceeding 45-50% through 2030. Market projections through 2036 indicate significant growth potential. A decisive turning point is expected between 2030 and 2031; when green hydrogen will begin to be cost-comparative with blue hydrogen in suitable regions, thus accelerating its industrial adoption. Production volumes underscore the true scale of this emerging industry. Green hydrogen production, which started at less than one million tons in 2024, is projected to reach 100 to 138 million tons by 2036, representing a 100-to 150- time increase in twelve years.

I.4.1. Hydrogen Development in Algeria

Le pompage Algeria aims to establish itself as a key player in the global green hydrogen market as part of its long-term energy transition strategy. Thanks to its abundant renewable energy resources, the development of green hydrogen is expected to modernize the national energy sector and stimulate economic diversification. The 2023 National strategy focuses on developing a renewable (green) and clean (blue) hydrogen sector to drive Algeria's energy transition, enhance energy security, and support climate change commitments by establishing a robust industrial and regulatory framework to foster hydrogen production, storage, transport, and use. Key goals include:

- Becoming a regional and international leader in hydrogen production and export by 2040.
- Producing and exporting 30-40 TWh of hydrogen and derivatives to meet 10% of Europe's needs.
- In 2024, Germany and Algeria strengthened their cooperation in the field of green hydrogen by establishing a bilateral hydrogen working group and developing a pilot plant, while Sonatrach and Sonelgaz signed a memorandum of understanding with European partners to launch feasibility studies for the large-scale production and export of green hydrogen via pipelines to Europe.
- In October 2024, Cepsa and Sonatrach signed a memorandum to conduct a feasibility study for developing an integrated project for green hydrogen production in Algeria, targeting the europ market [37].

I.5. Applications and Uses of Hydrogen

Hydrogen can be converted into electricity, heat, or motive power, depending on the end use. It has the advantage of offering storage capacity (a problem with electricity) and can be produced without CO₂ emissions (although this is not currently the case for the most part, as mentioned earlier).

As an energy carrier, it has the following applications:

- Stationary applications: energy storage in buildings, providing electricity and heat through cogeneration, which would enable the development of net-positive energy buildings:
- Mobile applications: hydrogen can power vehicles equipped with internal combustion engines running on gas. Furthermore, a hydrogen tank can be combined with a fuel cell to improve the range of electric vehicles
- industrial applications: hydrogen is a chemical component widely used in industry. Most of the hydrogen is used by industrialists for its chemical properties, particularly in ammonia plants (60% of the world's hydrogen consumed by industry in 2022) and in oil refineries (desulfurization of gasoline and diesel, production of methanol, etc.) [38].

I.6. Terga Thermal Power Plant (SKA3)

The Terga power plant project is a 1200 MW combined-cycle natural gas-fired power plant located in the Terga region, Ain Temouchent Province, Algeria. The project is managed by Sharikat Kahraba Terga (SKT), a subsidiary of the Algerian state-owned company Sonelgaz. The plant plays a strategic role in the Algerian national electricity grid, utilizing advanced combined-cycle technology to maximize efficiency and minimize environmental impact[39].

I.6.1. Technical characteristics

The technical characteristics of the Terga Electrical Station (SKA3) are summarized in the table below:

Table I. 5: Technical characteristics of Terga Electrical Station (SKA3) [39]

Characteristics	Description
Type of station	Gas-fired combined cycle power generation facility (CCGT)
Capacity	1200 MW (3 blocks of 400 MW each)
Location	Terga, Ain Temouchent, Algeria
Site area	Approximately 40 hectares
Characteristics	Description
Gas turbines	Three (3) Alstom GT26 high-efficiency gas turbines
Steam turbines	Three (3) Steam turbines (one for each block)
Steam generators	Three (3) Heat Recovery Steam Generators (HRSGs)
Emissions control	Features advanced combustion technology (Dry Low NO _x) and water injection systems to reduce atmospheric emissions (CO ₂ , NO _x , SO ₂).

I.7. Conclusion

This chapter explores the role of renewable energies and hydrogen in the global energy transition. Green hydrogen produced from renewable sources is a promising solution for energy storage and carbon emission reduction. Algeria possesses significant potential for developing this sector thanks to its solar resources and energy infrastructure. Therefore, subsequent chapters will focus on modeling of green hydrogen production using photovoltaic systems to evaluate their performance

Chapter II: Litterateur review, modeling, and hydrogen system

II.1. Introduction

Understanding hydrogen production, storage, and conversion technologies is crucial for designing efficient systems. This chapter begins by providing a comprehensive literature review outlining available options, known failure patterns, performance limits, and experimental data, thus transforming guesswork into informed component selection and sound assumptions. This qualitative foundation directly informs the mathematical modeling of the system under consideration, quantitatively integrating the behavior of discrete components within a virtual test environment. The model then enables a detailed performance analysis by identifying trade-offs (e.g., efficiency versus weight), determining key loss mechanisms, and specifying component sizes for operating cycles. This allows the designer to predict and compare system behavior under realistic conditions rather than relying on static data tables.

II.2. Literature review

II.2.1. Hydrogen production technologies

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Three technologies currently dominate the industrial and scientific landscape: alkaline electrolysis (ALK), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC). [40]

- **Study 1**

In a comprehensive 2025 study published in *Applied Energy*, J. Wang and colleagues conducted a side-by-side experimental comparison of ALK and PEM systems. Comparative investigations have indicated that alkaline electrolysis typically consumes approximately 4.6–4.8 kWh/m³ under standard conditions. Operation at up to 30% of the rated load is achievable, contingent upon diligent control of gas purity. Although this electrolysis method is recognized for its stability, it presents comparatively lower operational flexibility when contrasted with proton exchange membrane (PEM) electrolysis systems [41].

- **Study 2**

Research led by C.K. Kjartansdóttir, published in the *International Journal of Hydrogen Energy*. Further research, specifically concerning advanced electrode designs, has revealed advancements in both efficiency and durability. These improvements are characterized by reduced energy losses and a demonstrated capacity for stable operation extending beyond

9,000 hours. Such developments suggest that alkaline electrolysis is increasingly well-suited for deployment in large-scale industrial contexts [42].

- **Study 3**

A 2025 study by Chen Aijun and colleagues, published in Scientific Reports. An investigation into PEM electrolysis systems underscored their rapid dynamic response and significantly reduced start-up times, achieving reductions of up to 82%. It was noted, however, that sustaining system stability requires meticulous control over gas concentrations throughout the operational phase [43].

- **Study 4**

As part of the same comparative framework established by J. Wang et al. (2025). Furthermore, comparative studies have indicated that proton exchange membrane (PEM) electrolysis generally offers higher efficiency, consuming approximately 4.1–4.3 kWh/m³ under standard conditions. Its capacity for stable operation at low loads, down to 10%, renders it particularly well-suited for integration with intermittent renewable energy sources [44].

- **Study 5**

In a 2025 study published in the International Journal of Sustainable Energy, S. Hasbi and colleagues addressed this challenge by using numerical simulations combined with Response Surface Methodology (RSM). Simulation-based research has indicated that optimizing the thermal operating conditions can mitigate internal stress and enhance durability. This, in turn, contributes to an improved performance of SOEC systems when operating at elevated temperatures [45].

- **Study 6**

In a notable development for the Power-to-Liquid sector, M. Tandl and colleagues presented a study in the 2025. An experimental investigation further demonstrated that the co-electrolysis of H₂O and CO₂ has the potential to reduce electricity consumption by 16–37%. This approach also contributes to an enhanced efficiency in the production of synthetic fuels [46].

II.2.2. Hydrogen storage technologies

Hydrogen storage is a crucial element in the development of hydrogen-based energy systems. Due to its low volumetric density and high diffusivity, the efficient and safe storage of hydrogen presents a major challenge for its large-scale use. Several technologies have been developed to

Address this need, including compressed gas storage, liquid storage, and solid-state storage based on specific materials. Each method has advantages and limitations depending on the intended application [48].

- **Gas storage**

Gaseous storage is the most widespread and technically mature method. In this technology, hydrogen is compressed and stored in tanks under high pressure, typically between 200 and 700 bars.

- **Study 1**

In a 2025 study published in *Energy Technology*, M.D. Solomon and colleagues conducted a detailed techno-economic analysis of gaseous hydrogen storage in pressure vessels ranging from 200 to 540 bar. The research focused on the technical challenges of the filling process, particularly the pressure and temperature variations that occur at high mass flow rates. The study found that while rapid filling leads to significant temperature fluctuations requiring precise thermal management, the Levelized Cost of Hydrogen Storage (LCOHS) decreases substantially as the scale of demand increases. The researchers concluded that 350-bar trailers currently represent the most cost-effective solution for short-to-medium distances, whereas 540-bar systems offer superior economic performance for long-distance transportation. These insights provide a critical foundation for optimizing the infrastructure required for large-scale hydrogen distribution [49].

- **Study 2**

Research led by M. Altuntas-Vahapo, published in the *International Journal of Hydrogen Energy* in 2026, investigated the environmental and economic trade-offs between traditional steel (Type I) and advanced composite (Type II–V) hydrogen storage tanks. The methodology utilized a comprehensive model to assess cradle-to-gate emissions and material costs for tanks operating at pressures up to 1000 bar. The findings revealed that Type I steel tanks have the lowest environmental impact, with emissions ranging from 82 to 143 kgCO₂e/kg H₂, and the

lowest costs, between \$81 and \$189/kg H₂. Conversely, high-pressure composite tanks incurred significant environmental penalties due to the energy-intensive nature of carbon fiber production. The study emphasizes that while composite tanks are essential for weight-sensitive mobile applications, steel tanks remain the most sustainable and cost-effective solution for stationary storage where space is not a primary constraint. [50].

- **Liquid storage**

The process of storing liquid hydrogen involves cooling hydrogen to approximately -253°C to liquefy it and increase its volumetric energy density. This method allows for the storage of large quantities of hydrogen in a relatively small volume. However, liquefying hydrogen requires a significant amount of energy, potentially between 25% and 40% of its energy content. Furthermore, deep-cooled tanks experience evaporation losses estimated at 0.1% to 0.5% per day. For these reasons, this technology is typically used for transporting large quantities of hydrogen over long distances.

- **Study 1**

A 2026 study by Y.M. Seo and colleagues, published in the International Journal of Hydrogen Energy, developed a reproducible experimental framework for quantifying boil-off gas (BOG) generation in liquid hydrogen storage. Moving away from indirect pressure-based estimation methods, the researchers employed a vent-line Coriolis mass flow meter to directly measure vaporization rates under controlled thermal loads. The experimental results successfully isolated intrinsic heat ingress from externally induced vaporization, demonstrating a clear and predictable response of BOG flow rates to thermal stress. This research provides an experimentally grounded framework for evaluating "Zero Boil-Off" (ZBO) concepts and serves as a vital tool for testing the performance of next-generation insulation materials in real-world liquid hydrogen systems [51].

