



الجمهورية الجزائرية الديمقراطية الشعبية

République Algérienne Démocratique et Populaire

وزارة التعليم العالي و البحث العلمي

Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

المدرسة الوطنية المتعددة التقنيات

École Nationale Polytechnique

Département d'Électrotechnique

End-of-study project dissertation for obtaining the State Engineer's
degree in Electrotechnics, Option: Hydrogen Technology.

Cost-Optimal Design and Dynamic Modeling of a Power-to-Hydrogen System in Algeria

Presented by: **MANAA IMANE**

Under the direction of: Mr. Fouad KHALDI Pr

Mr. Aissa CHOUDER Pr

Presented and defended publicly on: **23/06/2026**

Composition of the jury:

President	Mr. Farid KHOUCHA	MCA	ENP
Examiner	Mrs. Soumaya TADJINE	Dr	ENP
Promoter	Mr. Fouad KHALDI	Pr	ENP
Promoter	Mr. Aissa CHOUDER	Pr	Univ. M'sila



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Mémoire de projet de fin d'études pour l'obtention du Diplôme
d'Ingénieur d'État en Électrotechnique, Option : Technologie de
l'hydrogène.

Conception à coût optimal et modélisation dynamique d'un système Power-to-Hydrogen en Algérie

Présenté par: **MANAA IMANE**

Sous la direction de: M. Fouad KHALDI Pr

M. Aissa CHOUDER Pr

Présentée et soutenu publiquement le: **23/06/2026**

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يهدف مشروع التخرج هذا إلى تقييم الجدوى الاقتصادية والتقنية لإنتاج الهيدروجين الأخضر في الجزائر بالاعتماد على الطاقة الشمسية الكهروضوئية، مع اتخاذ ولاية المسيلة كمنطقة دراسة. تم استخدام برنامج PyPSA لتحسين تصميم النظام وتحليل سيناريوهات تشغيلية مختلفة بهدف تحديد التكوين الأمثل وتحقيق أدنى تكلفة لإنتاج الهيدروجين. كما تم تنفيذ محاكاة ديناميكية للنظام باستخدام بيئة Simscape في MATLAB لدراسة سلوكه التشغيلي تحت ظروف مناخية متغيرة، مما يتيح إجراء تقييم شامل يجمع بين الأداء التقني والاقتصادي للنظام.

الكلمات المفتاحية: الهيدروجين الأخضر، الطاقة الشمسية الكهروضوئية، PyPSA، Simscape، MATLAB، تحسين الأنظمة، الجدوى الاقتصادية والتقنية، التكلفة المستوية لإنتاج الهيدروجين.

Résumé

Ce projet de fin d'études vise à évaluer la faisabilité économique et technique de la production d'hydrogène vert en Algérie à partir de l'énergie solaire photovoltaïque, avec la wilaya de M'sila choisie comme zone d'étude. L'environnement open-source PyPSA a été utilisé pour optimiser le design du système et analyser différents scénarios opérationnels afin de déterminer la configuration optimale et de minimiser le coût actualisé de l'hydrogène. De plus, une simulation dynamique du système a été réalisée à l'aide de l'environnement Simscape dans MATLAB pour étudier son comportement opérationnel sous des conditions climatiques variables, permettant ainsi une évaluation complète qui combine à la fois les performances techniques et l'évaluation économique du système.

Mots-clés: Hydrogène vert, énergie solaire photovoltaïque, PyPSA, Simscape, MATLAB, optimisation des systèmes, faisabilité économique et technique, coût actualisé de l'hydrogène.

Abstract

This final year project aims to evaluate the economic and technical feasibility of green hydrogen production in Algeria using photovoltaic solar energy, with the Wilaya of M'sila selected as the case study area. The open-source environment PyPSA was used to optimize the system design and analyze different operational scenarios in order to determine the optimal configuration and minimize the levelized cost of hydrogen. In addition, a dynamic simulation of the system was carried out using the Simscape environment in MATLAB to study its operational behavior under variable climatic conditions, enabling a comprehensive assessment that combines both technical performance and economic evaluation.

Keywords: Green hydrogen, photovoltaic solar energy, PyPSA, Simscape, MATLAB, system optimization, economic and technical feasibility, levelized cost of hydrogen.

DEDICATION

To my mother,

This work is dedicated to your memory.

Your absence remains a silent pain, but your memory walks with me every day.

I wish you were here to see this moment, to see that I did not give up.

Your dreams for me live on in every page of this work, and I dedicate it to your soul

with love, respect, and loyalty.

May Allah grant you mercy and eternal peace.

To my sisters,

Thank you for your love, support, and encouragement.

You have always believed in me, and this achievement is shared with you.

To my friends

Thank you for every moment you spent motivating me.

Your presence throughout this journey made the experience more meaningful.

THANKS

First and foremost, I would like to express my deepest gratitude to Allah, who granted me the health, strength, and determination to pursue my studies and complete this work.

I would like to express my sincere gratitude to my supervisors, **Professor Aissa Chouder** and **Professor Fouad Khaldi**, for their valuable advice, as well as for all the facilities and ease they provided me during the study and preparation of this project.

I am also grateful to the members of the jury for their interest in my work and for agreeing to evaluate it.

Finally, I would like to thank all the teachers for the richness and quality of the knowledge they passed on to us during these three year

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General introduction

General introduction

Today, climate change is creating one of the most serious global problems, created largely in response to human activity, including the burning of fossil fuels, deforestation, and industrialization. Many countries are now experiencing higher average global temperatures, rising average global sea levels, and melting glaciers, and many countries are experiencing extreme weather conditions, which have serious negative impacts on humans as well as the ecological systems surrounding us [1]. In response to climate change, the global energy system is transitioning away from fossil fuels and toward renewable and low-carbon sources of energy; however, some sectors, such as heavy manufacturing and long-distance transportation, will prove to be extremely difficult to decarbonize using alternative energy sources. Alternatively, green hydrogen is an emerging clean, flexible, and low-emission energy solution across numerous energy sectors, including energy storage, industrial processes, and clean transport.

Algeria, with its abundant solar resources and strategic location, has great potential to contribute to this energy transition by producing green hydrogen from renewable sources. However, implementing such systems comes with several challenges. Technically, the intermittency of solar energy creates difficulties in ensuring a stable and reliable hydrogen supply. Economically, factors like investment costs and electricity prices have a strong impact on the Levelized Cost of Hydrogen (LCOH).

The primary objective of this study is to analyze the economic and technical feasibility of producing green hydrogen using a photovoltaic-based hydrogen production system in Algeria. This study intends to analyze whether the use of this system is economically and technically feasible and reliable under real Algerian conditions. To achieve this goal, the following research questions are proposed:

1. Is photovoltaic-based hydrogen production economically viable in Algeria, and what is the achievable Levelized Cost of Hydrogen?
2. Under which strategy is the LCOH cheapest?
3. Is photovoltaic-based hydrogen production technically feasible in Algeria?

To address the research objectives, a comprehensive methodology combining techno-economic optimization and dynamic simulation is adopted. An open-source environment based on linear optimization will be used “PyPSA” to determine the optimal sizing and operation of the system, aiming to minimize the total annualized cost, which gives the minimum LCOH. The integration of battery storage and grid interaction will also be considered, along with different operational

scenarios such as selling surplus electricity or purchasing from the grid, in order to evaluate their impact on economic performance. The model will then be simulated dynamically in Simscape (MATLAB) to assess the system's technical feasibility.

The present thesis is structured into three chapters. Chapter 1 presents the global context of the energy transition and decarbonization and introduces the theoretical background of hydrogen, detailing hydrogen production technologies, storage solutions, its role in sustainable energy systems, and its development in Algeria. The second chapter focuses on Power-to-Hydrogen systems, their typical architecture, the economic and technical challenges they face, optimization, modeling, and simulating energy systems methods and tools. Chapter 3 describes the adopted methodology, including the proposed system architecture, the techno-economic optimization model, and the dynamic simulation framework used. The last part of the third chapter presents and discusses the results, covering both economic feasibility and technical performance, answering the research questions. Finally, the thesis concludes by summarizing the main findings and outlining recommendations and perspectives for future work.

Chapter 1

Global Energy Transition and Decarbonization of Energy Systems

1.1 Introduction

Climate change and the increasing need to reduce greenhouse gas emissions have accelerated the search for sustainable energy solutions. Green hydrogen has emerged as a promising low-carbon energy carrier capable of supporting the decarbonization of sectors that are difficult to electrify. As part of its energy transition strategy, Algeria aims to develop a green hydrogen sector by using its abundant renewable energy resources to enhance energy security, reduce emissions, and promote sustainable economic development.

This chapter presents the energy transition context and the fundamentals of hydrogen, including its production, storage, role in sustainable energy systems, and development in Algeria.

1.2 Climate Change and International Commitments

1.2.1 Global Climate Change and Rising Greenhouse Gas Emissions

The term ‘‘Climate Change’’ is used to describe changes in the state of the climate that can be identified by changes in the average and/or the variability of its properties and that persist for an extended period, typically decades or longer [2].

Climate change may be due to natural internal processes such as modulations of the solar cycles, volcanic eruptions, and persistent human-induced changes in the composition of the atmosphere, ocean, or land use, or external forcings resulting from human activities, which are already affecting many weather and climate extremes in every region across the globe [2].

The global climate crisis is increasingly defined by a widening gap between economic activity and environmental stability. Carbon dioxide remains the most significant driver of this shift, with energy-related emissions rising by 0.8% in 2024 to reach a record 37.8 Gt CO₂. This surge has pushed atmospheric concentrations to 422.5 ppm, approximately 50% above pre-industrial levels [3]. While a marginal decline in industrial process emissions (-2.3%) and a decoupling of emissions from global GDP (Gross Domestic Product) growth (+3.2%) offer a glimmer of structural progress, the absolute volume of greenhouse gases continues to climb [3]. This trend is exacerbated by rising concentrations of Methane (CH₄), primarily from agriculture and fossil fuel leaks, which reached 1921.79 ppb in 2024, alongside potent synthetic gases like Sulfur Hexafluoride (SF₆) and Nitrous Oxide (N₂O) [4]. The physical manifestations of these chemical imbalances are now undeniable as 2024 surpassed 2023 as the warmest year on record, marking the first time global average temperatures exceeded the critical 1.5 °C threshold above pre-industrial levels [3]. These record-breaking temperatures and shifting atmospheric patterns underscore an urgent imperative for rapid mitigation strategies, moving beyond incremental

efficiency toward a fundamental systemic transformation of the global energy landscape.

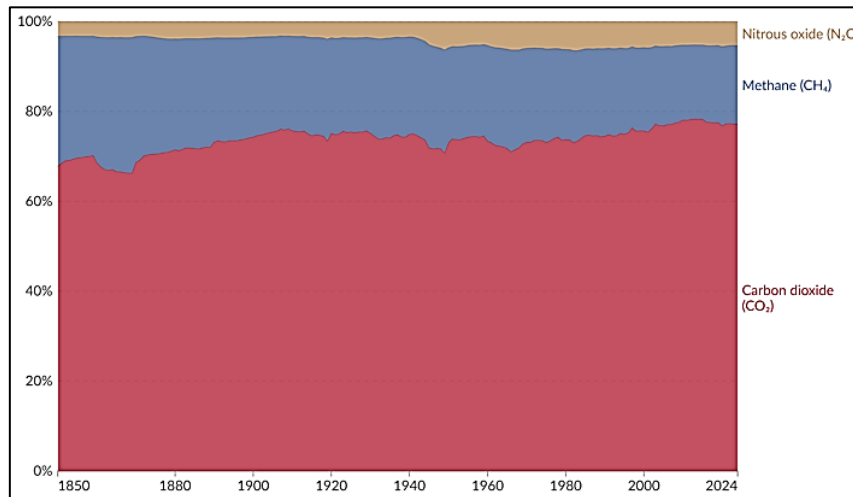


Figure 1.1. Greenhouse gas emissions by gas, World, 1850–2024, measured in tonnes of carbon [68].

1.2.2 International Climate Agreements and Policy Frameworks

Nations have established international agreements to coordinate efforts in addressing climate change, setting goals and rules to reduce greenhouse gas (GHG) emissions. The cornerstone of this framework is the United Nations Framework Convention on Climate Change (UNFCCC), opened for signature in 1992 and ratified by nearly all countries. Its long-term objective is to stabilize GHG concentrations to prevent dangerous human-induced climate interference, aiming for “net zero” emissions where human emissions are balanced by removals. The Convention outlines general responsibilities, such as monitoring emissions and developing adaptation plans, but does not impose differentiated economy-wide reduction targets [5].

The Kyoto Protocol (KP) of 1997 was the first UNFCCC protocol to set legally binding emission reduction targets, but only for certain developed nations. Its major limitation was the exclusion of developing countries from mitigation obligations, which contributed to non-ratification by some countries, including the United States [5].

The Paris Agreement (PA), adopted in 2015, represents the latest global climate framework, intended to supersede the KP. It introduces a universal approach whereby all countries participate through nationally determined contributions (NDCs), outlining their climate mitigation and adaptation plans. The PA sets the long-term goal of keeping global temperature rise well below 2°C, preferably limiting it to 1.5°C above pre-industrial levels. It also incorporates a “ratchet mechanism”, requiring countries to submit increasingly ambitious pledges every five years, alongside a framework for transparency and accountability that relies on expert review and international peer pressure rather than punitive measures. Also, the Agreement reaffirms developed countries’ collective responsibility to provide financial support to assist developing nations in implementing climate actions [5].

1.2.3 The Net Zero Emissions Scenario for 2050

The term “Net Zero” means achieving a balance between the carbon emitted into the atmosphere and the carbon removed from it [6].

The Paris Agreement sets an international objective to limit global warming to well below 2 °C and to make efforts to stay close to 1.5 °C. In order to support this objective, the International Energy Agency proposed the Net Zero Emissions by 2050 (NZE) Scenario, which describes how the global energy sector could evolve in line with the 1.5 °C target. It also recognizes that countries will not follow identical pathways, as national conditions and resources differ. However, the NZE Scenario is based on four main elements that can be applied worldwide: increased electrification using clean energy, greater improvements in energy efficiency, wider use of low-emissions fuels, and significant reductions in methane emissions [6].

According to the NZE Scenario, renewable energy capacity grows rapidly and is expected to be almost four times higher by 2035 compared to current levels. At the same time, nuclear energy and other low-emissions technologies contribute to covering the growing electricity demand, which is projected to represent about one-third of total energy consumption. Energy efficiency also improves more quickly, reaching an average annual increase of around 4% by 2035, which is twice the rate observed in 2022 [6]. In addition, sustainable fuels such as biofuels, biogases, and low-emissions hydrogen are increasingly used, with their overall consumption rising more than fourfold by 2035. Methane emissions are reduced significantly, with a decrease of more than 80% [6].