- **Study2**

In a study focused on extreme-performance insulation, Y. Yu and colleagues presented research in the 2025 journal *Astrodynamics* regarding thermal protection strategies for liquid hydrogen tanks in Martian environments. The researchers investigated the unique challenge of rarefied CO₂ condensation within multilayer insulation (MLI) and developed a New Insulation Scheme (NIS) to maintain thermal integrity. The proposed NIS achieved a remarkably low heat leakage rate of 0.298 W/m², which is two to four orders of magnitude more efficient than conventional composite

insulation structures. Although the study was conducted within the context of space exploration, the findings offer profound insights into high-efficiency insulation techniques that can be adapted for terrestrial liquid hydrogen storage, particularly for minimizing losses during long-duration storage and transport [52].

- **Solid storage**

Solid-state storage relies on the absorption of hydrogen in specific materials such as metal hydrides. In this process, hydrogen molecules dissociate into atoms that are then absorbed into the crystalline structure of the metal to form a metal hydride. This process is reversible: the hydrogen can be released by heating the material. [53].

- **Study 1**

Research led by M.W. Davids, published in the Journal of Alloys and Compounds in 2025, focused on the development and optimization of a medium-scale (1.4 Nm³) metal hydride container for on-board fuel cell applications. The system utilized a powdered composite of Laves-type hydride doped with copper and graphite oxide to enhance both heat transfer and structural stability. Experimental results showed that the container could reach 70% of its hydrogen capacity in just 10 to 15 minutes at a pressure of 50 bar. Furthermore, the study demonstrated that 90% of the stored hydrogen could be released at a steady flow rate by heating the container to a moderate temperature of 40°C. This work highlights the feasibility of metal hydride systems as a safe, low-pressure alternative to compressed gas tanks for industrial mobile applications like fuel cell forklifts [54].

- **Study 2**

In a 2025 study published in the Journal of Energy Storage, S. Parashar and colleagues investigated the performance of a stationary metal hydride reactor using a newly developed La-Ce-Ni-Co alloy. To overcome the traditional bottleneck of slow thermal management, the researchers designed a novel disc-finned multi-tube reactor to enhance hydrogen absorption and desorption kinetics. Parametric testing revealed that this design achieved absorption rates 55% to 84% faster than previously reported reactor configurations, absorbing nearly 270 g of hydrogen in under 12 minutes. The reactor attained a volumetric hydrogen storage density of 26.4 kg/m³ and demonstrated high heat transfer effectiveness. These results prove that advanced heat exchanger designs can significantly improve the operational efficiency of metal hydride systems, making them a viable high-performance option for stationary energy storage [55].

Table II. 1: Comparison of the main hydrogen storage technologies [53]

Technology	Storage Capacity	Efficiency	Volumetric Density	Advantages	Disadvantages
Gaseous storage (200–700 bar)	0.1 – 10 MWh	85 – 91 %	670 – 1300 kWh/m ³	Mature technology, suitable for long-term storage	Risk associated with high pressure
Liquid storage	0.1 – 100 GWh	55 – 75 %	1400 – 1600 kWh/m ³	High energy density	High cost and evaporation losses
Metal hydrides	0.1 kWh – 25 MWh	80 – 98 %	Up to 4200 kWh/m ³	High safety, operation at low pressure	High weight and long charging time

II.2.3. Hydrogen-based Energy Conversion Technologies

The conversion of hydrogen into usable energy is a crucial step in integrating hydrogen into modern energy systems. This conversion transforms the chemical energy of hydrogen into electricity or usable mechanical energy for various sectors, including transportation, industry, and power generation. Key technologies used for this conversion include fuel cells and hydrogen internal combustion engines, which represent two distinct approaches to harnessing the energy potential of hydrogen [56, 57].

Fuel cells are electrochemical devices that directly convert the chemical energy of hydrogen and oxygen into electricity, while producing water and heat as byproducts. Unlike traditional combustion systems, fuel cells allow for more efficient energy conversion and generate very few polluting emissions, making them a promising technology for sustainable energy systems [56].

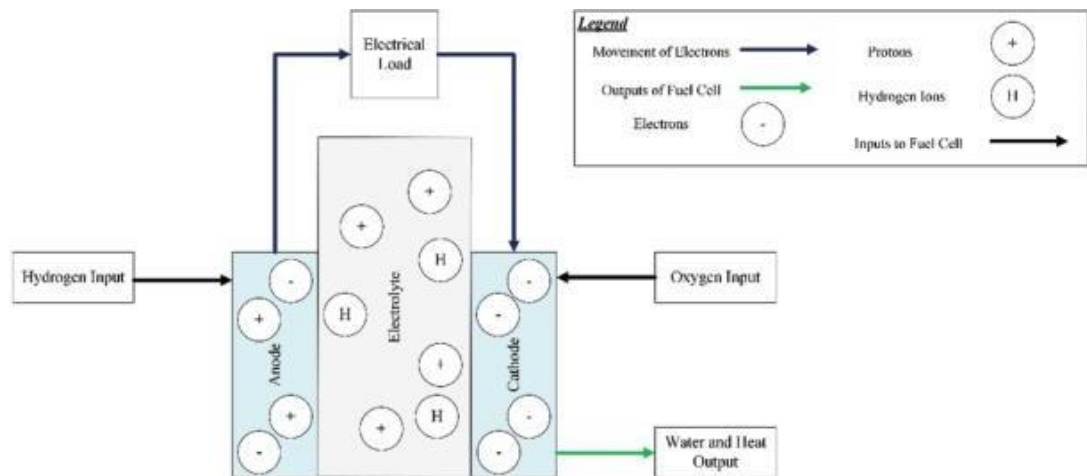


Figure II. 1: Hydrogen-based Energy Conversion Technologies [55]

- **PEMFC**

Operate at low temperatures, typically between 60 and 80 °C, and use a polymer membrane as an electrolyte to transport protons between the anode and cathode. They are characterized by rapid start-up, high power density, and a compact design.

- **Study 1**

In a study published in 2026 in the Journal of Renewable Energy, an experimental analysis of the reversible degradation of proton exchange membrane fuel cells (PEMFCs) under dynamic loading cycles was conducted. The researchers focused on the interconnected stresses of dynamic operation, which are common in transportation applications. By subjecting a set of PEMFCs to accelerated durability tests, the study quantified the performance loss associated with rapid load changes. The results revealed that a significant portion of the voltage degradation observed during dynamic operation is reversible through specific recovery protocols. This research provides a crucial framework for developing advanced control strategies capable of reducing degradation and extending the operational lifespan of fuel cells in hydrogen vehicles [58].

- **Study 2**

In a 2025 article published in the journal Energy, a team of experimental researchers investigated the dynamic response of a 1-kilowatt proton exchange membrane fuel cell

(PEMFC) array. The methodology involved loading the cell array from its open-circuit state to its nominal state while monitoring voltage stability and response time. The results showed that, although PEMFCs provide fast start-up and high power density, transient behavior during large load changes can lead to a "temporary voltage drop," affecting the overall system efficiency. The study highlights the importance of optimizing the air and fuel subsystems to match the electrochemical response time, thus ensuring stable performance under the highly variable power demands of modern electrical systems [59].

- **Solid oxide fuel cells (SOFC)**

operate at high temperatures, typically between 600 and 1000 °C, and use a solid ceramic electrolyte that conducts oxygen ions. Thanks to their high operating temperature [57].

- **Study 1**

Controlling internal thermal gradients is one of the major challenges in solid oxidation fuel cell (SOFC) technology, as it can lead to mechanical failures. A review and experimental analysis published in 2025 in the journal Energy Resources presented a systematic study of heat transfer phenomena within solid oxidation fuel cells. Researchers used a combination of numerical modeling and experimental verification to analyze how the geometry and flow rates of the gas channels affect temperature distribution. The study concluded that improving the thermal management unit can significantly reduce internal stresses and thus extend the lifetime of the ceramic electrolyte. These results are fundamental for the design of robust, large-scale SOFC systems for stationary power generation [60].

- **Study 2**

A 2025 study published in the Journal of Applied Thermal Engineering provided a comparative evaluation of six different configurations of solid oxidation fuel cell power plants. Researchers analyzed the efficiency of these systems when combined with various reforming methods, such as steam methane reforming and partial oxidation. The results showed that hybrid systems based on solid oxidation fuel cells (SOFCs) are capable of achieving electrical efficiency exceeding 60% by efficiently recovering waste heat. The study emphasizes the diverse applications of solid oxidation fuel cells with different fuel types and highlights the technical pathways needed to increase the efficiency of high-temperature hydrogen energy conversion [61].

Table II. 2: Comparison between PEMFC and SOFC [55]

Characteristic	PEMFC (Proton Exchange Membrane Fuel Cell)	SOFC (Solid Oxide Fuel Cell)
Operating temperature	60–80 °C	600–1000 °C
Electrolyte	Polymer membrane	Solid oxide (ceramic)
Catalyst	Platinum (expensive)	Usually not required
Fuel	Pure hydrogen	Hydrogen, natural gas, biogas
Electrical efficiency	40–60 %	45–65 %
Start-up time	Fast	Slow
Main applications	Transportation, portable systems, small to medium stationary power	Large stationary power generation and cogeneration

- **Hydrogen internal combustion engines**

represent another technology for converting the chemical energy of hydrogen into mechanical energy. In these systems, hydrogen is injected into the combustion chamber and burned with air to produce mechanical energy used for propulsion or electricity generation.

- **Study 1**

While hydrogen-powered internal combustion engines offer a path to zero carbon emissions, the high combustion temperatures of hydrogen can lead to increased nitrogen oxide (NO_x) production. In a study published in 2025 by Springer-Verlag, A.Your. Prajapati and colleagues conducted an experimental investigation of the effect of adding hydrogen on the emissions and performance of internal combustion engines. The research focused on the trade-offs between thermal efficiency and NO_x levels. The results indicated that while hydrogen significantly improves combustion speed and efficiency, it requires the application of sophisticated after treatment systems or mitigation combustion strategies to keep NO_x

emissions within environmental standards. This study provides vital data for the development of clean hydrogen engines for heavy-duty transportation [62].