In 2024, global energy-related carbon dioxide emissions were about 38 gigatonnes. Under the NZE Scenario, these emissions decrease strongly and reach around 18 gigatonnes by 2035. Even with this reduction, global temperatures are expected to temporarily exceed 1.5 °C around 2030 and reach a maximum of approximately 1.65 °C around 2050. Nevertheless, the NZE Scenario remains consistent with international climate goals, as it supports the COP28 objectives of doubling energy efficiency improvements and tripling renewable energy capacity by 2030, while keeping global warming below 2 °C over the long term [6].

The NZE Scenario also takes into account that a temporary exceedance of the 1.5 °C limit is likely, which means that carbon dioxide removal technologies will be needed in the future. Since these technologies are expensive and not yet fully developed, reducing emissions as early as possible is essential to limit their required use. By the end of the century, the scenario indicates that global temperatures could return to below 1.5 °C. Achieving this transition requires higher energy investments, reaching around USD 4.8 trillion per year over the next decade. However, these investments are partly compensated by lower fuel costs, improved

efficiency, and reduced energy imports, especially for countries that depend on imported fuels. As electricity becomes more important in the energy system, ensuring electricity security and reliable supply chains for energy technologies becomes increasingly critical [6].

1.3 The Energy Transition

1.3.1 Concept and Evolution of the Energy Transition

An energy transition refers to the shift from one dominant energy resource, or set of resources, to another, typically moving from low-efficiency energy sources toward more efficient ones. Throughout human history, three major energy transitions have occurred. The first was the replacement of firewood with coal; the second involved the transition from coal to oil; and the third, which is currently underway, is the shift from fossil fuels, primarily oil and coal, toward clean and renewable energy sources [7].

By its nature, the current low-carbon energy transition envisions an energy production and consumption pattern increasingly dominated by clean electricity to achieve net-zero emissions by 2050. Energy transition is fundamentally a process of structural transformation of the energy system, leading to a new configuration of energy services. This process involves a complex and interconnected system encompassing energy production, storage, transmission, and consumption, as well as energy technologies, management practices, and issues related to energy security, geopolitics, and energy governance [7].

The structural transformation of the energy system is mostly seen in the quick use of renewable energy technologies. Because electricity is so important for reducing carbon emissions in end-use sectors, making more renewable energy has become a top priority around the world. The rising share of clean electricity in the world's energy mix shows that the goals of the energy transition are being met in real ways [8].

In 2023, renewable energy reached a record level of growth, with a total of 473 GW of renewable power capacity added, representing 86% of all new power capacity installed during the year. This strong growth was supported by government policies, financial incentives, better regulations, technological progress, lower costs, and increasing concerns about energy security and the environment. Renewables now account for 43% of the total global power generation capacity [8].

Solar photovoltaic (PV) was the main driver of this growth. It represented about 73% of the total renewable capacity added in 2023. By the end of the year, global solar PV capacity reached 1,411 GW, with 347 GW added in 2023 alone. This was 73% higher than the previous record set in 2022 [8].

Wind energy also continued to grow. Global installed wind capacity reached 1,017 GW in 2023, with around half located in Asia. New wind installations totaled 114.5 GW, setting a new record. Most of this growth came from onshore wind (103.9 GW), while offshore wind increased by 11 GW. Offshore expansion was slower due to high material costs, delays in project approvals, policy uncertainty, and supply chain problems. Hydropower capacity (excluding pumped storage) reached 1,265 GW in 2023, representing 33% of total renewable capacity. Also, new additions were relatively low at 6.6 GW. The development of large hydropower projects has slowed because many suitable sites have already been developed, and some projects face financial and regulatory difficulties [8].

Other renewable technologies, such as bioenergy, geothermal, concentrated solar power (CSP), and marine energy, reached a combined capacity of 171 GW by the end of 2023. In that year, 5.2 GW was added, with bioenergy representing the largest share (87%) [8].

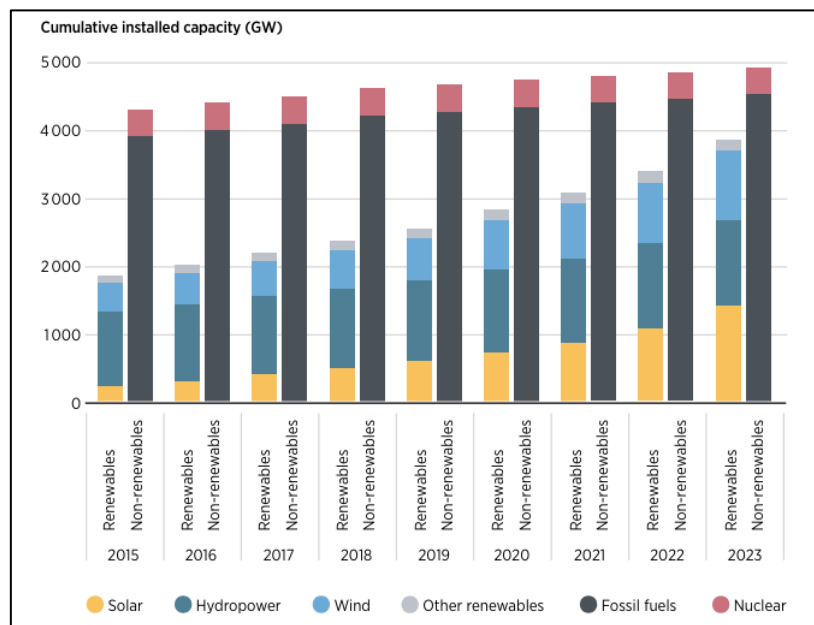


Figure 1.2. Global power capacity by technology, 2015–2023 [69].

A quick increase in the use of renewable energy is only one part of the energy transition. The transition should also work to lower energy intensity. The connections between electrification and energy efficiency are very important for decarbonization across sectors. Combining electrification with energy efficiency can cut down on CO₂ [8].

One way to cut down on emissions is to use renewable electricity in heat pumps. Switching to electric appliances in buildings, along with good insulation and energy efficiency, can lower energy use and encourage the use of renewable energy. [8].

When it comes to transportation, electric vehicles use less energy than cars that run on gas. Smart grid technologies make energy use and distribution more efficient by better managing load and lowering peak demand. The combination of electrification and better energy efficiency is good for the long-term future of energy [8].

1.3.2 Hydrogen as a Key Decarbonization Solution

1.3.2.1 Nature and Color Spectrum

Hydrogen gas, or H_2 , is the lightest and most abundant element in the universe. It is found naturally in diatomic form under standard conditions. It is a colorless, odorless, and non-toxic gas. On Earth, hydrogen does not occur freely but is always chemically combined with other elements. Its natural sources are water (H_2O) and hydrocarbon compounds (methane (CH_4), petroleum, etc.) [9].

There are three naturally occurring isotopes or forms of hydrogen, namely, protium, deuterium, and tritium, which are denoted by ^1H , ^2H or D, and ^3H or T, respectively. These isotopes have one proton and one electron, but different numbers of neutrons, and behave similarly in chemical reactions; however, they differ in physical properties [10].

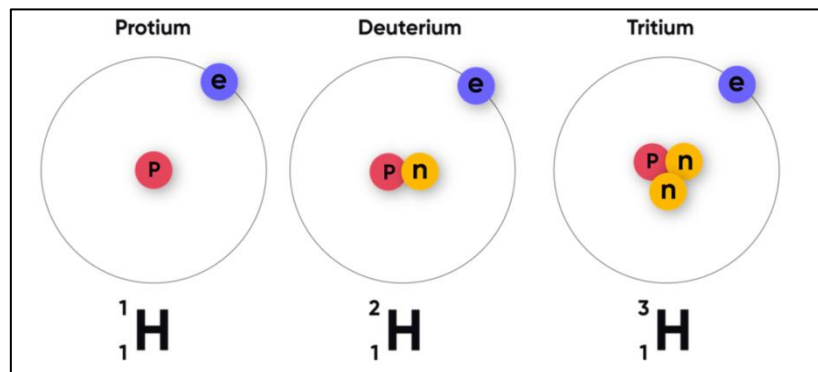


Figure 1.3. Isotopes of hydrogen [70].

Hydrogen, in its end-use form, is chemically identical but varies greatly in terms of environmental impact, based on the method of production. Hydrogen is frequently categorized using color codes that show its manufacturing route and carbon footprint in order to make these differences easier to understand. Hydrogen comes in several types. The main ones are grey, blue, and green, while newer classifications include turquoise, pink, yellow, and white hydrogen. Each type differs in terms of environmental impact, cost, and the technology used to produce it [11].

Table 1.1. Representing the hydrogen colors [71].

	Color	Fuel	Process
	Brown/Black	Coal	Steam reforming or Gasification
	White/Gold	N/A	Naturally occurring
	Grey	Natural Gas	Steam reforming
	Blue	Natural Gas	Steam reforming+CCS
	Turquoise	Natural Gas	Pyrolysis
	Red	Nuclear Power	Catalytic splitting
	Purple/Pink	Nuclear Power	Electrolysis
	Yellow	Solar Power	Electrolysis
	Green	Renewable Electricity	Electrolysis

1.3.2.2 Hydrogen production methods

Different hydrogen production methods can be employed, depending on the primary energy source used, whether from fossil fuels or renewable resources.

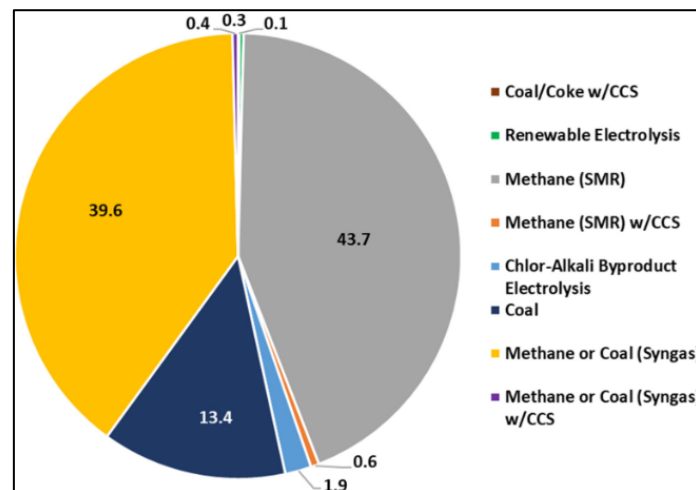


Figure 1.4. Global hydrogen production by method [72].

▪ Fossil Fuel-Based Hydrogen

While coal, oil, and natural gas share a common organic origin, their distinct physical states, solid, liquid, and gas, require specific industrial pathways to be converted into hydrogen. These pathways leverage the chemical bonds within the hydrocarbons to extract pure hydrogen gas through the following processes:

✓ Steam Methane Reforming Process

The conventional steam reforming process for hydrogen production involves two main steps. In the first reformer, methane reacts with steam at high temperatures (700-1000 °C) and pressures (5-20 bar) to produce carbon monoxide and hydrogen, an endothermic reaction that requires external heat, typically from natural gas combustion [12]. The carbon monoxide then reacts with additional steam in a water-gas shift reactor to form carbon dioxide and more hydrogen. Overall, the process can be summarized as :



Hydrogen is purified and separated from CO₂ and other impurities using techniques such as amine absorption or pressure-swing adsorption (PSA), with modern plants often favoring PSA systems [13].

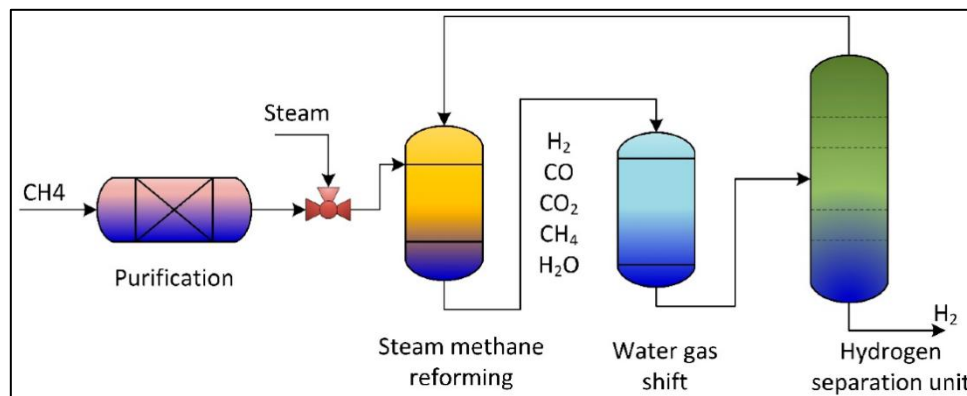


Figure 1.5. Hydrogen production by the SMR process [73].

✓ Dry Reforming of Methane

Dry reforming of methane converts two greenhouse gases, which are methane and carbon dioxide, into hydrogen and syngas.

The reaction is an endothermic reaction, which means that it needs heat for the reaction to occur. The reaction happens at a high temperature of about 800-1000°C [14].



✓ Partial oxidation

Partial oxidation (POX) is a mature and commercially available method for producing hydrogen from hydrocarbons, typically natural gas. In this process, hydrocarbons combust with a limited supply of oxygen, producing carbon monoxide and hydrogen, and, if air is used, nitrogen. The reaction occurs at high temperatures and can be catalyzed to improve hydrogen yield [15]. The overall process includes the water-gas shift reaction to convert CO into CO₂ and additional hydrogen [15]. Compared to steam reforming, POX is faster and requires a smaller reactor, but

it produces less hydrogen per unit of fuel. The final hydrogen is purified to remove CO₂ and other impurities [16].

✓ Autothermal reforming

The feedstock of this method is usually natural gas or other light hydrocarbons. The process is designed in such a manner that the heat produced by the partial oxidation of hydrocarbons is used for the endothermic steam reforming reaction in the presence of a catalyst, usually nickel [17].

Reaction 1: General partial oxidation reaction(exothermic)



Reaction 2: Steam reforming reaction(endothermic)



✓ Gasification

Coal gasification is an important hydrogen production method and can involve different techniques. It converts any carbon-based raw material into valuable outputs(syngas) using air, steam, or oxygen. The end products of the gasification process can include some (or all) of the following compounds: CO, H₂, CH₄, ash, tar, H₂S, NH₃, HCl, and HCN. The materials are generally gasified at temperatures higher than 900 °C by applying fixed bed gasification, moving bed gasification, fluidized bed gasification, entrained flow gasification, or plasma gasification. A purification process is needed to remove contaminants, particles, and other substances, thus decreasing its calorific value, and applying several gas clean-up processes to adequately separate the useful gases, such as CO, H₂, and CH₄ [18].

Four types of coal are usually utilized (Figure 1.6). These are lignite (low rank), sub-bituminous coal (low rank), bituminous coal (medium rank), and anthracite (high rank) [18].



Figure 1.6. Types of Coal [74].

▪ Renewable-Based Hydrogen Production

✓ Thermochemical Methods

Thermochemical processes drive high-temperature chemical reactions with heat supplied from renewable resources. They are usually done by decomposing water or other compounds that contain hydrogen using heat reactions without the use of electricity. As an example, in thermochemical water splitting cycles, heat is used to continuously promote a sequence of chemical processes that eventually split water into hydrogen and oxygen. Thermochemical methods hold potential to be a low-greenhouse-gas-emission route to clean, sustainable hydrogen, with the key distinction of using renewable heat as a feedstock rather than fossil fuels. Most of these technologies are still under development and need special materials and temperature control to be effective [11].

✓ Photoelectrochemical hydrogen production

The PEC process transforms solar energy into chemical energy, where sunlight is absorbed by semiconductor materials to create electron-hole pairs, which in turn cause processes that split water to form hydrogen. The semiconductor's capacity to absorb solar energy, promote charge separation, and accelerate water reduction and oxidation reactions is a major determinant of these systems' efficiency. New developments concentrate on improving these materials' light absorption, charge carrier mobility, and catalytic qualities (Figure 1.7) [19].

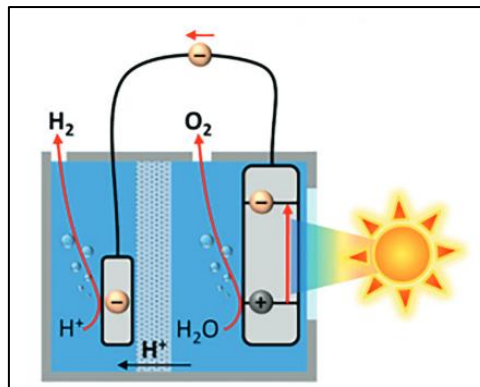


Figure 1.7. PEC system [19].

✓ Biological methods

Living organisms, especially microorganisms such as bacteria, algae, and cyanobacteria, produce hydrogen gas. The production of hydrogen gas occurs as a result of the metabolism of living organisms. This process involves certain enzymes, particularly hydrogenase and nitrogenase. These enzymes catalyze the production of hydrogen in living organisms under certain environmental conditions [11].

The process of biological hydrogen production forms part of the technology known as biohydrogen technology. This technology falls under the category of green energy technologies.

Green energy technologies are a class of technologies aimed at developing hydrogen as a clean and alternative source of energy. The process of biological hydrogen production is still in its early stages of industrial development [11].

✓ **Electrolysis**

○ **Historical Development of Water Electrolysis**

The process of electrolysis of water was first achieved in 1789 by the Dutch scientists Jan Rudolph Deiman and Adriaan Paets van Troostwijk, who utilized an electrostatic generator along with gold electrodes immersed in water. Further developments were achieved by Johann Wilhelm Ritter, who used Volta's battery for the process, allowing for better separation of the evolved gases [20].

The Russian engineer Dmitry Lachinov developed an industrial-scale process for the electrolysis of water for the production of hydrogen and oxygen in 1888. Further developments were achieved in 1902, as more than 400 industrial-scale electrolyzers were operational worldwide. Initially, the electrolyzers used aqueous alkaline electrolytes, which is an established technology to this day [20].

The major technological advancement in the field of electrolysis of water came in the mid-1960s, when the proton exchange membrane concept was developed by General Electric for the Gemini Space Program. Subsequently, this technology was adapted for the electrolysis of water for terrestrial applications [20].

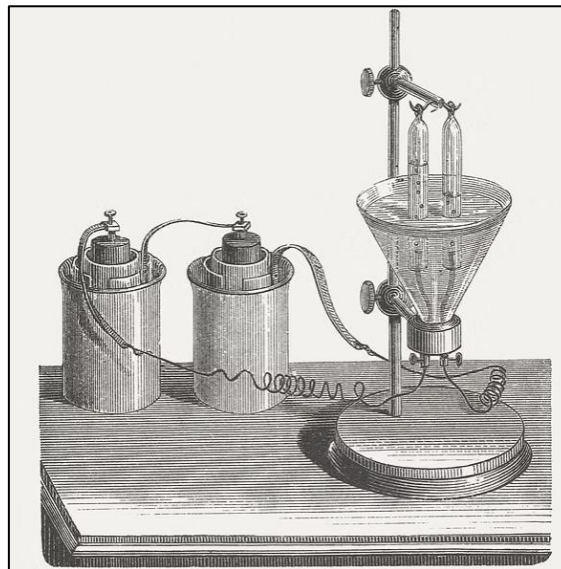
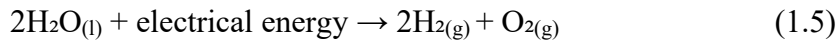


Figure 1.8. Early water electrolysis experiment in a laboratory, 1864, from Zöllner [21].

○ Principle of Water Electrolysis

An electrolyser contains a cathode and an anode separated by an electrolyte and connected to a power source [20]. Because water splitting does not occur spontaneously under normal conditions, electricity is needed to drive the reaction:



The type of electrolyte determines the technology: it can be an alkaline solution, a proton exchange membrane (PEM), or a ceramic oxygen-ion-conducting membrane. When direct current is applied, electrons flow to the cathode, producing hydrogen, while oxidation at the anode generates oxygen and returns electrons to complete the circuit [20].

○ Electrolyser Technologies

Hydrogen can be produced using a variety of electrolyzers. Each kind has its own characteristic and is suitable for particular uses [20].

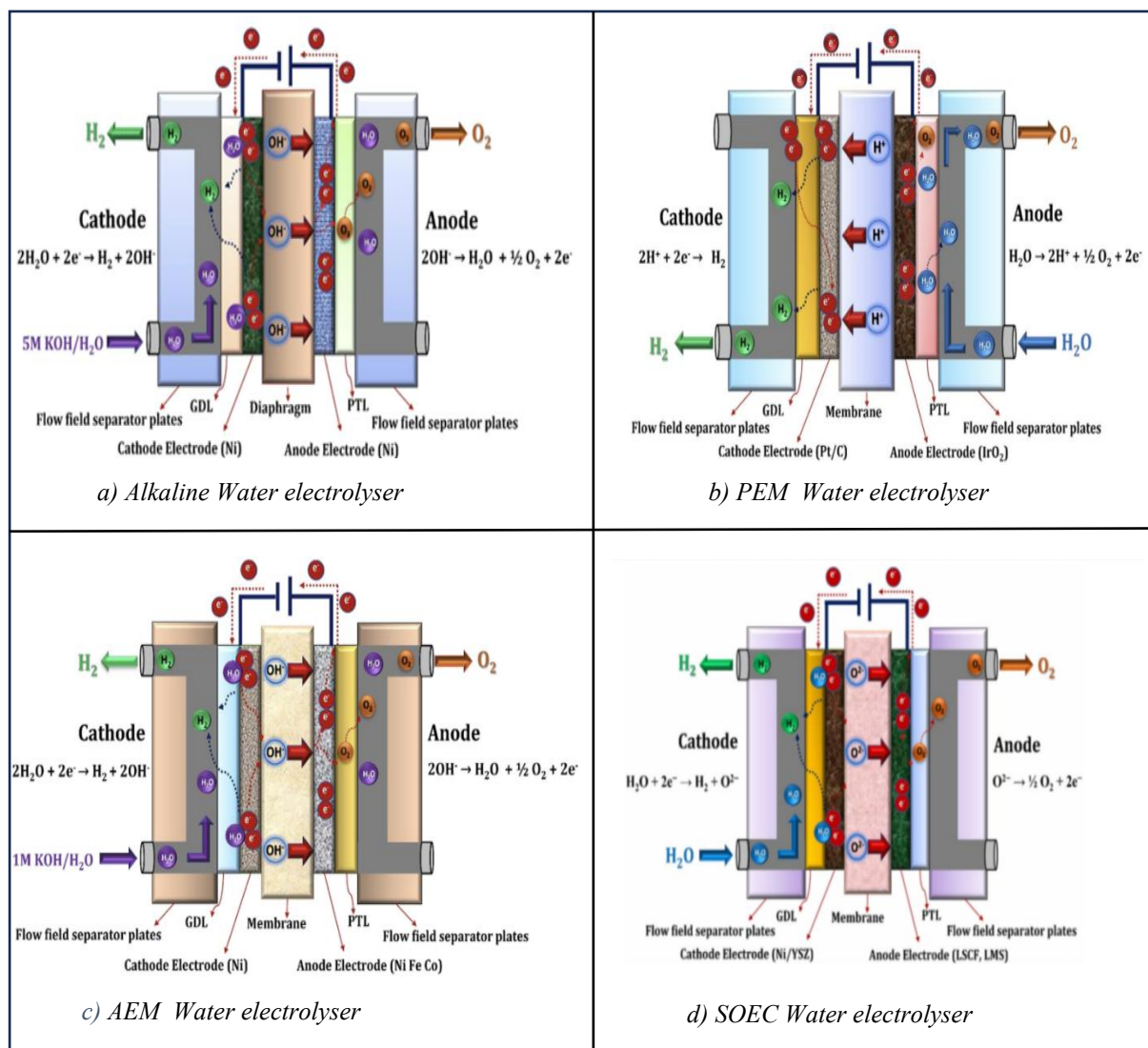


Figure 1.9. The Main Water Electrolysis [22].

The two primary varieties are the Proton Exchange Membrane (PEM) electrolyser and the Alkaline Electrolyser (AWE). Commercial acceptance of these two types has already been attained. The newest kind, the Anion Exchange Membrane (AEM) electrolyser, combines the advantages of PEM and AWE. Higher efficiency and the ability to use heat sources are features of high-temperature electrolyzers such as the Solid Oxide Electrolysis Cell (SOEC) and the Proton Conducting Ceramic Electrolysis Cell (PCCEL) [20].

Table 1.2. Key characteristics of different hydrogen electrolysis technologies [20].

Technology	Electrolyte Type	Operating Temperature	Pressure	Catalysts
AWE	Liquid alkaline solution (KOH/NaOH) with a porous diaphragm	60–90 °C	1–30 bar	Nickel-based (non-precious)
PEM	Proton-conducting polymer membrane (e.g., Nafion)	50–80 °C	1–30 bar	Platinum (cathode), Iridium oxide (anode)
AEM	Anion-conducting polymer membrane	60–90 °C	1–30 bar	Nickel, cobalt (non-precious)
SOEC	Oxygen-ion conducting ceramic electrolyte	700–1000 °C	1–30 bar	Nickel-based cermets, perovskite oxides
PCCEL	Proton-conducting ceramic electrolyte	>700 °C	10–100 bar	Noble metals (e.g., platinum)

Each electrolyser technology offers distinct advantages while also presenting certain limitations that influence its overall performance and suitability for different applications. The choice of the most appropriate electrolysis technology depends on several factors, including the required hydrogen production capacity, efficiency, operating conditions, system flexibility, lifetime, investment and operational costs, as well as the availability of resources and the specific needs of the intended application. Therefore, understanding the strengths and challenges associated with each technology is essential for selecting the most suitable.

The main advantages and limitations associated with each electrolyser technology are summarized in Table 1.3.

Table 1.3. The main advantages and limitations of different hydrogen electrolysis technologies [20].

Technology	Main Advantages	Main Limitations	Maturity Level
AWE	Low capital cost, simple and robust design, suitable for large-scale hydrogen production	Lower dynamic response, possible gas crossover, lower flexibility	Fully commercial (most mature)
PEM	High efficiency, high hydrogen purity, compact design, good integration with renewables	High capital cost due to precious metals and the membrane	Commercial and rapidly expanding
AEM	Lower catalyst cost than PEM, combines the advantages of AWE and PEM	Lower efficiency than PEM; durability is still under development	Emerging / early commercial
SOEC	Very high efficiency, heat integration possible, suitable for co-electrolysis	High operating temperature, material degradation, and high capital cost	Pilot/demonstration stage
PCCEL	High efficiency, high hydrogen purity, dual electrolysis/fuel cell operation	High temperature complexity, high cost, limited commercial maturity	Research / early development

1.3.2.3 Hydrogen Storage Technologies

Hydrogen storage technologies encompass the methods and processes used to safely store hydrogen in different physical or chemical forms.

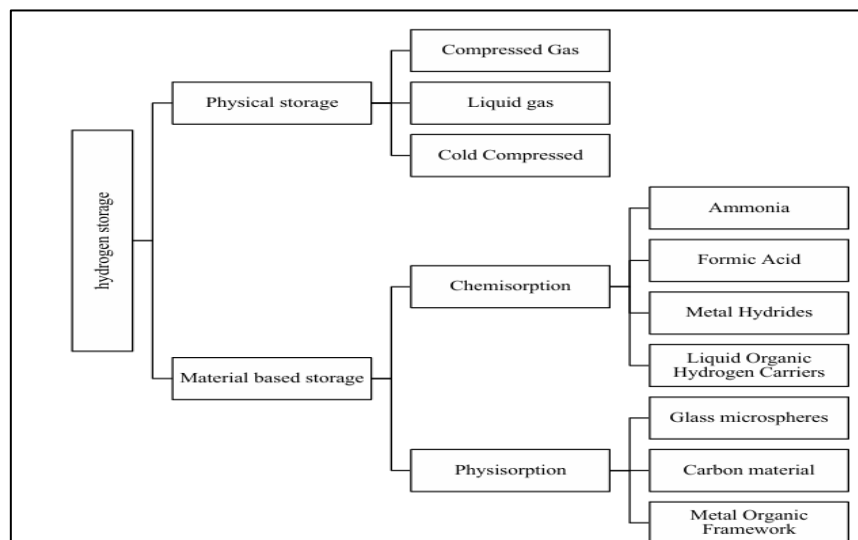


Figure 1.10. Hydrogen storage classification [23].

- **Gaseous Hydrogen Storage**

Gaseous hydrogen storage includes compressed hydrogen storage and underground storage. Compressed hydrogen is typically stored at pressures between 200 and 700 bar in high-pressure cylinders (Type I to Type IV), which differ in materials, weight, and cost [20]. Underground storage, used for large-scale and long-term applications, involves geological formations such as salt caverns, depleted oil and gas reservoirs, and aquifers [20].

- **Liquid Hydrogen Storage**

Liquid hydrogen storage requires cryogenic conditions (around $-253\text{ }^{\circ}\text{C}$) and highly insulated tanks to maintain hydrogen in liquid form [20]. It offers higher volumetric energy density than gaseous storage but involves high liquefaction energy consumption, boil-off losses, and strict safety requirements [20].