- **Study 2**

A 2025 study published by the Society of Automotive Engineers International (SAE International) explored the mixing and combustion characteristics of direct-injection hydrogen engines. The study used a high-performance stoichiometric combustion engine to analyze how fuel injection timing and pressure affect the homogeneity of the hydrogen-air mixture. The results revealed that direct fuel injection (DI) systems are capable of significantly reducing the risk of back burning and premature ignition, two common problems in port-injection hydrogen engines. Furthermore, the researchers demonstrated that precise control of the injection process can lead to a more stable combustion cycle and a reduction in gross NO_x emissions, making direct-injection hydrogen-powered internal combustion engines (DI H₂-ICE) a promising technology for the transition to zero-emission mobility [63].

II.3. Modeling of hydrogen systems

II.3.1. Description of the system studied

- **General system architecture**

The proposed system is a hydrogen production system using solar energy, and consists of two main interconnected subsystems. The first is a photovoltaic power generation system, which includes an array of solar panels that convert solar radiation into direct current electrical energy, directly feeding the electrolyzer. The second is the hydrogen production system, which receives electricity from solar panels and feeds an electrolyzer, where water is electrolyzed to produce hydrogen (H₂) and oxygen (O₂). The hydrogen produced is measured by a hydrogen collector and then stored in a storage tank for later use. This design includes a direct and simple energy conversion chain, from solar energy to storable hydroge

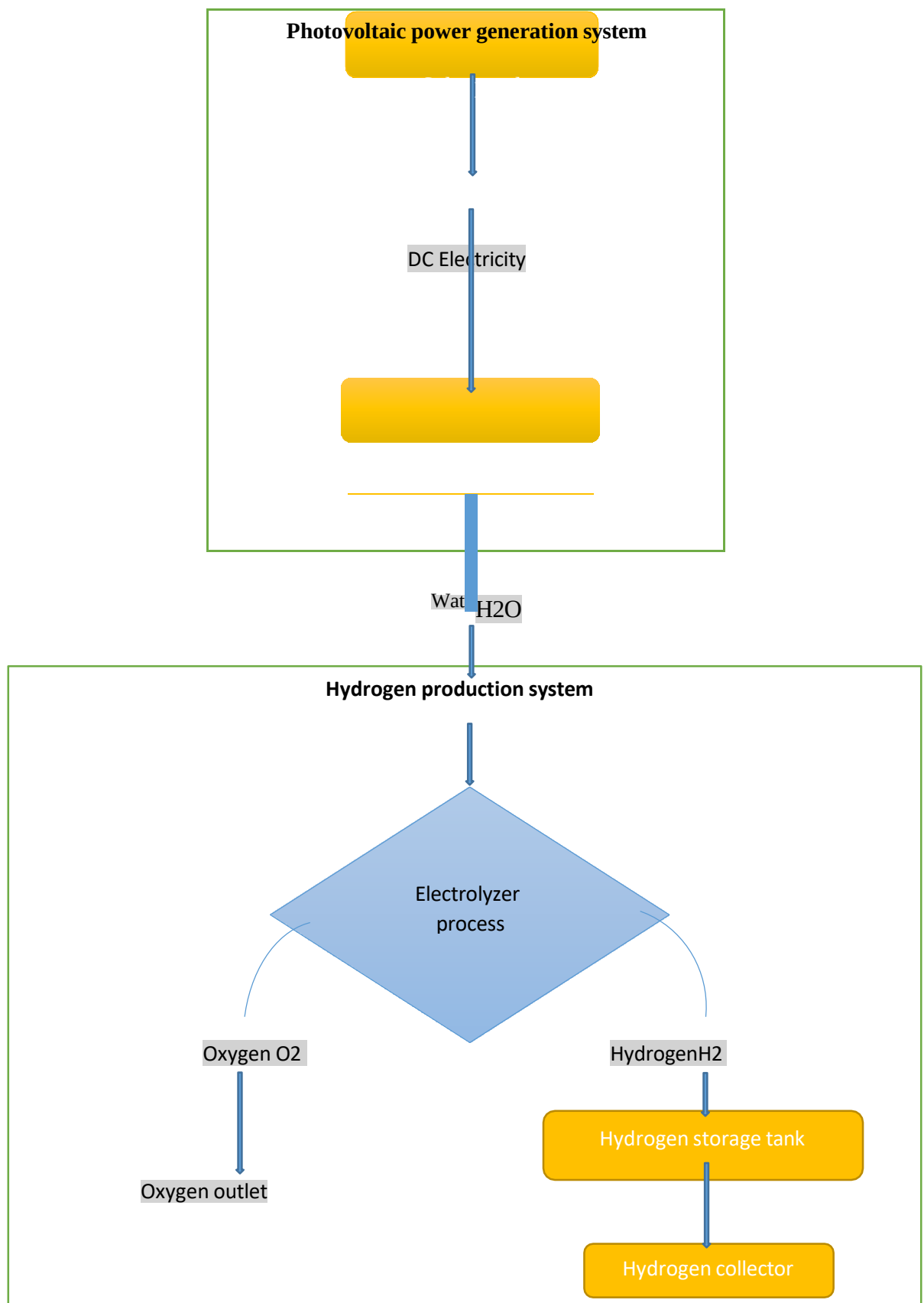


Figure II. 2:General system architecture

II.4. Mathematical modeling

These models are essential for simulating system behavior, evaluating its performance, and optimizing its sizing and operation.

II.1.1. Photovoltaic model Description

The PV Array block implements an array of photovoltaic (PV) modules. The array is built of strings of modules connected in parallel, each string consisting of modules connected in series.

This block allows modeling of preset PV modules from the National Renewable Energy Laboratory (NREL) System Advisor Model (2018), as well as PV modules that you.

The PV Array block is a five-parameter model using a light-generated current source (I_L), a diode, series resistance (R_s), and shunt resistance (R_{sh}) to represent the irradiance- and temperature-dependent I-V characteristics of these modules [64].

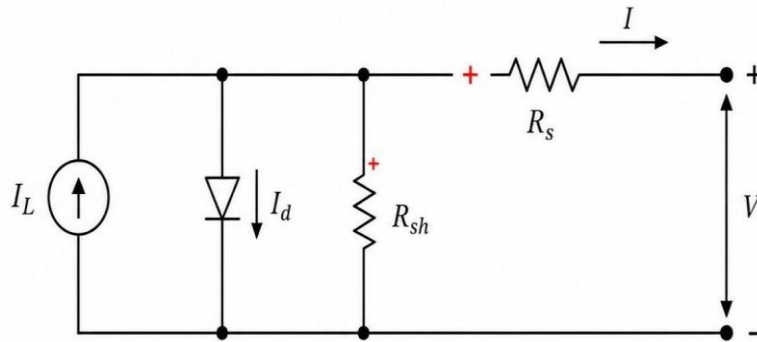


Figure II. 3: Equivalent circuit [59]

- **Equivalent Circuit Component Summary**

Table II. 3: Equivalent Circuit Component Summary [64]

Symbol	Parameter description
I_L	Light-generated current source proportional to irradiance
I_d	Diode current models charge carrier recombination
R_s	Series resistance (models internal wiring and contact resistance)
R_{sh}	Shunt (parallel) resistance (models internal leakage currents)
V	Output voltage of the module (V)
I	Output current of the module (A)

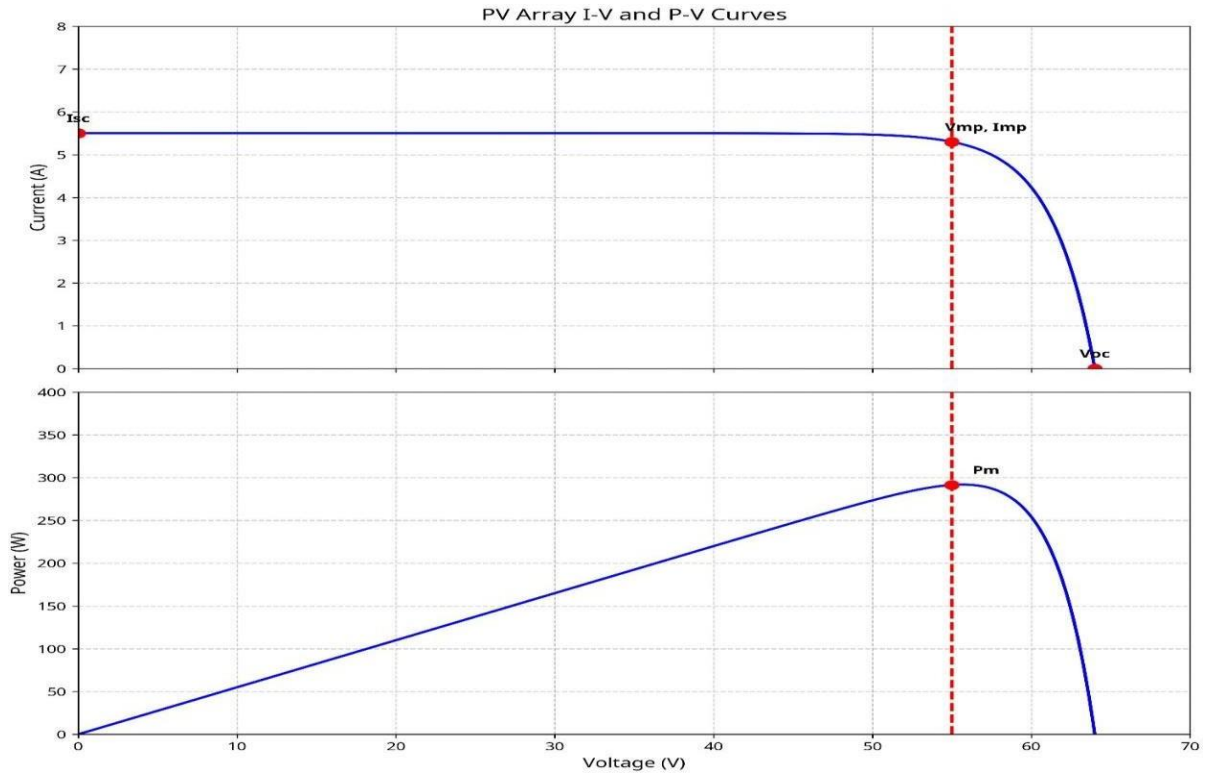


Figure II. 4: (I-V), (P-V) Curves [64]

- **Key Operating Points on the I-V Curve**

Table II. 4: Key-Operating Points on the I-V Curve [64]

Symbol	Parameter description
Isc	Short-circuit current (current when output terminals are shorted)
Voc	Open-circuit voltage (voltage when no current flows)
Vmp	Voltage at Maximum Power Point (MPP)
Imp	Current at Maximum Power Point (MPP)
Pmax	Maximum output power = $V_{mp} \times I_{mp}$ (W)

- **Governing Equations**

Diode Current Equation:

$$I_D = I_0 \times [e^{(V_D/V_T)} - 1]$$

Thermal Voltage:

$$V_T = \frac{K \times T}{q} \times n_I \times N_{cell}$$

- **Variable Definitions**

Table II. 5: Variable Definitions [64]

Symbol	Parameter description	Value / Unit
Id	Diode current	A
Vd	Diode voltage	V
I0	Diode saturation current	A
nI	Diode ideality factor (close to 1.0)	—
k	Boltzmann constant	$1.3806 \times 10^{-23} \text{ J} \cdot \text{K}^{-1}$
q	Electron charge	$1.6022 \times 10^{-19} \text{ C}$
T	Cell temperature	K
Ncell	Number of cells in series per module	—
IL	Light-generated current source	A
Rs	Series resistance	Ω
Rsh	Shunt (parallel) resistance	Ω

- **Input Ports**

Table II. 6: Input Ports [64]

Port	Type	Range	Description
Ir	Scalar	[0, 1000] W/m ²	Irradiance control signal applied to solar panels
T	Scalar	Any value °C	Cell temperature control signal (negative / zero / positive)

Note: Port T is only available when the Robust discrete model parameter is cleared (unchecked).