- **Solid-State Hydrogen Storage**

Solid-state hydrogen storage stores hydrogen within solid materials through chemical bonding or physical adsorption [20]. This category includes metal hydrides (such as AB_5 , AB_2 , and magnesium-based hydrides), complex hydrides (e.g., sodium alanate and lithium alanate), and adsorbent materials like activated carbon, metal–organic frameworks, and carbon nanotubes. Solid-state systems provide high volumetric density and improved safety but may require specific temperature and pressure conditions for hydrogen release [20].

- **Advanced Hydrogen Storage Technologies**

Advanced storage approaches include cryo-compressed hydrogen, which combines high pressure and cryogenic temperature to increase density while reducing boil-off losses [20]. Chemical carriers such as ammonia, formic acid, and liquid organic hydrogen carriers (LOHCs) store hydrogen in chemical form and allow storage under near-ambient conditions [20]. These systems offer high energy density and improved transport flexibility, though they depend strongly on catalyst performance and thermal management [20].

Overall, the selection of a hydrogen storage method depends on the intended application, scale of use, efficiency requirements, and economic constraints.

The main advantages and challenges of different hydrogen storage technologies are summarized in Table 1.4.

Table 1.4. Summary of advantages and disadvantages of green hydrogen storage methods [20].

Storage Type	Advantages	Challenges
Gaseous Hydrogen	Mature technology; suitable for mobility and industry; large-scale seasonal storage (underground)	High-pressure safety requirements; large volume needed
Liquid Hydrogen	High volumetric density; compact storage	High liquefaction energy; boil-off losses; cryogenic risks
Solid-State Storage	High volumetric density; safer; low pressure	Slow kinetics; high desorption temperature; material cost
Cryo-Compressed Hydrogen	Reduced boil-off; high density; suitable for FC vehicles	Complex system; cost
Chemical Carriers	High storage density; ambient storage conditions	Catalyst dependency: energy for hydrogen release

1.3.2.4 Hydrogen for Industrial and Energy System Decarbonization

▪ Industrial Sector

The sector where hydrogen can have the biggest impact on decarbonization is heavy industry. Oil refining, ammonia production, and methanol synthesis already depend on hydrogen as a feedstock. By substituting low-carbon hydrogen for conventional fossil-based hydrogen, emissions can be greatly reduced without affecting essential industrial processes. Hydrogen can be used as a reducing agent in direct reduction processes in conjunction with electric arc furnaces in the iron and steel industry, allowing for the production of steel with almost zero emissions. Conventional blast furnaces can lower emissions by partially substituting hydrogen for coke, but this method does not offer a long-term decarbonization route [24].

In industrial processes that need high-temperature heat, like the manufacturing of cement, glass, and ceramics, hydrogen and its derivatives can also be used in place of fossil fuels. Although technical challenges remain, hydrogen remains a promising option for large-scale industrial processes that are difficult to electrify [24].

▪ Transport Sector

The mode of transportation has a significant impact on hydrogen's suitability for transportation. For long-haul aviation and maritime shipping, where direct electrification is difficult because of energy density limitations, hydrogen and hydrogen-based fuels are especially promising. Ammonia and synthetic fuels made from hydrogen have the potential to drastically cut lifecycle

emissions in these industries. Short-range and light-duty land transportation applications are anticipated to be dominated by battery electric solutions, whereas long-range and heavy-duty vehicles, like trucks and some rail applications, are better suited for hydrogen fuel cells. Off-road and industrial vehicles that operate in remote or logistical hubs have a lot of promise for hydrogen as well [24].

▪ Power System Integration

Hydrogen can enhance system flexibility and dependability as electricity systems depend more and more on erratic renewable energy sources like solar and wind. Surplus renewable energy can be electrolyzed to create hydrogen, which can be stored for a long time and then transformed back into electricity when demand is high. The resilience of renewable-based power systems is increased, and seasonal energy storage is made possible by this power-to-hydrogen-to-power pathway. The accessibility of storage facilities, the proximity of production and consumption sites, and the availability of infrastructure all affect how economically viable such systems are [24].

▪ Heating Sector

Hydrogen is anticipated to have a smaller role in heating homes and businesses than electrification technologies like heat pumps. Hydrogen is less competitive for small-scale heating applications due to its higher costs and lower efficiency, even though it can be used in boilers or combined heat and power systems. Large buildings, district heating networks, and certain commercial applications are better places to use hydrogen. Hydrogen blending into natural gas networks is regarded as a temporary rather than a permanent solution, and it only provides slight emission reductions [24].

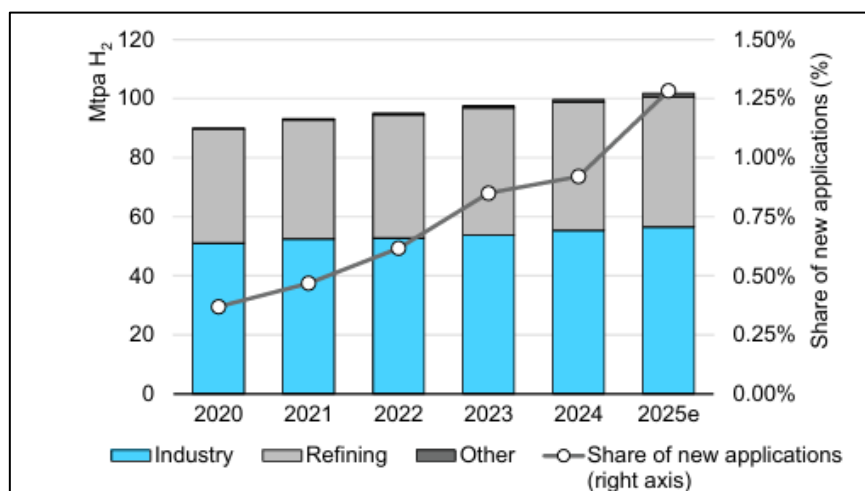


Figure 1.11. Hydrogen use by sector 2020-2025 (Source: IEA analysis based on data from Argus Media Group, All rights reserved, International Fertilizer Association).

1.4 Hydrogen Development in Algeria

1.4.1 Energy Resources and Hydrogen Potential in Algeria

▪ Renewable Energy Potential :

Algeria is one of the countries with the largest solar and wind resources in the world. It is one of the largest countries on the planet with an area of more than 2.4 million km², and more than 80% of this surface is classified as desert, in addition to the coastal strip that surrounds the Mediterranean and the low and high solar irradiation of 2000 hours per year, reaching up to 3900 hours per year in the south. Therefore, Algeria is a promising land for setting up renewable energy infrastructure, which in turn positions Algeria as a major center for the production of green hydrogen [25].

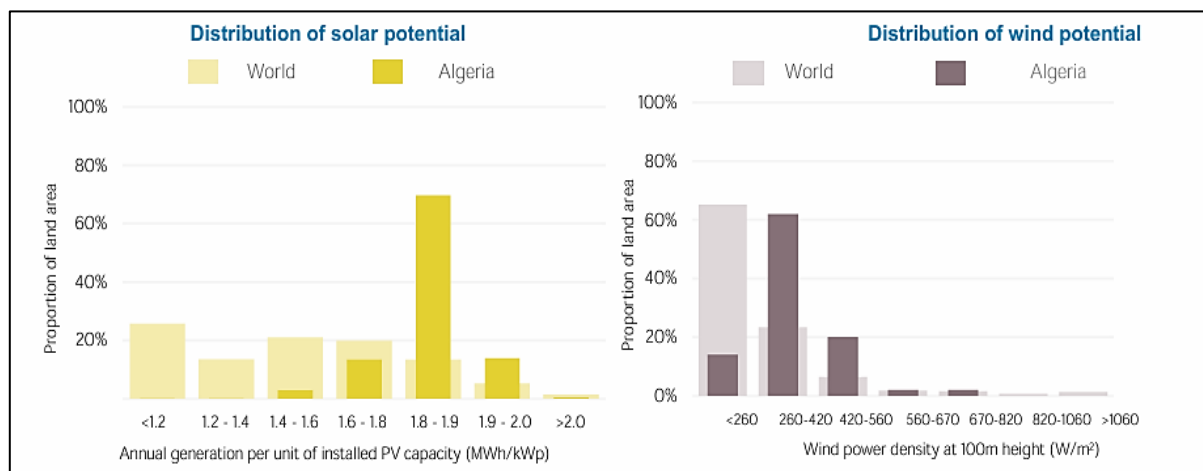


Figure 1.12. Distribution of solar and wind potential for Algeria (IRENA 2023).

Algeria depends heavily on fossil fuels for its electricity and power generation. Renewables currently account for less than 10% of Algeria's electricity generation through the use of solar, wind, and hydropower. Although the country began the transition to diversifying its energy mix in 2011, the use of gas as a primary source of electricity remains prevalent, and consumption has increased from 25 TWh in 2000 to 72 TWh in 2020 [25].

▪ Water Availability and Existing Infrastructure

One of the major challenges in the production of green hydrogen is access to pure water. Under severe water stress, Algeria has to turn off all of its hydroelectric power stations due to a lack of water. In consequence, the country is reliant on seawater desalination with many existing plants and many more planned. Desalination is an energy-hungry process, and a side product of the process is large quantities of salt-laden brine, which can have detrimental impacts on the environment. These will be some of the challenges that will need to be addressed in the future when looking at sustainable hydrogen production [25].

It is possible to use the infrastructure of Algeria for hydrogen production and transport, such as the long network of pipelines and the national gas transportation system, as well as the large number of ports located on the northern coast, in addition to the large number of desalination plants, which could be used for water production needed to operate the electrolysis process [25].

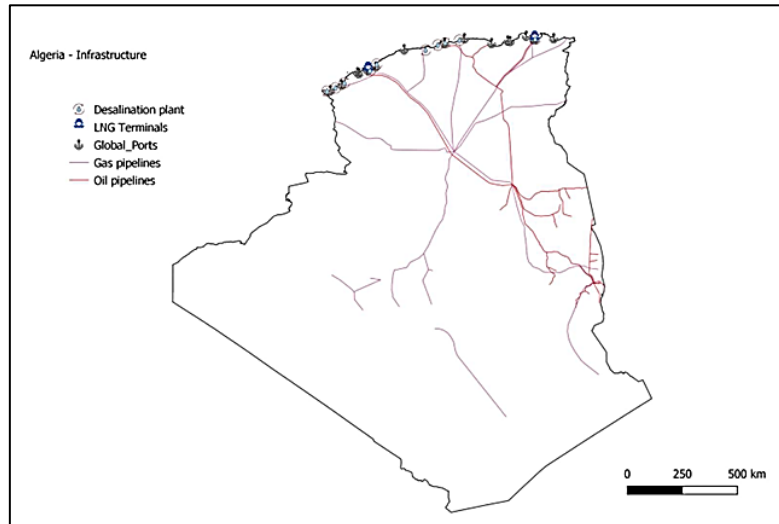


Figure 1.13. Algeria's key hydrogen infrastructure (Jaroudi 2023).

▪ Human Resources

Algeria has a relatively young population, average levels of education in the ECO region, and moderate levels of poverty. Unemployment is a major challenge facing the country, particularly affecting young people, women, and those with higher education. The labour market is highly dependent on the oil and gas sector. The development of the hydrogen industry could also create new employment opportunities, including for workers requiring key and advanced skills, and therefore requires investment in vocational education and training (VET) [25].

▪ Research and Development

Algeria has a large number of laboratories, research centers, and universities dedicated to Research and Development activities. The Center for the Development of Renewable Energies (CDER) is home to the hydrogen research program in Algeria. Although the petroleum legacy and the current dominance of oil and gas have only started to open the door to renewable energy and hydrogen research and development activities, a higher allocation of the state budget to research and development activities, as well as better integration of the hydrogen sector in the national skill development strategy, are necessary to increase the capacities of Algerian actors in this area [25].

1.4.2 The national hydrogen strategy

By integrating hydrogen into Algeria's national strategy, the country aims to solve two problems at once: meeting rising domestic energy needs and securing its future as a major clean energy exporter. The plan is ambitious but structured. The government targets 22000 MW of renewable energy by 2030, eventually reaching 19 GW by 2040, mostly powered by Algeria's vast solar resources (70%) and wind (30%) [25]. To turn this electricity into fuel, the roadmap calls for 2.5 GW of electrolyzer capacity, aiming for an annual production of 40 TWh of green hydrogen by 2040. This massive undertaking, requiring an estimated USD 25 billion investment, will be built using two main methods: large-scale central plants in the north and smaller units placed directly near industrial sites or gas pipelines for easy transport [25].

Table 1.5. Axes of the Algerian Hydrogen Strategy [25].

STRATEGIC AXE	DESCRIPTION	TIME FRAME
Adapted Regulatory and Institutional Framework	- Elaborate on the necessary regulatory and institutional framework.	2023–2025
Development of Human Capital	-Capacity building, adapting education and training to the needs of the industry. -Development of specialized training and curriculum. -Expand national research programs. -International scientific and technological cooperation.	2023/continuous
Industrial Integration	-Industrialization of the Renewable Energies and Hydrogen sectors. -Production of equipment and inputs for this sector. -Provision and management of related services (studies, engineering, maintenance, operation, etc.).	2025-2030
Financing Mechanisms and Incentivizing Measures	-Access to the advantages of common and preferential programs. -Access to local and foreign funds. -Benefit from state and intergovernmental aid.	2023/continuous
International Cooperation	-Participate in strategic alliances. -Strengthening bilateral and multilateral cooperation.	2023/continuous
Pilot Projects and Deployment	-Implementation of pilot projects. -Industrial deployment.	2023-2030 2030-2045
Deployment and Exports	-Mass production of green hydrogen. -Export of green hydrogen	2030-2040 2040-2050

1.4.3 Recent Hydrogen Initiatives and International Partnerships in Algeria

▪ SouthH₂ Corridor Initiative

In October 2024, Algerian energy companies Sonatrach and Sonelgaz signed a Memorandum of Understanding with several European partners from Germany, Italy, and Austria to evaluate the feasibility of green hydrogen production in Algeria. The project aims to export 4 million tons of green hydrogen per year to Europe through the proposed SouthH₂ Corridor pipeline, which is part of the European Hydrogen Backbone. This initiative seeks to facilitate the large-scale import of green hydrogen into the European Union by 2030 (Offshore Energy, 2024).

▪ German–Algerian Green Hydrogen Pilot Plant

In February 2024, Algeria and Germany agreed to strengthen their cooperation in green hydrogen development. A bilateral hydrogen task force was established, and plans were announced for the construction of a 50 MW green hydrogen pilot plant in Algeria. The project is supported by financial assistance from the German development bank and aims to develop hydrogen production infrastructure, enhance technical expertise, and promote technology transfer (BMWK, 2024).