- **Output Port m (Five-Element Vector)**

The output m is a five-element vector accessible via the Bus Selector block in the Simulink library.

Table II. 7: Output Port m (Five-Element Vector) [64]

Signal Name	Definition
V_PV	PV array voltage (V)
I_PV	PV array current (A)
I_diode	Diode current (A)
Irradiance (W/m ²)	Solar irradiance (W/m ²)
Temperature (deg C)	Cell temperature (°C)

- **Conserving Ports (Specialized Electrical)**

Table II. 8: Conserving Ports (Specialized Electrical) [64]

Port	Description
+ (Positive)	Specialized electrical conserving port — positive terminal of the PV array
– (Negative)	Specialized electrical conserving port — negative terminal of the PV array

II.1.2. Electrolyzer Model

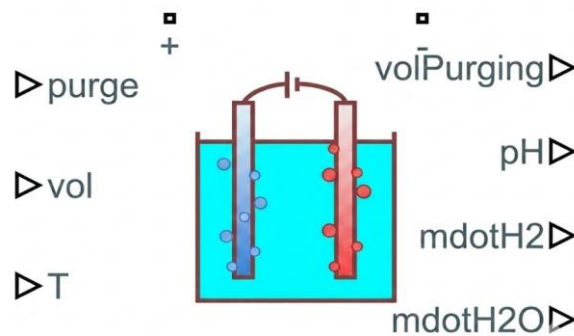
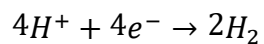
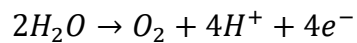


Figure II. 5: Electrolyzer Model [65]

The electrolyzer model describes the relationship between voltage, current, and hydrogen production. In polymer electrolyte membrane (PEM) electrolyzers, these chemical reactions define the anode and cathode conversions[59]



The Electrolyzer block calculates the electrical power by using

$$P_E = \frac{V^2}{R_T}$$

Where v is the voltage and R_T is the total resistance. The total resistance, R_T , is defined by

$$\frac{1}{R_T} = \frac{1}{R_{el}} + \frac{1}{R}$$

Where:

R is the external resistance.

$R_{el} = \frac{\rho(\text{pH})x}{A}$ This value is a resistive term obtained from the cross-sectional transport area, A , the distance anode-cathode, x , and the electrical resistivity of the solution, $\rho(\text{pH})$.

The molar energy stored across the electrical load enables the process of water electrolysis and is calculated by this equation:

$$G_E = \frac{P_E}{1\text{mol/s}}$$

To accomplish electrolysis, the electrolyzer requires a minimum amount of energy

$$G_{min} = \Delta H - \frac{T}{T_0} \times T_{\Delta s}$$

Where:

ΔH is the water enthalpy.

$T_{\Delta s}$ Is the reaction entropy.

T is the water temperature.

T_0 is the reference temperature.

II.1.3. Hydrogen Storage Model

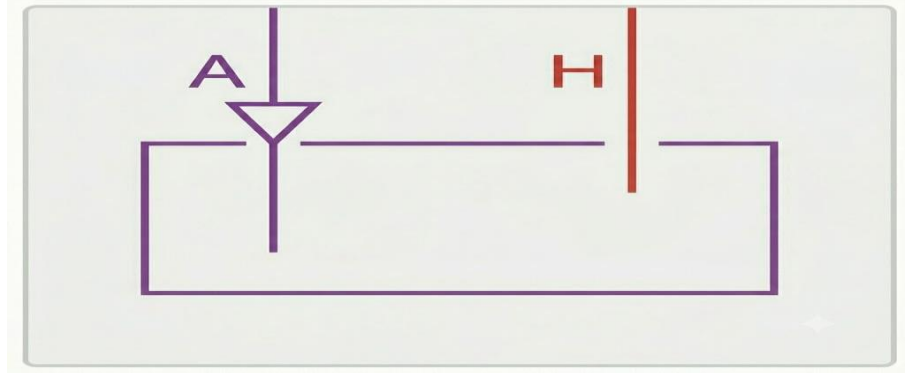


Figure II. 6: Hydrogen Storage Model [65]

The Constant Volume Chamber (G) block models mass and energy storage in a gas network. The chamber contains a constant volume of gas. It can have between one and four inlets. The enclosure can exchange mass and energy with the connected gas network and exchange heat with the environment, allowing its internal pressure and temperature to evolve over time. The pressure and temperature evolve based on the compressibility and thermal capacity of the gas volume.

- **Mass Balance**

Mass conservation relates the mass flow rates to the dynamics of the pressure and temperature of the internal node representing the gas volume [64]:

$$\frac{\partial M}{\partial P} \cdot \frac{dP_I}{dt} + \frac{\partial M}{\partial T} \cdot \frac{dT_I}{dt} = \dot{m}_A + \dot{m}_B + \dot{m}_C + \dot{m}_D$$

Where:

$\frac{\partial M}{\partial P}$ is the partial derivative of the mass of the gas volume with respect to pressure at constant temperature and volume.

$\frac{\partial M}{\partial T}$ is the partial derivative of the mass of the gas volume with respect to temperature at constant pressure and volume.

P_I is the pressure of the gas volume. The pressure at ports **A**, **B**, **C**, and **D** is assumed to be equal to this pressure, $P_A = P_B = P_C = P_D = P_I$.

T_I is the temperature of the gas volume. The temperature at port **H** is assumed to be

equal to this temperature, $T_H = T_I$.

t is time.

$\dot{m}_A$ is the mass flow rate at port **A**. The flow rate associated with a port is positive when it flows into the block.

$\dot{m}_B$ is the mass flow rate at port **B**. The flow rate associated with a port is positive when it flows into the block.

$\dot{m}_C$ is the mass flow rate at port **C**. The flow rate associated with a port is positive when it flows into the block.

$\dot{m}_D$ is the mass flow rate at port **D**. The flow rate associated with a port is positive when it flows into the block

- **Perfect Gas Model**

The partial derivatives of the mass M and the internal energy U of the gas volume, with respect to pressure and temperature at constant volume, depend on the gas property model. For perfect and semiperfect gas models, the equations are [64]:

$$\frac{\partial M}{\partial p} = V \cdot \frac{\rho_I}{P_I}$$

$$\frac{\partial M}{\partial T} = -V \cdot \frac{\rho_I}{T_I}$$

$$\frac{\partial U}{\partial p} = V \left(\frac{h_I}{ZRT_I} - 1 \right)$$

$$\frac{\partial U}{\partial T} = V \rho_I \left(c_{pI} - \frac{h_I}{T_I} \right)$$

Where:

ρ_I is the density of the gas volume.

V is the volume of gas.

h_I is the specific enthalpy of the gas volume.

Z is the compressibility factor.

R is the specific gas constant.

c_{pI} is the specific heat at constant pressure of the gas volume.

- **Real Gas Model**

For real gas model, the partial derivatives of the mass M and the internal energy U of the gas volume, with respect to pressure and temperature at constant volume, are [64]:

$$\frac{\partial M}{\partial T} = V \frac{\rho_I}{\beta_I}$$

$$\frac{\partial M}{\partial T} = -V \rho_I \alpha_I$$

$$\frac{\partial U}{\partial p} = V \left(\frac{\rho_I h_I}{\beta_I} - h_I \alpha_I \right)$$

$$\frac{\partial U}{\partial T} = V \rho_I (c_{pI} - h_I \alpha_I)$$

where:

β is the isothermal bulk modulus of the gas volume.

α is the isobaric thermal expansion coefficient of the gas volume.

II.5 Conclusion

This chapter provides an literature review and the development of mathematical models for production, storage, and conversion are presented, along with a description of the system under study.

Mathematical models are developed for each component, forming the basis for system simulation and performance analysis.

Chapter III: Simulation and results

III.1. Introduction

In light of the global trend towards renewable energy, this study proposes the design of a green hydrogen production system using photovoltaic solar energy, with the aim of meeting the needs of a 1200 MW power plant in Ain Temouchent Province. In this chapter, we will simulate a green hydrogen production system using solar panels, employing MATLAB/Simulink software to model the various system components.

III.2. Load profile

III.2.1. Geographic location and climate of Aïn Temouchent

The state of Ain Temucent is located in northwestern Algeria, about 500 kilometers west of the capital. We see in (table III.1) Coordinate of Aïn Témouchent and in (fig III.1) Location of Ain Temouchent.

Table III. 1: Coordinate of Aïn Témouchent

Coordinate	Value
Latitude	35.300° N (35° 18' 00" N)
Longitude	1.133° W (1° 08' 00" W)
Altitude	~296 meters above sea level



Figure III. 1: Location of Ain Temouchent.

- **Geographical location of the study site**

The Terga thermal power station is a combined-cycle thermal power plant located in north of Algeria, 10 km from Aïn Témouchent to the town of Ouled Boudjemaa road of sessel.

III.2.2. Solar irradiance and meteorological data

- **General climate of the region**

Ain Temouchent has a classic Mediterranean climate with hot, dry summers and mild, humid winters. The area generally enjoys comfortable and sunny weather year-round.