▪ Sonatrach–Cepsa Green Hydrogen Project

In October 2024, Sonatrach signed a Memorandum of Understanding with a Spanish energy company to conduct a feasibility study for an integrated green hydrogen production project in Algeria. The project targets the European market and includes the development of hydrogen production plants based on water electrolysis, renewable energy installations such as solar and wind power, and infrastructure for producing hydrogen derivatives, including green ammonia and methanol (Offshore Energy, 2024).

▪ Sonatrach–Eni Partnership

Sonatrach has an ongoing partnership with an Italian energy company focused on renewable energy and hydrogen development. This collaboration, formalized through a Memorandum of Understanding signed in 2021, aims to explore joint projects in green hydrogen production, biofuels, and other sustainable energy solutions in Algeria (Eni, 2023).

▪ Hybla Hydrogen Project in Sicily :

In 2023, Sonatrach participated in the Hybla project in Sicily in collaboration with an international energy company. The project focuses on the production of low-carbon hydrogen and syngas and is expected to become one of the largest hydrogen production facilities in Italy, contributing significantly to the low-carbon energy transition (Reuters, 2023).

- **MedHySol Project and HySolThane**

The MedHySol and HySolThane projects are national initiatives in Algeria that integrate renewable energy with hydrogen production. Both aim to harness Algeria's high solar potential to produce green hydrogen, supporting sustainable development, reducing carbon emissions, enhancing energy security, and promoting cleaner energy systems (Matalucci, 2025).

- **Integrated Green Hydrogen for Green Steel Industry (Sonatrach + Hecate + Tosyali)**

Sonatrach signed a Memorandum of Understanding with U.S. company Hecate Energy Global Renewables and Tosyali Iron Steel Industry Algeria SPA to jointly study and eventually develop a green hydrogen production project powered by renewable energy. This project is intended to support green steel manufacturing in Algeria by supplying hydrogen from renewables (Sonatrach, 2025).

- **“TaqaHy” Green Hydrogen Feasibility and Export Study**

The TaqaHy project, implemented by GIZ Algeria in cooperation with the Algerian Ministry of Energy, Mines, and Renewable Energies, conducted a German-Algerian study confirming Algeria's strong potential for green hydrogen production and exports to European markets (Portail Algérie, 2025).

1.5 Conclusion

This chapter presented the urgent global climate crisis, the rising levels of greenhouse gas (GHG) emissions, and how hydrogen is becoming an important part of the race to save our planet by introducing the different hydrogen production and storage methods and its role to decarbonise hard to abate sectors. We focus on Algeria, a country that is changing from a traditional gas giant to a future leader in green energy.

Chapter 2

Power to Hydrogen Systems

2.1 Introduction

This chapter presents the fundamental concepts of Power-to-Hydrogen (PtH₂) systems. It describes their typical architecture and examines the main technical and economic challenges associated with their deployment. It also introduces the concept of the Levelized Cost of Hydrogen (LCOH) and energy (LCOE) and reviews the principal tools used for system optimization and simulation.

2.2 Power-to-Hydrogen Systems

2.2.1 Concept of PtH₂

Power-to-Hydrogen (P2H) systems are energy conversion systems that use electricity, often from low-carbon or renewable sources, to produce hydrogen through the electrolysis of water. The process transforms electrical energy into chemical energy stored as hydrogen, which can then be stored, transported, or used later in industrial processes, fuel cells, or as an energy carrier[26].

2.2.2 Typical Architecture of a PtH₂ System

A typical PtH₂ system architecture consists of renewable energy sources, power electronics, electrolyzers, storage systems, and often a grid interface to balance supply and demand. The power supply topology for hydrogen electrolyzers plays a central role in ensuring that electricity from PV, wind, batteries, and the grid is properly managed to supply stable hydrogen production[27].

Depending on the energy supply strategy and the level of system integration, Power-to-Hydrogen (PtH₂) systems can be set up in different ways. They can usually be put into two groups: stand-alone systems and hybrid systems.

Stand-alone systems connect the electrolyzer directly to a renewable energy source, like solar or wind.

Hybrid systems use a mix of renewable sources, grid electricity, and/or electrical storage systems, like batteries, to power the electrolyser.

The choice between stand-alone and hybrid PtH₂ configurations depends on several factors, including renewable energy availability, desired hydrogen production continuity, economic considerations, and system flexibility. Stand-alone systems enable the production of fully renewable hydrogen but are affected by the variability of renewable energy sources. In contrast,

hybrid systems enhance reliability and flexibility by combining multiple energy sources and storage systems to ensure a more stable hydrogen production.

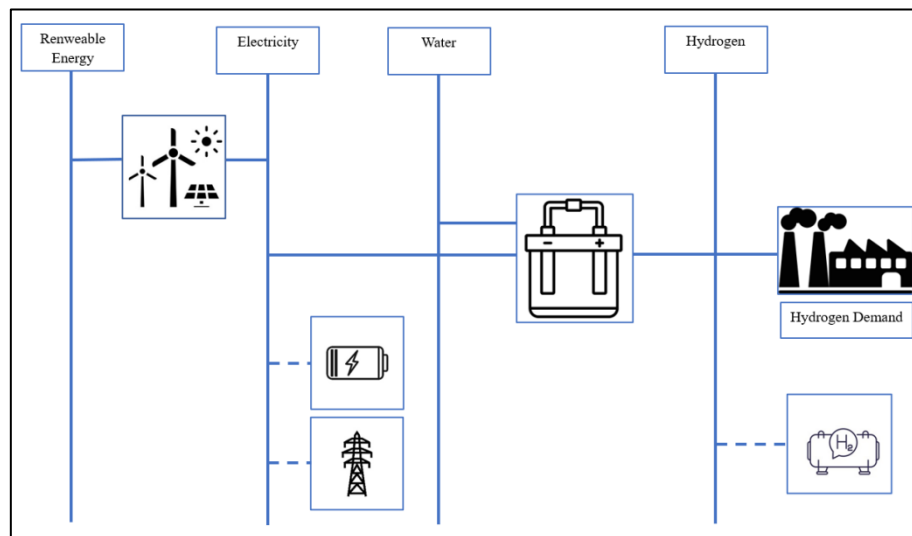


Figure 2.1. Typical Architecture of PtH₂ System.

2.2.2.1 Renewable Electricity Sources

Power-to-Hydrogen (PtH₂) systems get their energy from renewable sources. Photovoltaic (PV) solar systems and wind turbines are two common types of these sources. They convert natural sources into electrical power that the electrolyzer can use. Solar power generation relies on solar irradiance and is not accessible at night, whereas wind power is affected by meteorological conditions. This variability has a direct effect on how the electrolyser works. It can cause it to run at partial load, shut down for a while, or need extra energy sources like grid electricity or energy storage systems. Sizing and integrating renewable electricity sources are therefore very important for figuring out how well a system works, how much hydrogen it can make, and whether or not PtH₂ systems are worth the money.

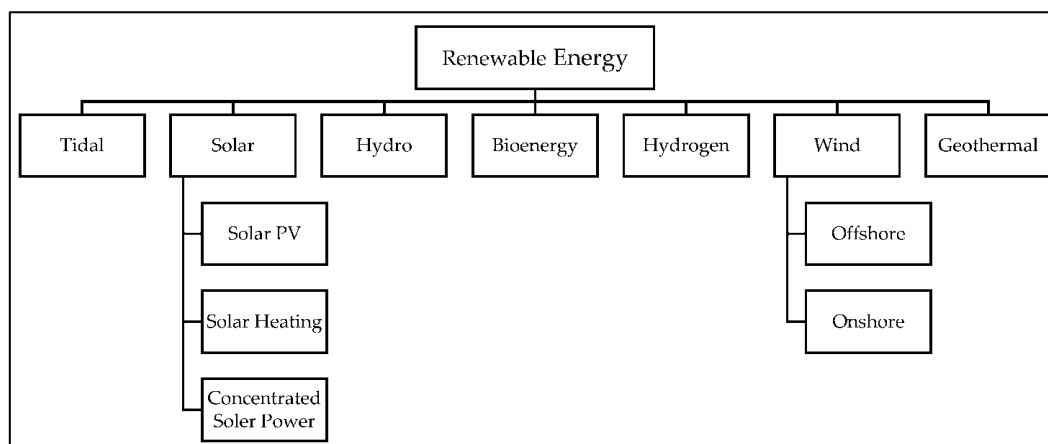


Figure 2.2. Classification of renewable energy sources [28].

2.2.2.2 Electrolyser unit

The most important component in the hydrogen production system is the electrolyser, it converts renewable electricity and purified water into hydrogen via electrolysis. If a local freshwater source is not available, a desalination or water treatment unit can be installed to provide the purified water required for electrolysis.

There are different types of electrolyzers; they have different construction approaches, operational processes, efficiencies, and maturity levels. The electrolyzer technologies are constantly evolving at different levels (stack or cell level and whole system level), aiming to increase the systems' efficiencies and scalability, while optimizing the amount of materials used and extending their lifetime [29].

2.2.2.3 Storage Systems

To ensure continuous operation of the electrolyzer, the PtH₂ system is often connected to the electrical grid or batteries, and to meet fluctuating hydrogen demand and decouple hydrogen production from consumption, hydrogen storage tanks are integrated into the system.

▪ Grid Connection (Virtual Storage)

The grid connection serves several purposes: Supplying electricity when renewable production is insufficient (e.g., at night for PV systems), allowing excess renewable electricity to be injected into the grid, and improving electrolyzer utilization rate.

The Delegated Acts (Commission Delegated Regulation (EU) 2023/1184) that add to the Renewable Energy Directive (RED II) set out a phased approach to making sure that the produced hydrogen is still green. There is a transition period in place until December 31, 2029, during which producers can show that their hydrogen is renewable by showing that it changes over time every month. This makes it possible to balance the amount of renewable electricity added to the grid and the amount of electricity used by the electrolyzer over the course of a month. Until January 1, 2030, the requirement will only be for hourly correlation. This means that the renewable electricity used must have been made in the same hour as the hydrogen production. Also, to avoid grid congestion, the electrolyzer and the renewable source should usually be in the same bidding zone (geographical correlation). Also, to avoid grid congestion, the electrolyzer and the renewable source should usually be in the same bidding zone (geographical correlation). This makes sure that making green hydrogen doesn't cause fossil fuel power generation to go up in other parts of the grid [30].

▪ Physical Storage

Energy storage is a dominant factor. It can reduce power fluctuations, enhance system flexibility, and enable the storage and dispatch of electricity generated by variable renewable energy sources such as wind and solar. Different storage technologies are used, including electrical, chemical, or electrochemical, and mechanical or thermal [31].

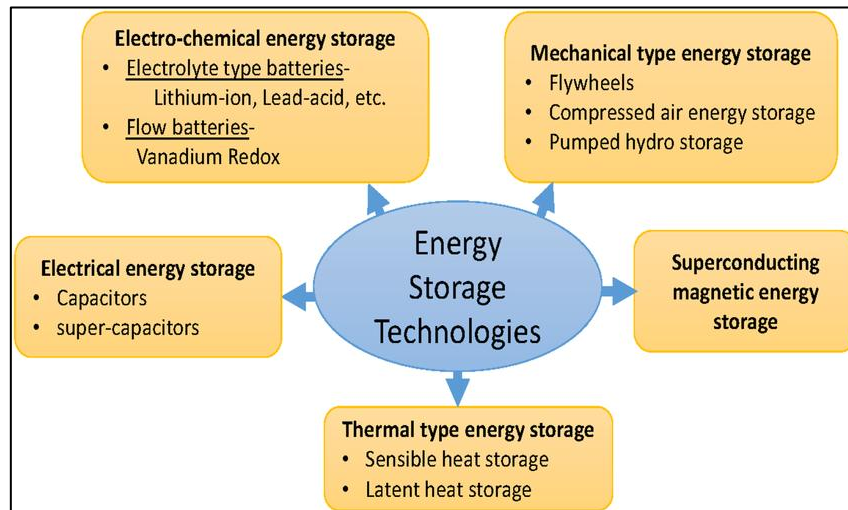


Figure 2.3. Different energy storage technologies [32].

▪ Hydrogen Storage

In many industrial processes, such as ammonia production, steel manufacturing, and oil refining, hydrogen demand is typically fixed or continuous, so storing hydrogen during high production periods and using it later is one of the solutions to ensure a flexible and more secure system.

2.2.3 Challenges of Power-to-Hydrogen Systems

While PtH₂ systems are promising for sector coupling and energy storage, several challenges limit large-scale deployment.

2.2.3.1 Economic Challenges

The high production cost is one of the main economic challenges facing green hydrogen development [33]. The levelized cost of green hydrogen currently ranges from approximately USD 3.9–12.8/kg H₂ depending on the renewable energy source, while conventional gray hydrogen produced from natural gas costs around USD 1.6–6.4/kg H₂ [33]. The largest part of the production cost comes from electricity, which accounts for about 47–78% of the total hydrogen cost [33].

High capital expenditures (CAPEX), including electrolyzer stacks, balance of plant (BoP),

installation, and renewable energy integration, also significantly increase the initial investment [33].

Operational expenditures (OPEX), such as maintenance, labor, and replacement of degraded components like PEM membranes and catalysts, contribute approximately 2–10% of the total hydrogen cost [33]. In addition, significant investments are required for large-scale hydrogen production plants, storage systems, transportation infrastructure, and the adaptation of existing industrial facilities [33].

The need for additional storage to overcome the variability of renewable energy sources further increases the overall cost [33]. Despite increasing global interest in green hydrogen, limited financial incentives and government support continue to reduce its competitiveness compared with fossil fuel-based hydrogen [33].

2.2.3.2 Technical Challenges

Although Power-to-Hydrogen (P2H) systems offer an attractive solution for renewable energy storage and sector coupling, several technical challenges still affect their performance, reliability, and large-scale deployment.

These challenges are mainly related to electrolyzer performance, the variability of renewable energy sources, hydrogen storage, and system integration [33]. Water electrolyzers currently operate with efficiencies of approximately 60–80%, meaning that a portion of the electrical energy is lost during the conversion process [33]. In addition, the long-term performance of electrolyzer components, particularly catalysts and membranes in PEM electrolyzers, is affected by degradation caused by continuous operation, high current densities, and corrosion, leading to increased maintenance requirements and replacement costs [33].

The intermittent nature of renewable energy sources, such as solar photovoltaic (PV) and wind energy, causes fluctuations in electricity supply, creating operational challenges for electrolyzers, which generally perform better under stable operating conditions [33]. Moreover, the low volumetric energy density of hydrogen makes its storage technically challenging, often requiring high-pressure compression or liquefaction and advanced safety measures [33].

Finally, the effective integration of P2H systems with renewable energy plants and electrical grids requires advanced control strategies, power electronics, and energy management systems to ensure stable and efficient operation [33].

2.3 Economic and Technical Criteria of PtH₂ System

2.3.1 Economic Criteria

▪ Levelized Cost of Hydrogen and Energy

Levelized Cost of Hydrogen (LCOH) is the average cost per unit of hydrogen produced for a PtH₂ system over its lifetime, considering all capital, operational, maintenance, and energy costs. It allows comparison between different hydrogen production technologies on a consistent economic basis [34]. It can be expressed in $\frac{\text{€}}{\text{kg}_{\text{H}_2}}$ according to the following expression [35]:

$$LCOH = \frac{\sum_{i=1}^n AC_i}{PROD} \quad (2.1)$$

Where AC represents the total discounted annual cost of investments, including the operational cost for all system components i of the hydrogen production system (HPS) [35]. The annual costs are divided by the total amount of the annual hydrogen production ($PROD$) of the HPS.

$$AC_i = \frac{CAPEX_i}{AF} + OPEX_i \quad (2.2)$$

Where AF is the annuity factor

CAPEX, or Capital Expenditure, refers to the upfront investment required to acquire, construct, and commission long-term physical assets that will be used over the lifetime of a project [35].

OPEX, or Operational Expenditure, refers to the recurring annual costs required to operate and maintain a system during its lifetime [35].

If the system is connected to the grid, the LCOH becomes:

$$LCOH = \frac{\sum_{i=1}^n AC_i - C_{GRID, \text{sell}}}{PROD} \quad (2.3)$$

Where $C_{GRID, \text{sell}}$ is the annual revenue from selling excess electricity to the grid.

On the other hand, the levelised cost of energy (LCOE, expressed in €/MWh) is a measure of the average net present cost of electricity generation for a generator over its lifetime.

$$LCOE = \frac{CAPEX_{RES} + CAPEX_{BESS} + OPEX_{RES} + OPEX_{BESS}}{\sum_{t=1}^{8760} Generation_{RES,t}} \quad (2.4)$$

Where $CAPEX_{RES}$ is the annualized capital cost of renewable energy systems (RES), $CAPEX_{BESS}$ is the annualized capital cost of battery storage, $OPEX_{RES}$ is the RES operation & maintenance cost, $OPEX_{BESS}$ is the battery O&M cost, and $\sum_{t=1}^{8760} Generation_{RES,t}$ is the total yearly RES production (hourly summed).

In order to ensure consistent LCOH calculations in future studies, Agora recommends a pragmatic approach that can serve as guidance for the preparation of such analyses [35].

Table 2.1. Summary of the recommendations for a pragmatic approach to calculating LCOH [35].

Parameter	Notes	
Electrolyser CAPEX		Account for CAPEX scaling influence.
Discount rate		Also known as Weighted Average Cost of Capital (WACC).
Electricity price		Should include all charges.
Electrolyser efficiency		Specific energy consumption including auxiliary power [kWh/kgH ₂].
Electrolyser system lifetime		Major cost driver due to the distribution of CAPEX.
Stack lifetime & replacement		Costs for stack replacement to be included in the CAPEX.
Stack degradation		Considered through average specific energy consumption.
Engineering, Procurement, Construction		It usually contains detailed planning and control, purchasing, execution of construction, installation work, and commissioning.
Buildings		Reflect the cost difference between greenfield/brownfield.
Balance of Plant (BoP)		BoP typically includes power supply, water conditioning, and process utilities like pumps, process-value-measuring devices, and heat exchangers.
OPEX		Typically in the range of 1.5%–5% of CAPEX.
Compression		Consider compression costs for system output below reference pressure.
Hydrogen quality		Identified as a minor cost driver. Nevertheless, it is recommended to calculate with a 5.0 quality to ensure that there are no technical issues.
Water supply		Costs are to be considered if a seawater desalination plant is required.
Electrical grid		Assumption of an existing grid.
Contingency		Not taken into account in most studies.
Funding		Funding programmes strongly influenced by political conditions and vary over time.
Properties		Vary significantly between countries as well as urban and rural areas.
Hydrogen transport & storage		Multiplicity of further possible applications.
By-product revenues		Omit revenues from by-products (waste heat, oxygen).
To be considered	Individual decision	Not be considered

▪ Annuity Factor and Interest Rate

The annuity factor is normally used from an investing perspective to calculate the present value of a cash flow series [29]. It can be expressed according to the following expression:

$$AF = \frac{(1+r)^n - 1}{r \cdot (1+r)^n} \quad (2.5)$$

Where n stands for the lifetime of the corresponding technology " i ", and r is the weighted average cost of capital (WACC) [29].

The capital costs are divided into equity capital and debt capital. The equity capital represents the cost of money funded by the company stakeholders, which is the minimum rate of return expected to take the risk of investing. On the other hand, debt capital represents the money funded by loans, usually from banks. Each type of capital cost is weighted depending on the company's capital structure so that they contribute differently to the WACC [29].

$$r = \text{WACC} = \frac{E}{V} \cdot R_e + \frac{D}{V} \cdot R_d \cdot (1 - T) \quad (2.6)$$

Where E/V is the share of equity capital, D/V is the share of debt capital, R_e is the cost of equity, calculated usually by the Capital Asset Pricing Model (CAPM), from investors, R_d is the cost of debt, which is the interest rate of the obtained loan, and T represents the tax rate to consider the tax-deductible share of the loan [29].

2.3.2 Technical Criteria

▪ Energy efficiency of water electrolyzers

The efficiency of an electrolyzer shows how well it turns electrical energy into hydrogen. It is usually shown as a percentage, which compares the amount of energy stored in the hydrogen made to the amount of electricity used. There are two ways to measure the energy in hydrogen: Higher Heating Value (HHV), which includes the energy in water vapor, and Lower Heating Value (LHV), which does not. Different systems have different efficiency values, so it's important to check the reference when comparing them [36].

Another useful way to think about efficiency is to look at how much energy it takes to make one kilogram of hydrogen. The theoretical minimum amount of energy needed to split water is about 39.4 kWh/kg. However, commercial low-temperature electrolyzers usually use 50–60 kWh/kg, which means they use 30–50% more energy than the ideal minimum [36].

$$\eta_{el} = \frac{\dot{m}_{H_2} \times HHV_{H_2}}{P_{el}} \quad (2.7)$$

Or

$$\eta_{el} = \frac{\dot{m}_{H_2} \times LHV_{H_2}}{P_{el}} \quad (2.8)$$

Where $\dot{m}_{H_2}$ is the hydrogen production rate (kg/s or kg/h), HHV_{H_2} is the higher heating value of hydrogen (≈ 39.4 kWh/kg), LHV_{H_2} is the lower heating value of hydrogen (≈ 33.3 kWh/kg), and P_{el} electrical power consumed (kW), it can be expressed according to the following expression :

$$P_{el} = n_{cell} V_{cell} I_{cell} \quad (2.9)$$

Where n_{cell} is the number of cells in series, I_{cell} is the cell current, and V_{cell} is the cell voltage (it depends on temperature and pressure conditions [37]).

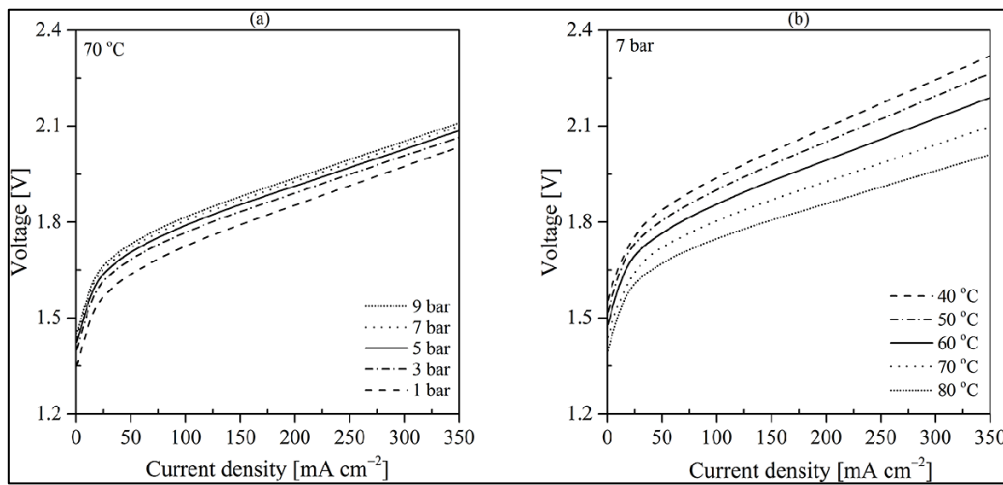


Figure 2.4. Cell voltage variation under varying temperature and pressure conditions [38].

▪ Number of Shutdowns of the Electrolyzer

The number of on/off is an important operational parameter for electrolyzer systems supplied by renewable energy, which must be as low as possible to avoid fast performance degradation and consequent reduction of the stack lifetime [39]. The number of on/off can be higher in the case of cloudy days [39].

Electrolyzers don't shut down randomly; they do so because of operational constraints or external conditions. They have a minimum allowable operating load below which operation becomes unsafe or inefficient. At low loads, increased gas crossover and impurity levels can exceed safety thresholds, leading to automatic shutdown to prevent hazardous conditions [40].

2.4 Optimization of Energy Systems

Energy system optimization involves the application of mathematical and computational techniques to enhance the performance of energy systems. The primary goal is to minimize

costs, reduce energy consumption, and maximize efficiency while meeting the required energy demand. One of the most commonly used methods is linear optimization or linear programming [29].

2.4.1 Linear optimization or linear programming

The linear optimization, or linear programming method, consists of minimizing or maximizing an objective function, which represents a measurement for a real-world process or problem. This objective function is a linear equation composed of specific variables, called decision variables, whose value is to be determined [29]. Only a certain combination of values for the decision variables will minimize or maximize the objective function. Additionally, the objective function is subject to a set of constraints that limit the possible values of the decision variables. These constraints are defined as extra equality and inequality linear equations of the decision variables. Non-negativity constraints are common in different linear models, especially in energy system models; for example, the amount of electricity cannot be negative. Moreover, the constraints should not contradict each other to keep the feasibility of the optimization problem [29]. The three elements of a linear optimization problem in standard form are [29]:

Objective function

$$\min \text{ or } \max f(x_j) = c_1x_1 + c_2x_2 + \dots + c_nx_n \quad (2.10)$$

Decision variables

$$x_j, j = 1, 2, \dots, n \quad (2.11)$$

Constraints: The decision variables must satisfy a set of linear constraints:

$$x_1 \geq 0, x_2 \geq 0 \quad (2.12)$$

This condition ensures non-negativity, meaning that variables such as energy production or capacity cannot take negative values.

$$a_1x_1 + a_2x_2 + \dots + a_nx_n \begin{cases} \leq \\ = \\ \geq \end{cases} b \quad (2.13)$$

The linear optimization problem can also be written in compact matrix form [29]:

$$\min \text{ or } \max f = C'X \quad (2.14)$$

subject to:

$$AX \leq b \quad (2.15)$$

$$X \geq 0 \quad (2.16)$$

where:

$$C = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix}, X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}, b = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

The simplex method is one of the most popular methods to solve linear optimization problems, invented in 1947 by G.B. Dantzig [29].

A wide variety of Open-Source software for linear optimization of power systems can be easily found, such as PyPSA, urbs, PSAT, PYPOWER or DIETERpy, among others.

Table 2.2. Different open-source software for LP [29].

Software	General	Suitable	Automatable	Flexible
PyPSA	✓	✓	✓	✓
urbs	✓	✓	✓	✓
PyPOWER	✓	✓	✗	✗
DIETERpy	✗	–	✗	–
PSAT	✗	–	–	–

2.4.2 Non-linear optimization or Non-linear programming

Non-linear programming (NLP) is a field of mathematical optimization where the objective function or any of the constraints are non-linear. Non-linear programming problems can be more complex and challenging to solve due to the possible presence of local optima, non-convexity, and the complexity of the objective function and constraints [29].

Nonlinear programming (NLP) problems are generally solved using numerical optimization methods such as Sequential Quadratic Programming (SQP), Interior Point, and Newton-based methods.

2.5 Modeling and simulation of energy systems

A simulation is a mathematical representation of a real-world process or system over time. It involves building a model that mimics the dynamic behaviour of physical components.

The purpose of simulating a system is to analyse system behavior under extreme conditions without physical danger, balance component sizing, forecast long-term performance, including aging and seasonal weather impacts, study the temporal behavior (dynamics) of a complex system, and it helps bridge the gap between theoretical design and real-world implementation.

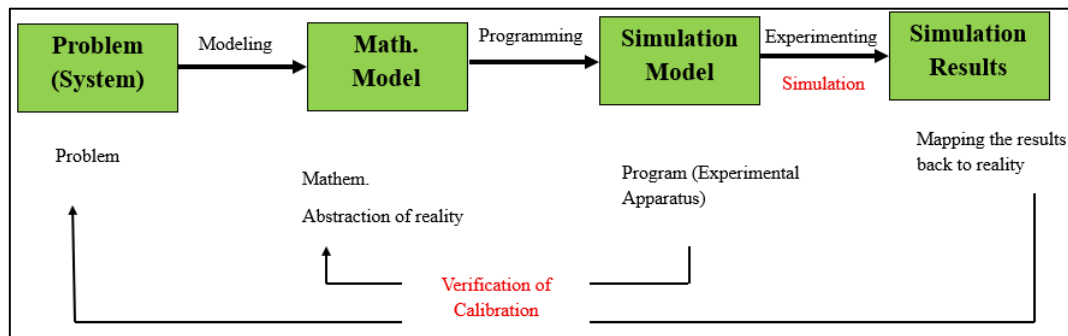


Figure 2.5. Procedure of simulation.

Several simulation tools are used for the modeling and analysis of hydrogen energy systems. These tools are presented in Table 2.3.

Table 2.3. Different simulation tools for modeling and analyzing HPS.

Software Tool	Modeling Approach	Main Application	Electrolyzer Dynamic Simulation	Thermal Effects Analysis	System Integration Analysis
Simulink / Simscape	Dynamic physical modeling	Detailed component-level simulation and control	✓	✓	✓
TRNSYS	Transient system simulation	Renewable and thermal energy systems	Limited	✓	✓
HOMER Pro	Techno-economic optimization	Hybrid renewable energy system design	Limited	✗	Limited
Aspen HYSYS	Process simulation	Chemical and hydrogen production process modeling	Limited	✓	✓

2.6 Conclusion

However, Power to Hydrogen systems represent a potential option that can convert the electricity generated through renewable sources into a transportable and storable form of energy. The Levelized Cost of Hydrogen stands out as a key metric for assessing its economic viability, linking system design choices to overall performance.