- **Temperature data**

Temperature is one of the most important climatic factors that control the behavior of photovoltaic systems. As temperature increases, solar panels' electricity production decreases. Accurate temperature accounting in the simulation model includes a realistic estimate of the photovoltaic array output, which in turn determines the amount of electrical energy available to produce hydrogen. To characterize the thermal conditions at the project site, 20 years of meteorological data recorded at Ain Temouchent (2004–2024) were analyzed. The results are displayed through two complementary files: the intermediate daytime file (figure. 3.2), which shows the typical hourly temperature change over a representative day, and the average monthly profile (figure. 3.3), which captures seasonal variation throughout the year. Both coils are used as meteorological inputs for the photovoltaic array.

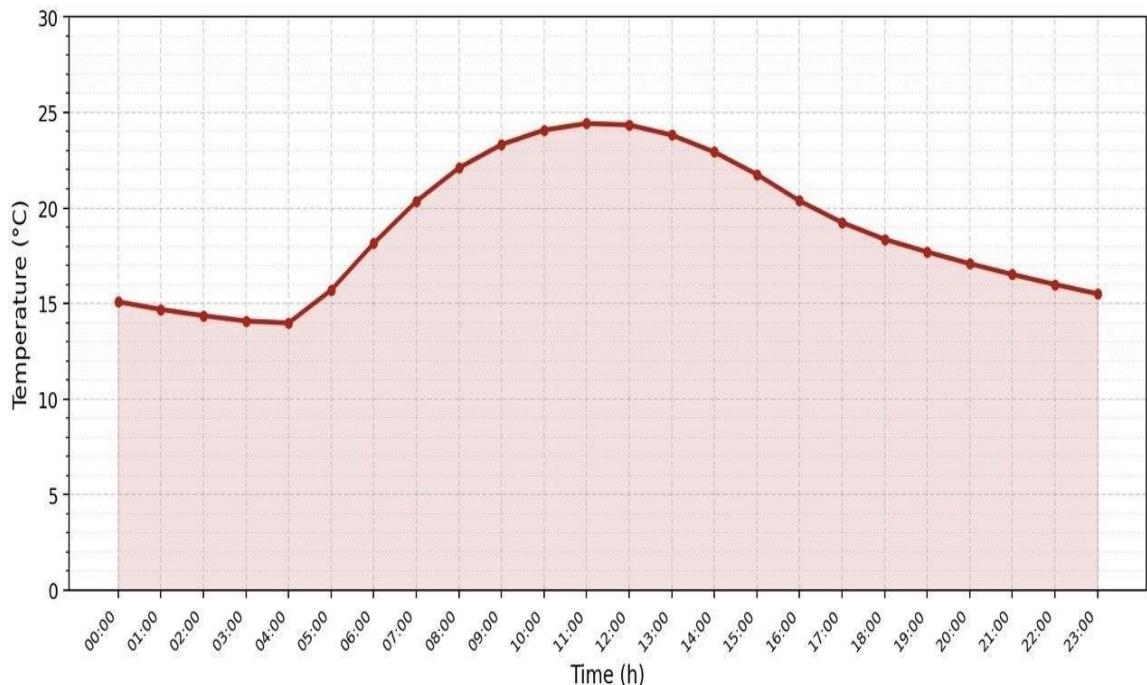


Figure III. 2: Mean Diurnal Ambient Temperature Profile Ain Temouchent (2004–2024)



Figure III. 3: Monthly Mean Ambient Temperature - Ain Temouchent (2004-2024)

- **Solar irradiance data**

Solar radiation is the primary input to any photovoltaic system and directly determines the amount of electricity generated. The more radiation, the more energy is produced by the solar panels, thus increasing hydrogen production through electrolysis. To characterize the solar resources available at the project site, 20 years of meteorological data recorded at Ain Temouchent (2004–2024) were analyzed. Average daytime appearance (figure 3.4) shows that radiation follows a bell-shaped curve during the day, peaking at about 835 W/m² near midday, while the monthly profile (figure. 3.5) He confirms that the site benefits from stable and relatively abundant solar resources throughout the year. These profiles are used as direct inputs to the photovoltaic simulation model developed in this work.

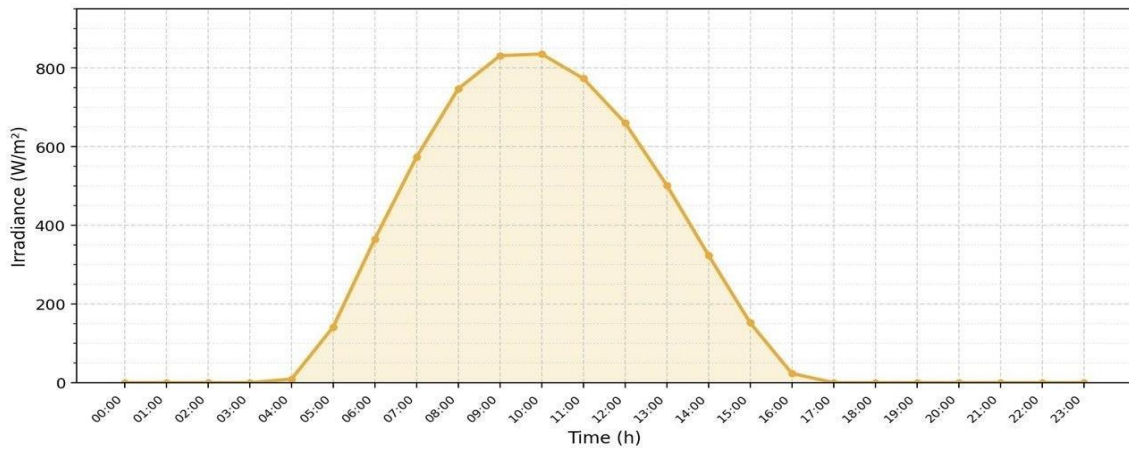


Figure III. 4: Mean Diurnal Solar Irradiance Profile Ain Temouchent (2004-2024)

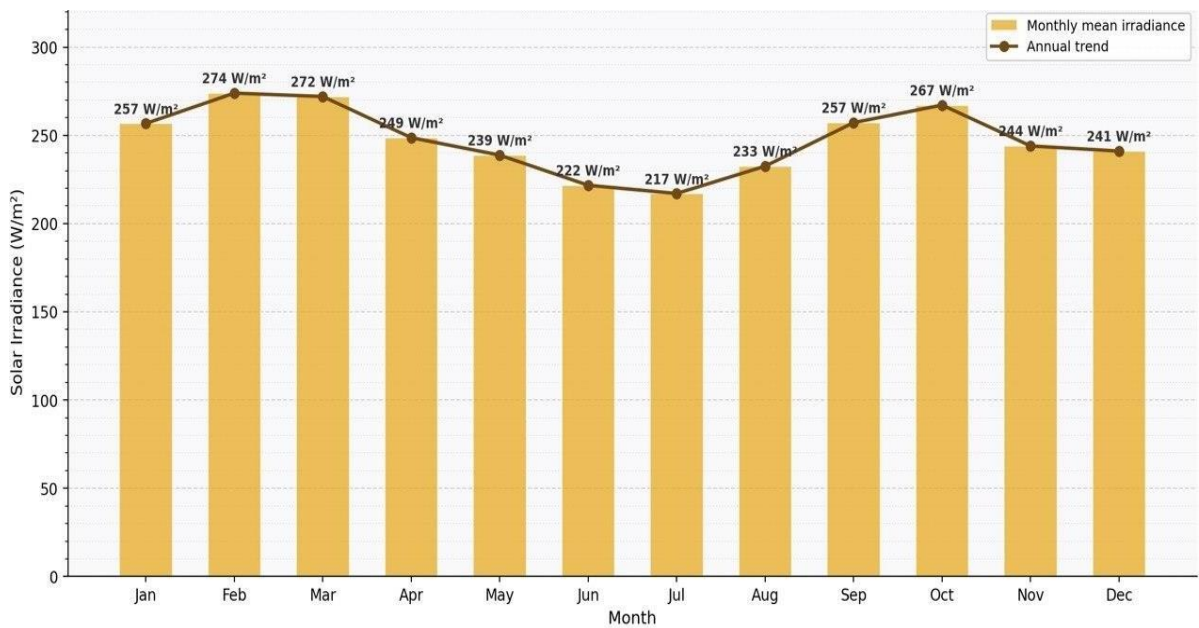


Figure III. 5: Monthly Mean Solar Irradiance - Ain Temouchent (2004-2024)

III.2.3. Hydrogen demand and production objectives.

- **Role of hydrogen at Terga**

Used to cooling alternator. The Terga station has alternators that use hydrogen to cool them. We will simulate a system to meet their needs with green hydrogen.

- **Hydrogen consumption of the Terga power plant**

The initial hydrogen charge required per alternator is 367 Nm³, yielding a total of 1101 Nm³ for the three units.

The daily hydrogen replenishment does not exceed 9Nm³/day per alternator,

corresponding to a total daily refill flow of $\leq 27 \text{ Nm}^3/\text{day}$ across the plant.

Mass equivalents are derived using a hydrogen density of $\rho = 0.0899 \text{ kg/Nm}^3$, And from it the total need 102 kg.

- **Surplus strategy**

Since the cooling system is a closed loop, we do not need to refill it every time. Given the world's tendency to use green hydrogen, we will take advantage of the opportunity to sell hydrogen, and through this we will recover the cost of completing the project.

Thus, we have benefited environmentally by using green hydrogen to meet our needs and have gained economic income.

III.3. Simulation of the system

III.3.1. System architecture and components

- **PV Array**

The photovoltaic array is the primary power source for the proposed system. It converts incident solar radiation into direct current (DC) electricity, which is later supplied to the electrolyzer to produce hydrogen. The photovoltaic array model was implemented in MATLAB/Simulink using a compact photovoltaic array block, taking solar radiation data (G_{data}) and ambient temperature data (T_{data}) as inputs. The array is connected directly to the electrolyzer through a load resistor. Since the primary goal of this system is to meet the demand for hydrogen in the Terga power plant and market surplus production, the stages of maximum power point tracking (MPPT) and DC-DC conversion were deliberately omitted, as

improving system efficiency was not the focus of this study. The resulting Simulink model of the photovoltaic array is illustrated in Figure 3.6.