A clear understanding of system architecture, combined with appropriate optimization and simulation approaches, is important for evaluating these systems under realistic operating conditions.

Building on this foundation, the next chapter will focus on the practical application of these concepts by employing one optimization tool for power systems and one energy modeling tool to evaluate the technical and economic performance of the proposed PtH₂ system in Algeria.

Chapter 3

Methodology, System Modeling, and Case Study

3.1 Introduction

This chapter presents the methodology and data used to develop the PtH₂ system model in Algeria. It is divided into two main parts. The first part focuses on the economic assessment, where different system scenarios are modeled and optimized using PyPSA to assess the economic feasibility of producing green hydrogen in Algeria. The second part addresses the technical analysis, which is carried out through dynamic simulation of the electrolyzer using Simscape under real Algerian operating conditions, in order to evaluate its performance in terms of efficiency, hydrogen production rate, and operational behavior.

3.2 Methodology and Data

3.2.1 Economic Assessment

The overall structure of the proposed methodology for this part is illustrated in Figure 3.1. A LP-based optimisation framework (green box in Figure 3.1) was formulated to address the optimal sizing and operation of the PtH₂ system. The total annualized cost was selected as the objective function of the optimisation problem. The model was implemented in PyPSA, and the optimisation problem was solved using the “Highs” solver.

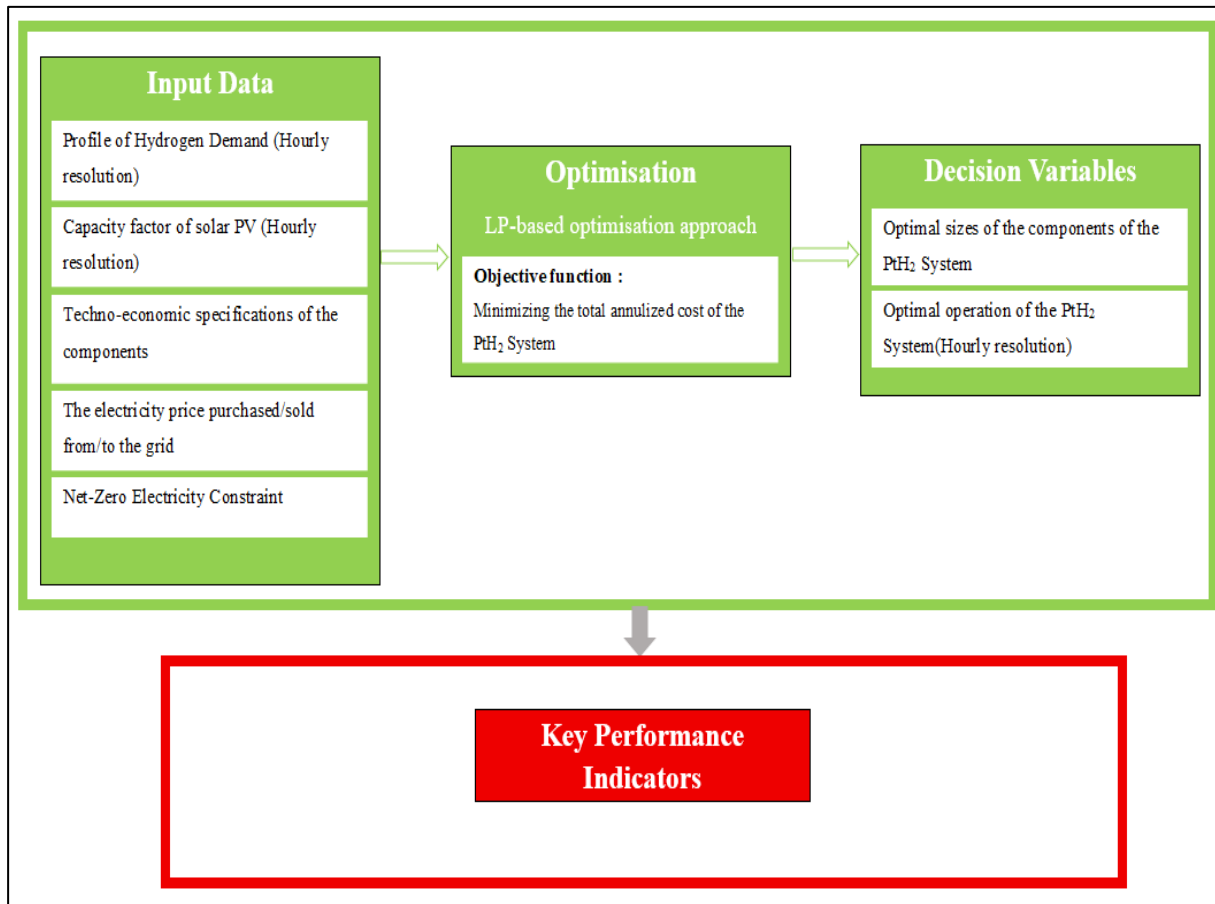


Figure 3.1. Schematic of the methodology, which includes an optimisation framework for the optimal design of the power-to-hydrogen system and a post-processing stage for the evaluation of the indicators.

Building upon the outcomes of the optimisation process, a set of indicators was derived to evaluate the cost-effectiveness of the PtH₂ system under different configurations, in order to answer the following questions :

- Is PV-to-hydrogen economically viable in Algeria, and what is the achievable levelized cost of hydrogen?
- Under which strategy is hydrogen cheapest?

3.2.1.1 Proposed System Architecture

The modeled electrolysis-based hydrogen production system represents a simplified version of the complete system described in Section 2.2.2. The diagram below illustrates the components included in the model.

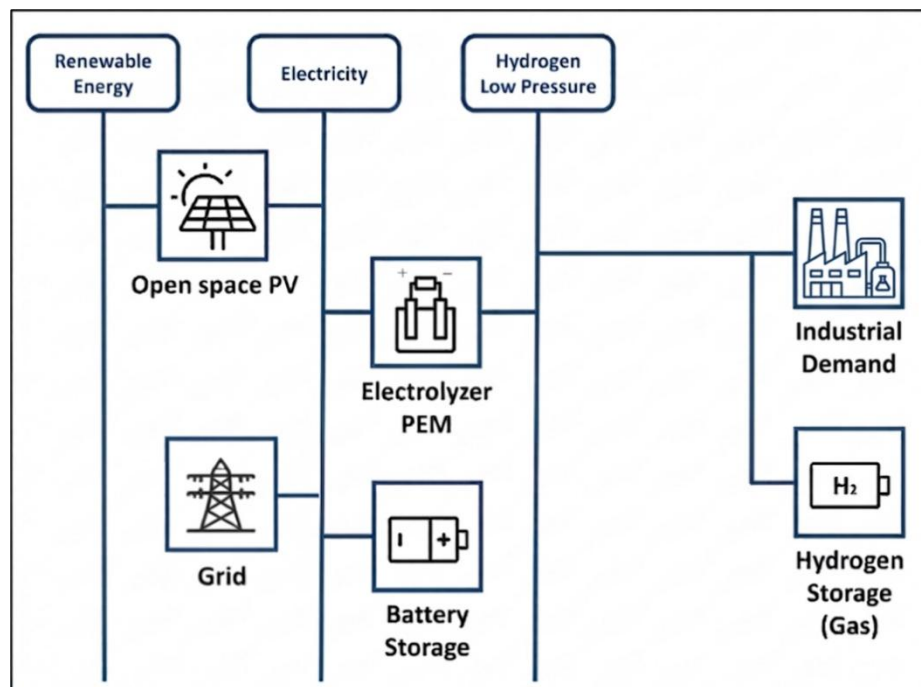


Figure 3.2. Simplified electrolysis-based hydrogen production system diagram.

The PtH₂ system considered in this work consists of a PEM electrolyzer (no extra heat being needed due to its exothermic operation [29]) powered primarily by electricity from an on-site photovoltaic (PV) system (only open-space PV is considered as a renewable energy source), the model includes a low-pressure hydrogen storage tank suitable for industrial applications (other studies consider high-pressure hydrogen storage (HPHS) systems, which require a hydrogen compressor), and that can meet the end-user's demand. A lithium-ion (Li-ion) battery storage system can be integrated to maximize the utilization of locally generated solar energy,

while any surplus renewable electricity that is not stored can be exported to the electrical grid and/or supplemented by the electrical grid when necessary.

Three configurations will be analyzed: the first one, PV with hydrogen storage; the second, PV with hydrogen storage and a lithium-ion (Li-ion) battery; and the last one, PV with hydrogen storage, a lithium-ion (Li-ion) battery, and a connection to the electrical grid.

3.2.1.2 Modelling implementation in PyPSA

▪ Overview of PyPSA

PyPSA is an open-source Python tool used to model and optimize modern energy systems. It can handle different types of power generation, including conventional plants, wind, solar, and hydropower, as well as energy storage and sector coupling. The framework also considers time-dependent operations, flexible demand, and power flows in both DC and AC networks with simplified loss calculations [41].

The Technical University of Berlin's Department of Digital Transformation in Energy Systems made PyPSA. It is used to find the best way to reduce costs in power flow systems; it can also be used to model other systems (sector coupling) [41].

▪ Features:

PyPSA has a lot of features for modeling, optimizing, and planning modern energy systems. These include:

- Economic Dispatch (ED): PyPSA can simulate short-term, market-based dispatch of energy systems, taking into account unit commitment, variable renewable generation, and both short-duration and seasonal storage, including hydro reservoirs with inflow and spillage dynamics. The framework also supports elastic demand, load shedding, and energy carrier conversion, using either perfect operational foresight or a rolling-horizon approach [41].
- Linear Optimal Power Flow (LOPF): The framework extends economic dispatch to account for network constraints in meshed AC and DC grids. Using linearized representations of power flow equations (KVL and KCL), with optional loss approximations, PyPSA determines the least-cost dispatch that satisfies network operational limits [41].
- Security-Constrained LOPF (SCLOPF): PyPSA improves LOPF by adding line outage contingencies, which lets users check reliability under N–1 security conditions [41].
- Capacity Expansion Planning (CEP): This software helps with long-term, least-cost system planning by helping to make decisions about investments in generation, storage, conversion,

and transmission infrastructure. There are options for both single-period and multi-period investments, as well as for continuous or discrete investments [41].

-Pathway Planning: PyPSA lets users optimize more than one investment period at the same time, which makes it easy to plan energy system transitions over time with perfect foresight[41].

-Stochastic Optimization: The framework uses a two-stage stochastic programming method that lets users use uncertain inputs that are weighted by scenario. Investments are seen as decisions made in the first stage, while dispatch decisions are seen as actions taken in response [41].

-Modeling-to-Generate-Alternatives (MGA): PyPSA can look into almost-optimal solution spaces, which gives us an idea of the different system setups that can achieve similar costs [41].

-Sector-Coupling: The framework makes it possible to model multiple energy carriers, such as electricity, heat, and hydrogen, all at once. It lets users show conversion technologies like heat pumps, PEM electrolyzers, battery electric vehicles, direct air capture units, and make synthetic fuel in a flexible way [41].

-Static Power Flow Analysis: PyPSA can use the Newton-Raphson method to calculate both full non-linear and linearized load flows for meshed AC and DC networks. This makes it easier to analyze grids in detail [41].

▪ **Dependencies**

PyPSA relies heavily on other open-source Python packages. Some of them are:

- pandas for storing data about components and time series
- numpy and scipy for linear algebra and matrix calculations
- linopy for preparing optimisation problems
- matplotlib, seaborn, and plotly for static and interactive plotting
- networkx for network calculations
- pytest for unit testing

PyPSA can be used with different solvers. For instance, the free solvers HiGHS (installed by default), GLPK, and CBC, or commercial solvers like Gurobi or FICO Xpress, for which free academic licenses are available [41].

▪ **Components**

PyPSA's representation of the power system is built by connecting the components listed in Table 3.1.

Table 3.1. Description of the main components of PyPSA [41].

Component	Description
Network	Container for all other network components.
Bus	Fundamental nodes to which all other components attach.
Carrier	Energy carrier (e.g., wind, solar, gas, etc.).
Load	A consumer of energy.
Generator	A generator whose feed-in can be flexible, subject to minimum loading or minimum down and up times, or variable according to a given time series of power availability.
Storage Unit	A device that can shift energy from one time to another, subject to efficiency losses.
Store	A more fundamental storage object with no restrictions on charging or discharging power.
Shunt Impedance	An impedance in shunt to a bus.
Line	A branch that connects two buses of the same voltage.
Transformer	A branch that connects two buses of different voltages.
Link	A branch with a controllable power flow between two buses.

▪ System Modeling

The system is modelled using PyPSA's standard component formulations. The core elements are implemented according to the native definitions provided by the tool. These formulations ensure a consistent representation of the system components and their interactions. They also facilitate reliable simulation and optimization of the overall energy system.

The interactions between these components are governed by energy balance equations, capacity limits, and operational constraints embedded within the PyPSA optimization framework.

The default PyPSA components employed in the system model are summarized in Table 3.2.

Table 3.2. PyPSA Model Components of the PtH₂ System

Component	PyPSA Component Class
Solar, Electricity, and Hydrogen	Carrier
The PV field	Generator
Grid	Generator
PEM Electrolyser	Link
Hydrogen Storage	Store
Battery Storage	Storage Unit
Hydrogen Demand	Load

To facilitate the implementation and ensure a clear understanding of the system modeling within PyPSA, we have developed the following diagrams to represent the three distinct scenarios:

- **Scenario 1 (PV Only):** Hydrogen is produced solely from a photovoltaic (PV) system

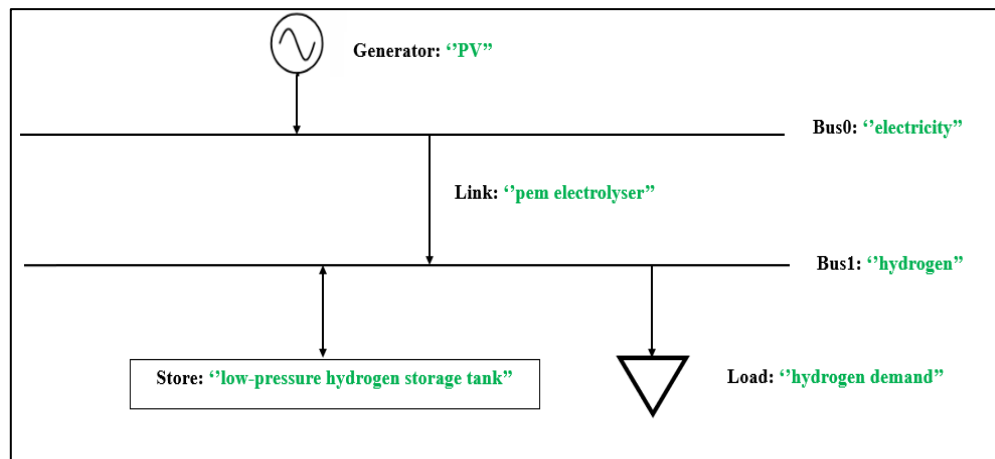


Figure 3.3. Simplified PyPSA Network Representation of Scenario 1.