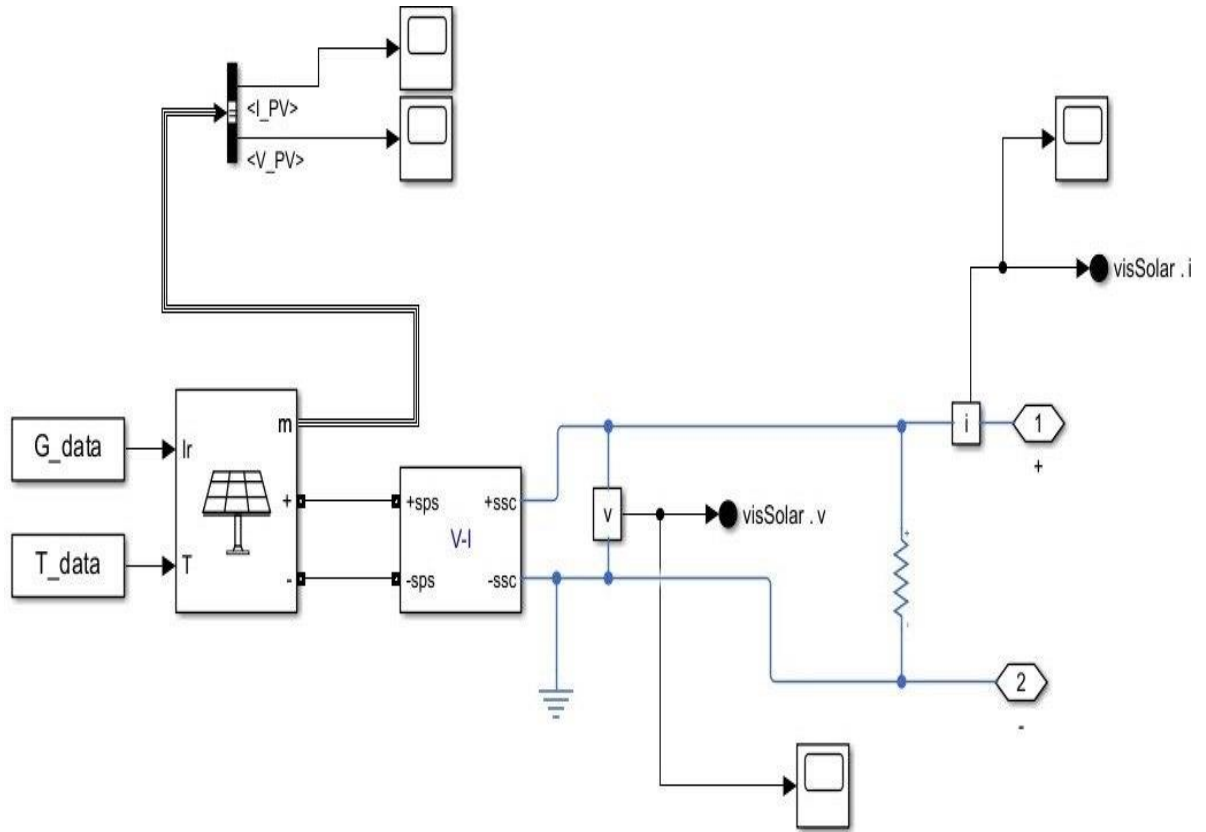


Figure III. 6: MATLAB/Simulink model of the PV array

- **Sizing of the PV array**

In this simulation, a photovoltaic array with a total installed capacity of approximately 1 MW was designed using 296 parallel series and 11 series-connected modules. The selected unit is a 300W monocrystallin panel manufactured by Condor Electronics Algeria. The electrical characteristics of the unit under standard test conditions (STC) are shown in Table III.2.

Table III. 2: Characteristics of the Condor 300W monocrystalline PV module

Parameter	Value	Unit
Maximum Power (Pmax)	300	W
Open Circuit Voltage (Voc)	44.69	V
Short Circuit Current (Isc)	9.005	A
Voltage at MPP (Vmp)	37.08	V
Current at MPP (Imp)	8.28	A
Maximum System Voltage	1000	V
Maximum Fuse Rating	15	A
Temperature Coefficients		
Power Coefficient (β_P)	-0.36	%/°C
Current Coefficient (β_I)	+0.06	%/°C
Voltage Coefficient (β_V)	-0.36	%/°C
NOCT	45 ± 2	°C
Mechanical Characteristics		
Cell Type	Monocrystalline with reflection	—
Number of Cells	72 (6×12)	—
Cell Dimensions	156 × 156	mm
Module Dimensions	1956 × 992 × 50	mm
Module Weight	21	kg
Frame	Anodized aluminum	—
Glass Type	Tempered glass, 3.2 mm	—
Junction Box	IP65, 3 bypass diodes, MC4 connector	—
Operating Temperature	-40 to +85	°C

➤ **PEM Electrolyzer**

In this study we relied on PEM electrolyzer and you return to:

- PEM electrolyzers produce hydrogen with a purity of up to 99.999%, which meets the stringent requirements for generator cooling applications.
- PEM electrolyzers can effectively handle load fluctuations due to their rapid dynamic response, making them particularly suitable for direct coupling with photovoltaic systems where solar radiation is intermittent.
- PEM electrolyzers operate at high pressures, typically between 15 and 30 bars at temperatures of 50–90° degrees Celsius, allowing hydrogen to be produced under pressure without the need for additional mechanical pressure.
- Coupling photovoltaic systems with PEM electrolyzers represents one of the most promising approaches to producing green hydrogen from renewable energy sources.
- **Type of PEM electrolyzer used**

The simulation model is based on POQELYZER (Järvinen et al., 2022). For real implementation, a commercial PEM electrolyzer such as the Nel Hydrogen M Series or Quest One ME450 with a capacity of 1 MW would be selected, as their specifications are consistent with our simulation parameters.

- **Parameters of PEM electrolyzer**

We see in table III.3 parameters of our electrolyzer

Table III. 3: parameters of electrolyzer in simulation

Parameter	Value	Unit
Stack Configuration		
Number of electrode pairs (Np)	20	—
Number of cells (N_cell)	250	—
Membrane Properties		
Membrane area (A)	1.5	m ²
Membrane thickness (Xd)	0.002	m
Electrical Parameters		
Electrolyzer resistance (R)	0.05	Ω
Heating resistor (R_heat)	25	Ω
Performance Parameters		
Efficiency range (η)	0.71 – 0.72	p.u.
Operating temperature range (T)	273.15 – 353.15	K

The PEM electrolysis unit at MATLAB/Simulink is designed as an integrated subsystem comprising several interconnected components. The current source provides the electrical energy needed for the electrolysis process. The built-in temperature source with heating resistance ensures that the electrolyzer operates within the required thermal range. The purge logic block manages the purge process to maintain hydrogen purity. Water supply is handled by water tank, pump and water property block. The electrolyzer output signals, including current, voltage, and hydrogen mass flow rate, are monitored via dedicated measuring blocks.

The resulting Simulink model of the electrolysis unit is illustrated in (Fig III.7).

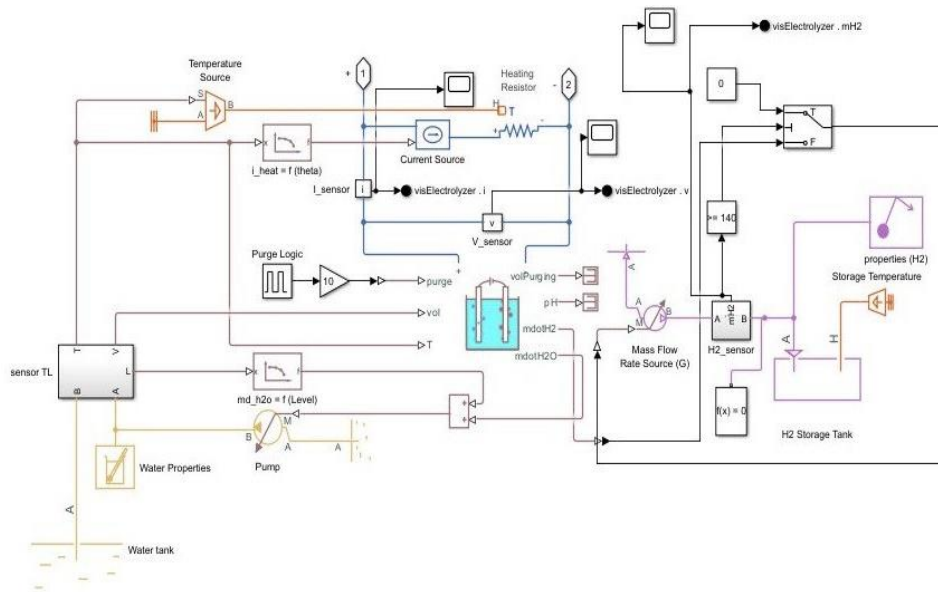


Figure III. 7: MATLAB/Simulink model of the PEM electrolysis unit

➤ Hydrogen Storage Tank

The produced hydrogen is stored in a high-pressure storage tank integrated within the electrolysis unit subsystem, as shown in Figure III.7. Due to the highly flammable and leak-prone nature of hydrogen, the chosen tank must meet strict safety and material standards,

including resistance to hydrogen embrittlement and leak-proof construction. The storage capacity is set at 170 kg, which corresponds to the maximum daily hydrogen production that can be achieved under peak solar radiation conditions. The tank receives the hydrogen mass flow rate from the electrolyzer, and is monitored by a dedicated H2 sensor to ensure accurate measurement of the accumulated amount.

➤ Complete System Architecture

The complete system model, shown in Figure III.8, consists of two main subsystems: the solar array and the electrolysis unit, connected directly without any intermediate stage. The DC output of the photovoltaic array is fed directly to the electrolysis unit, which produces hydrogen and stores it in the tank. All output signals from both subsystems are collected in the Scopes block for monitoring and analysis.

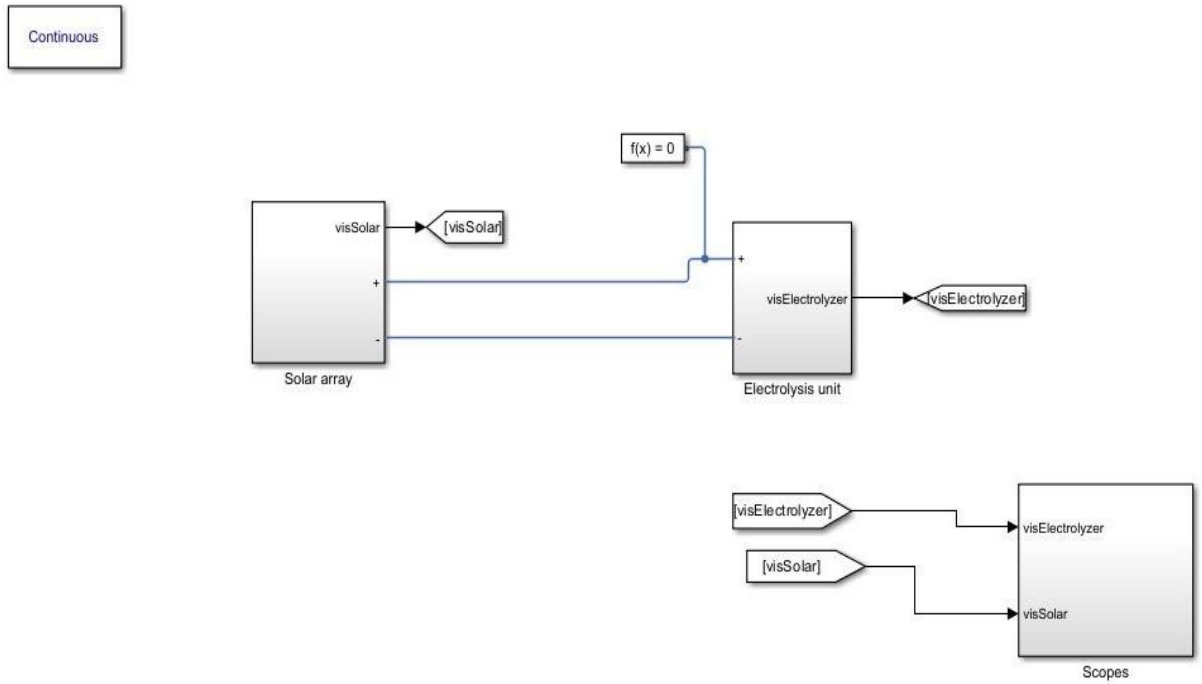


Figure III. 8: complete MATLAB/Simulink model of the green hydrogen production system

III.3.2. Results and Discussions

➤ PV Array output current

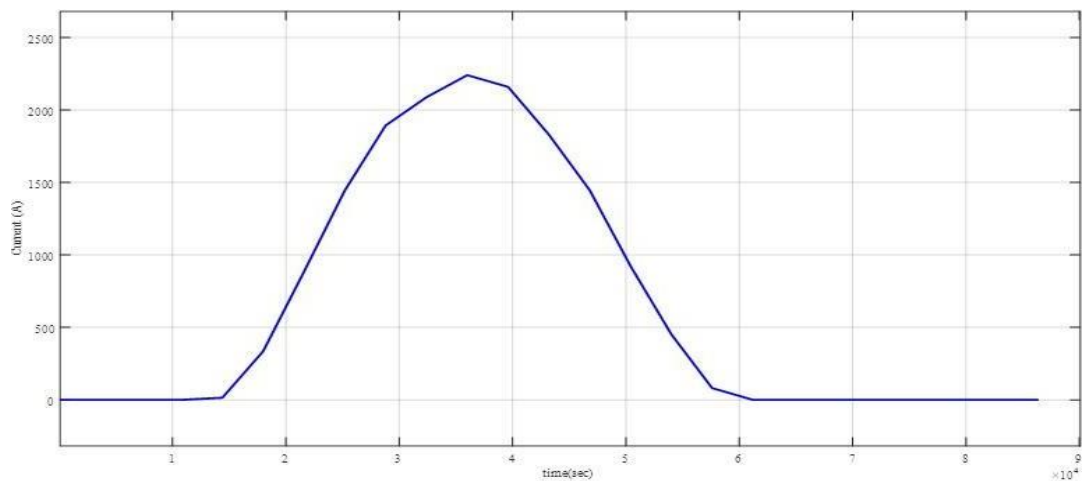


Figure III. 9: PV array output current (I_{PV}) over one day

Figure III.8 illustrates the PV array output current (I_{PV}) over a single representative day. The current remains negligible during the nighttime hours, begins to rise gradually at sunrise ($t \approx 1.5 \times 10^4$ s), reaches a peak value of approximately 2200 A around solar noon ($t \approx 3.5 \times 10^4$ s), and decreases progressively until sunset ($t \approx 5.5 \times 10^4$ s). This bell-shaped profile is characteristic of solar irradiance variation throughout the

day, confirming the direct proportionality between incident irradiance and the photogenerated current of the PV array.

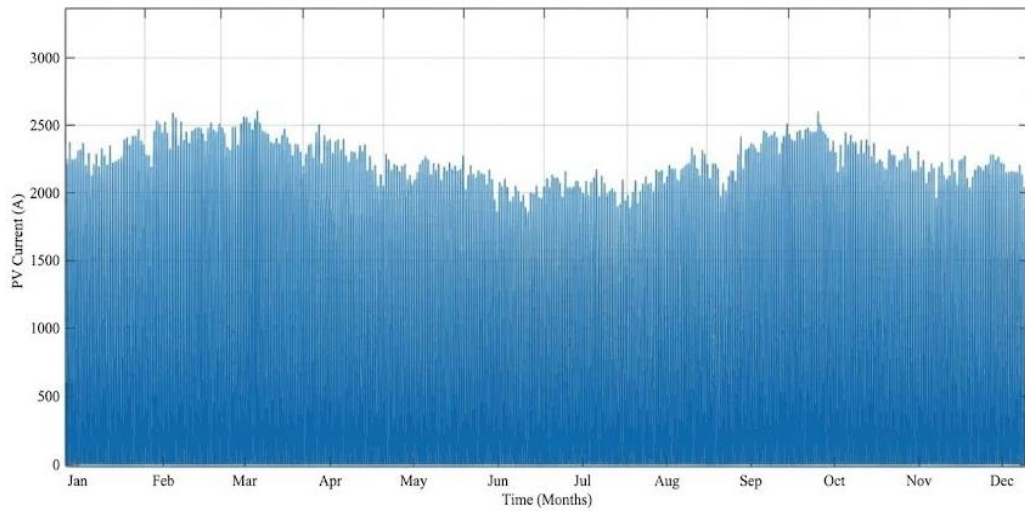


Figure III. 10: PV array output current (I_{PV}) over one year of simulation

Figure III.9 shows the PV array output current (I_{PV}) over a full year of simulation. The current follows the daily solar cycle, rising during daylight hours and dropping to zero at night, which explains the dense vertical patterns observed throughout the plot. The peak current reaches approximately 2600 A during summer months, when solar irradiance is at its highest in Ain Temouchent, while slightly lower values are recorded during winter. The current profile directly reflects the seasonal variation of solar irradiance, confirming that the PV array responds correctly to the real meteorological data used as input.

➤ PV Array output voltage

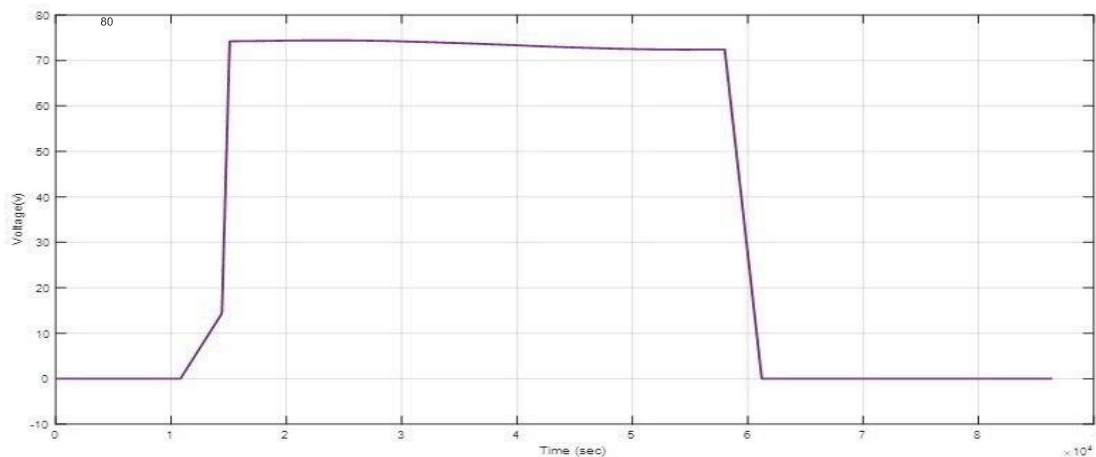


Figure III. 11: PV array output voltage (V_{PV}) over one day

Figure III.10 illustrates the PV array output voltage (V_{PV}) over a single representative day. The voltage rises rapidly at sunrise ($t \approx 1 \times 10^4$ s), stabilizes at approximately 75 V throughout the daylight period, and drops sharply to zero at sunset ($t \approx 6 \times 10^4$ s). This nearly flat profile during daytime confirms that the operating voltage is primarily determined by the electrolyzer load rather than solar irradiance, which is characteristic of a direct PV-electrolyzer coupling without MPPT.

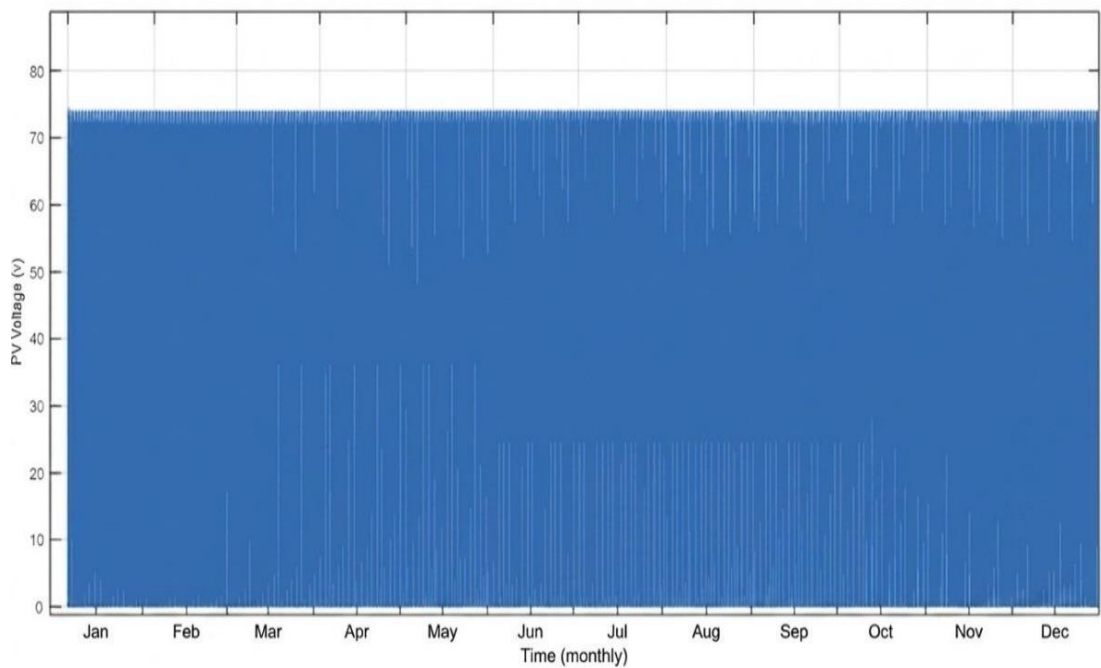


Figure III. 12: PV array output voltage (V_{PV}) over one year of simulation

Figure III.11 illustrates the PV array output voltage (V_{PV}) over a full year of simulation. Unlike the current, the voltage remains relatively stable throughout the year, fluctuating between 0 V at night and approximately 75 V during daylight hours. This behavior is consistent with the nature of PV modules, where voltage is primarily influenced by temperature rather than irradiance. The seasonal variation in voltage is therefore less pronounced compared to the current, and the voltage profile remains nearly uniform across all months. The sharp daily transitions between zero and the operating voltage reflect the abrupt changes between nighttime and daytime conditions.

➤ Hydrogen Production

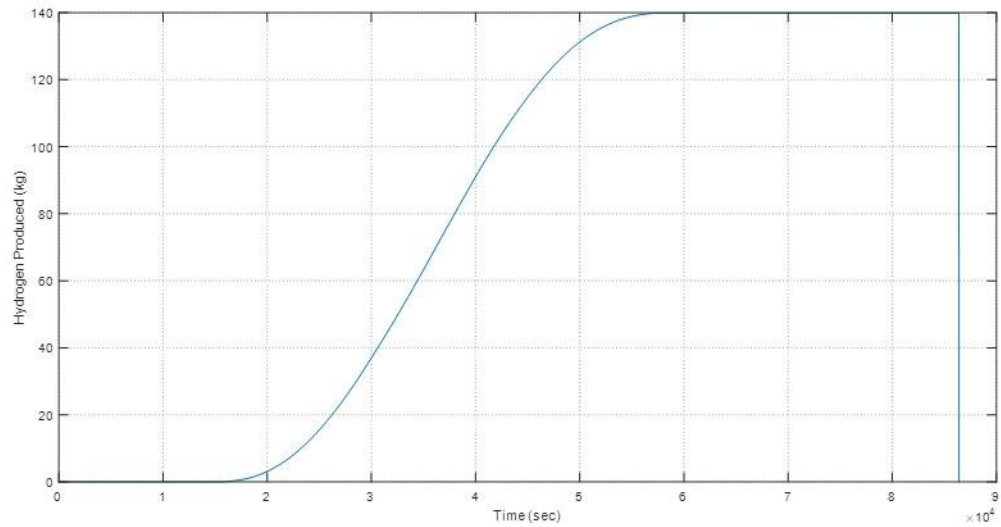


Figure III. 13: Daily hydrogen production (kg)

Figure III.12. Illustrates the cumulative hydrogen production over a single day. The produced hydrogen increases gradually from sunrise, accelerates during peak irradiance hours, and reaches approximately 145 kg by the end of the day. The return of the curve to zero indicates that the hydrogen produced has been fully consumed a portion is supplied to the Terga power plant to meet its cooling requirements, while the remaining surplus is directed for commercial sale. This daily cycle confirms that the system operates continuously and efficiently, with no hydrogen accumulation remaining at the end of each day.

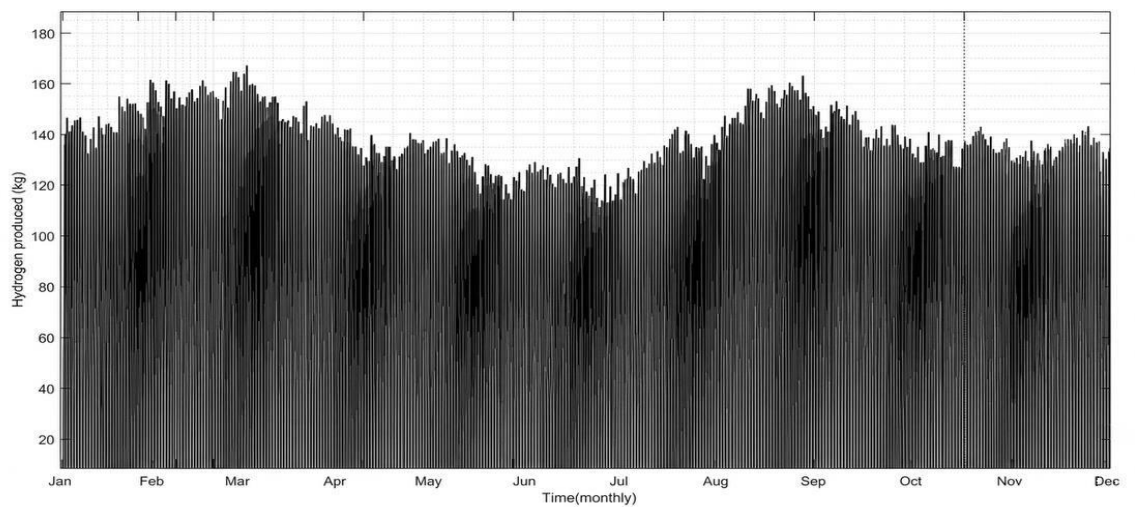


Figure III. 14: Annual hydrogen production over one year of simulation

Figure III.12 presents the daily hydrogen production over a full year of simulation. The production varies between 0 and approximately 170 kg/day, depending on the available solar irradiance. Higher production levels are observed during summer months, when solar irradiance is at its peak in Ain Temouchent, while a noticeable decrease is recorded around mid-year, corresponding to periods of lower irradiance. The average daily production remains approximately 145 kg/day throughout the year, confirming the system's ability to consistently meet the Terga power plant's hydrogen requirements and generate a significant surplus for commercial valorization. Notably, a strong correlation is observed between the hydrogen production profile and the PV array output current, as both curves follow the same seasonal pattern. This confirms that the available solar irradiance. Higher irradiance leads to higher PV current, which in turn drives a greater electrolysis rate and thus increased hydrogen output, directly govern the hydrogen production rate.

III.3.3. Economic Analysis

Table III. 4: Initial Investment Cost (CAPEX) of the System

Equipment	Quantity	Unit Price (DA)	Total Price (DA)
PV Modules (Condor 300W)	3,256	15,800.00	51, 444,800.00
PEM Electrolyzer	1	7, 324,970.00	7, 324,970.00
Hydrogen Storage Tank	1	512,747.90	512,747.90
Total			59, 282,517.90 DA

III.4. Conclusion

This chapter presented the MATLAB/Simulink simulation of a green hydrogen production system for the Terga power plant, using a 1 MW PV array directly coupled to a PEM electrolyzer. The annual simulation, conducted using real meteorological data of Ain Temouchent, confirmed that the system produces an average of

approximately 145 kg of hydrogen per day, with peak production reaching up to 170 kg during periods of high solar irradiance. The surplus beyond the plant's consumption is directed towards commercial valorization, enhancing the overall economic viability of the proposed system.

General Conclusion

General Conclusion

This work aims to design and simulate the production of green hydrogen by solar panels in order to meet the needs of the Terga power plant in Ain Timouchent, Algeria. In the first chapter, the study provided an overview of renewable energy systems and green hydrogen, covering the main electrolysis technologies along with the technical characteristics of the Terga power plant and its hydrogen cooling requirements. In the second chapter, a comprehensive literature review on hydrogen production, storage, and conversion technologies was conducted, followed by the mathematical modeling of the three main system components: the PV array, the PEM electrolyzer, and the hydrogen storage tank. In the final chapter, the complete system was simulated in MATLAB/Simulink using real meteorological data recorded over 20 years in Ain Témouchent. The results confirmed that the proposed system produces an average of approximately 145 kg of green hydrogen per day, with peak production reaching 170 kg under optimal solar irradiance conditions. The system successfully meets the Terga power plant's hydrogen cooling requirements, while generating a significant surplus directed towards commercial sale, allowing the revenue generated to offset the initial investment cost of 59,282,517.90 DA, making the project self-financing over time. This study demonstrates that Algeria, with its abundant solar resources, holds strong potential for green hydrogen production, and that photovoltaic-powered electrolysis represents a viable and promising pathway towards a cleaner and more sustainable energy future. As a perspective, future work could consider the integration of an MPPT controller and a DC-DC converter to improve system efficiency, as well as a more comprehensive techno-economic study to further evaluate the long-term viability of the project.

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Modeling and simulation of a green hydrogen production using photovoltaic system in Algeria

Abstract: The thesis presents the modeling and simulation of a green hydrogen production system powered by a photovoltaic power source in Algeria, specifically in the Ain Temouchent region. The study explores the technical feasibility of linking solar energy with proton exchange membrane (PEM) electrolysis to achieve carbonless energy storage. Using MATLAB/Simulink, the system's performance was evaluated under local meteorological conditions, demonstrating the high potential for converting solar energy into hydrogen in the region.

Keywords: Green hydrogen, Photovoltaics, Algeria, simulation, Matlab, Energy renewable, electrolyzer.

نمذجة ومحاكاة إنتاج الهيدروجين الأخضر باستخدام النظام الكهروضوئي في الجزائر

ملخص: تعرض الأطروحة نمذجة ومحاكاة نظام إنتاج الهيدروجين الأخضر الذي يعمل بمصدر للطاقة الكهروضوئية في الجزائر، وتحديدًا في منطقة عين تموشنت. تستكشف الدراسة الجدوى الفنية لربط الطاقة الشمسية بالتحليل الكهربائي لغشاء تبادل البروتونات (PEM) لتحقيق تخزين الطاقة بدون كربون. وباستخدام MATLAB/Simulink، تم تقييم أداء النظام في ظل ظروف الأرصاد الجوية المحلية، مما يدل على الإمكانيات العالية لتحويل الطاقة الشمسية إلى هيدروجين في المنطقة.

الكلمات المفتاحية: الهيدروجين الأخضر، الطاقة الكهروضوئية، الجزائر، المحاكاة، ماتلاب، الطاقة المتجددة، المحلل الكهربائي.

Modélisation et simulation d'une production d'hydrogène vert utilisant un système photovoltaïque en Algérie

Résumé : La thèse présente la modélisation et la simulation d'un système de production d'hydrogène vert alimenté par une source d'énergie photovoltaïque en Algérie, plus précisément dans la région de l'Aïn Témouchent. L'étude explore la faisabilité technique de lier l'énergie solaire à l'électrolyse par membrane échangeuse de protons (MEP) pour parvenir à un stockage d'énergie sans carbone. En utilisant MATLAB/Simulink, les performances du système ont été évaluées dans des conditions météorologiques locales, démontrant le fort potentiel de conversion de l'énergie solaire en hydrogène dans la région.

Mots-clés : Hydrogène vert, Photovoltaïque, Algérie, simulation, Matlab, Énergie renouvelable, électrolyseur.