- **Scenario 2 (PV + Battery Storage):** A lithium-ion battery is added to the PV system.

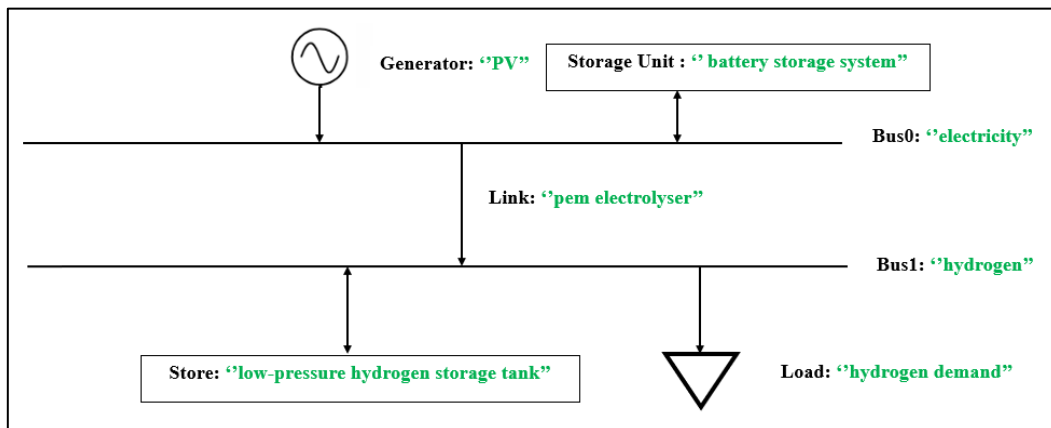


Figure 3.4. Simplified PyPSA Network Representation of Scenario 2.

▪ Scenario 3 (PV + Battery + Grid):

The system includes PV, battery storage, and a grid connection, with a monthly net-zero renewable electricity constraint to ensure the hydrogen remains green. Since Algeria does not currently have any regulations for such systems, the European Commission's Regulation (EU 2023/1184) will be applied on a monthly basis, where :

$$\sum_{t \in M} P_{\text{GRID,import},t} \leq \sum_{t \in M} P_{\text{GRID,export},t} \quad \forall \text{ month } M \quad (3.1)$$

Where $t \in M$ represents all hours t in month M , $P_{\text{GRID,import},t}$ is the imported power from the grid at hour t , and $P_{\text{GRID,export},t}$ is the power exported to the grid at hour t

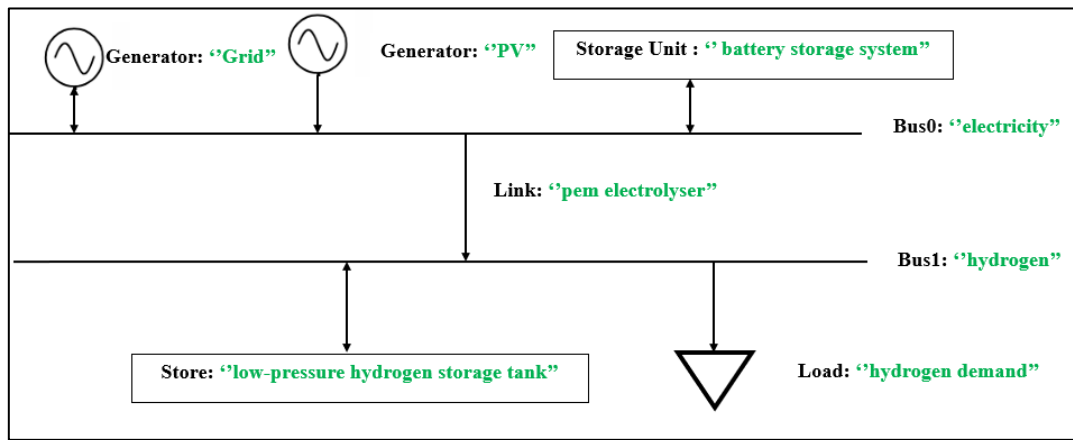


Figure 3.5. Simplified PyPSA Network Representation of Scenario 3.

It is very important to note that each scenario will be analyzed with and without revenue from excess PV electricity.

▪ The objective function

The objective function is to minimise the total annualized cost of the PtH₂ system in Algeria, taking into account all relevant components.

$$f_{\text{obj}} = \min\{C_{A,\text{tot}}\} \quad (3.2)$$

The total annualized cost $C_{A,\text{tot}}$ [M€ / year] is expressed as the sum of capital, fixed O&M, variable O&M, and replacement costs of all system components i [42]:

$$C_{A,\text{tot}} = \sum_i (C_{\text{CAPEX},i} \cdot \text{CRF}_i + C_{\text{FOM},i} + C_{\text{VOM},i} + C_{\text{ARC},i}) \quad (3.3)$$

The various contributors appearing in Eq. (3.3) are defined as [42]:

$$C_{\text{CAPEX},i} = c_{\text{CAPEX},i} \cdot S_i \quad (3.4)$$

$$CRF_i = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (3.5)$$

$$C_{FOM,i} = c_{FOM,i} \cdot S_i \quad (3.6)$$

$$C_{VOM,i} = \sum_t c_{VOM,i} \cdot P_i(t) \cdot \Delta t \quad (3.7)$$

$$C_{ARC,i} = c_{RC,i} \cdot S_i \cdot \sum_{y=Ry_i}^n \frac{r}{1 - (1+r)^{-Ry_i}} \quad (3.8)$$

Where $C_{CAPEX,i}$ is the capital cost, $c_{CAPEX,i}$ is the specific investment cost (€/kW), S_i is the installed capacity of component i , CRF_i is capital recovery factor, r is the weighted average cost of capital, n is the component life time (in years), $C_{FOM,i}$ is the fixed O&M cost, $c_{FOM,i}$ is the fixed O&M percentage of CAPEX per year, $C_{VOM,i}$ is the variable O&M cost, $c_{VOM,i}$ is the variable O&M cost per unit of energy, $P_i(t)$ is the energy produced or consumed by component i at hour t , Δt is the time step, $C_{ARC,i}$ is the replacement cost, $c_{RC,i}$ is the cost of replacing stack/module (€/MW or €/MWh), and Ry_i is the replacement year of component i (Only applies to components with finite lifetime (electrolyzer stacks, BESS)) [42].

The terms $C_{FOM,i}$, $C_{VOM,i}$, and $C_{ARC,i}$ together constitute the total operational expenditure (OPEX) of each component i [42].

It is important to note that the objective function does not account for revenues generated from excess electricity export. This assumption is adopted to prevent excessive investment in renewable generation capacity that could otherwise favor electricity export at the expense of hydrogen production [42].

▪ Indicators

In addition to the LCOH and LCOE indicators already explained in Section 2.3.1, other indicators can be considered to provide a more comprehensive evaluation of the system.

-The PV ratio (R_{PV}) is defined as the ratio between the rated PV power and the rated electrolyzer power (gives an indication of the relative size of the PV system compared to the electrolyzer) [42]:

$$R_{PV} = \frac{P_{PV, \text{rated}}}{P_{EL, \text{rated}}} \quad (3.9)$$

Where $P_{PV, \text{rated}}$ is the rated power of the PV [MW], and $P_{EL, \text{rated}}$ is the rated power of the electrolyzer [MW].

-The electrolyzer ratio (R_{EL}) indicates the size of the electrolyzer relative to the average hydrogen load [42]:

$$R_{EL} = \frac{P_{EL, \text{rated}} \cdot \eta_{EL, \text{rated}}}{P_{LD, H2, \text{avg}}} \quad (3.10)$$

Where $\eta_{EL, \text{rated}}$ is the efficiency of the electrolyzer under rated conditions, and $P_{LD, H2, \text{avg}}$ is the average hydrogen load to be covered [MW].

The electrolyzer ratio helps to determine whether the electrolyzer is oversized or undersized compared to the hydrogen demand [42].

-The hydrogen storage autonomy (A_{HS} , in hours) represents the period of time during which the hydrogen storage can cover the average hydrogen demand [42]. It indicates the ability of the storage system to supply the electrolyzer (or other hydrogen loads) without additional production [42]. It is mathematically defined as [42]:

$$A_{HS} = \frac{E_{HS, \text{rated}}}{P_{LD, H2, \text{avg}}} \quad (3.11)$$

Where $E_{HS, \text{rated}}$ is the rated energy capacity of the hydrogen storage [kWh or kg H₂ equivalent].

-The battery storage autonomy (A_{BS} , in hours) represents the period of time during which the battery storage can cover the energy demand of the electrolyzer under rated conditions [42]. It reflects the ability of the battery to supply the system without additional charging. It is defined as [42]:

$$A_{BS} = \frac{E_{BS, \text{rated}}}{P_{EL, \text{rated}}} \quad (3.12)$$

Where: $E_{BS, \text{rated}}$ is the rated energy capacity of the battery storage [mWh]

-The grid share (y_{GR} , in %) represents the fraction of electrical energy consumed by the electrolyser that comes from the grid [42]. The remainder is supplied locally by the PV plant. It is calculated as [42]:

$$y_{GR} = \frac{\sum_{t=1}^T P_{GR, \text{buy}}(t) \cdot \Delta t}{\sum_{t=1}^T P_{EL, \text{in}}(t) \cdot \Delta t} \times 100\% \quad (3.13)$$

Where $P_{GR, \text{buy}}(t)$ is the power imported from the grid at time t [MW], $P_{EL, \text{in}}(t)$ is the total power consumed by the electrolyzer at time t [MW], Δt is time step (usually 1 hour), and T is the total number of time steps

-The PV share (y_{PV} , in %) represents the fraction of electrical energy consumed by the

electrolyser that is supplied by the on-site PV plant [42]. It can be computed directly from the grid share [42]:

$$y_{PV} = 100\% - y_{GR} \quad (3.14)$$

3.2.1.3 Assumptions and constraints of the model

In developing the PtH₂ system model, several assumptions and constraints are considered to simplify the analysis and ensure feasible results:

▪ Assumptions regarding the hydrogen production system

- The system size will be optimized for only one Algerian site.
- Three scenarios will be studied with and without revenue from excess PV electricity.
- For the battery, a minimum and maximum state of charge are enforced
- The module replacement of the battery storage unit is included.
- All storage levels (hydrogen and battery storage) must equal the initial state of charge at the end of the optimization period of 8760 h, and the self-discharge losses for the hydrogen storage are negligible.
- The electrolyser can work between 0% and 100% of nominal power with a fixed efficiency; overloads are excluded (there is no imposed constraint on the minimum operation of the electrolyser, allowing it to operate flexibly depending on available power and hydrogen demand, only in the third scenario, where 519 hours of downtime are excluded for its maintenance). The stack replacement after a certain number of operation hours is included in the model.
- The efficiency of the electrolyzer is calculated based on the Lower Heating Value (LHV) of hydrogen.
- The hydrogen demand by heavy industry applications is constant over time and is fixed at 1000 tonnes/year.
- No constraints regarding the maximum component size are considered (all components can be freely invested in at the size that best serves the cost-minimisation objective), which means:

$$0 \leq P_{i,nom} \quad (3.15)$$

Where $P_{i,nom}$ is the rated power of the component ($i = PV, EL$).

$$0 \leq E_{i,rated} \quad (3.16)$$

Where $E_{i,nom}$ is the rated energy of the component ($i = BS, HS$).

▪ Assumptions regarding general optimization information

- Investment and operational costs, along with other technical parameters of the system components, are considered over the period 2020–2023 (Table 3.3).
- All costs are annualized using CRF to ensure comparability across the project lifetime.
- Meteorological data for solar irradiation correspond to the year 2023.
- The analysis is conducted with an hourly time resolution, corresponding to 8760 hours for the year 2023 (Using a 1-hour time step offers a balanced compromise between result accuracy and computational burden).

3.2.1.4 Input data for the PtH system modelling

▪ Site Selection and Hydrogen Demand

The M'sila region was selected as the case study site due to its exceptional solar energy potential, which provides highly favorable conditions for photovoltaic (PV) electricity generation. M'Sila, town, north-central Algeria. It is situated on the Plains of Hodna at an elevation of 1542 feet (470 metres) between the saline lake Chott el-Hodna (south) and the east-west-extending Hodna Mountains (a range of the Tell Atlas Mountains) to the north. A dam on the Wadi Ksob in the Hodna Mountains irrigates the cereal-growing area around the town. M'Sila is a farming and trading centre [43].

The site is characterized, from a climatic point of view, by moderate temperatures during winter and spring, which rise to high levels in summer and autumn. It benefits from a strong solar potential, with an annual average of around 7 kWh/m², making it highly suitable for solar energy applications. The relative humidity is generally low, contributing to dry atmospheric conditions [44].

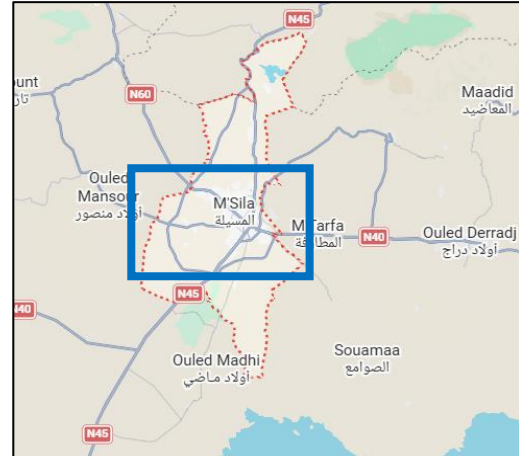


Figure 3.6. Geographic location of the study area: M'Sila, Algeria.

Additionally, the area experiences a high number of clear-sky days throughout the year, enhancing solar irradiation. However, it is also subject to frequent dust storms, particularly during the spring season [44]. In this study, hydrogen demand is modeled to represent a continuous industrial application operating 24 hours per day, seven days per week, over the

course of an entire year. This constant demand profile mirrors the operational requirements of industrial processes that rely on a stable and uninterrupted hydrogen supply. The annual hydrogen requirement is set at 1000 tonnes per year and is uniformly distributed across the 8760 hours of the year, resulting in a consistent hourly consumption rate. This approach provides a conservative and systematic representation of industrial hydrogen demand, facilitating reliable modeling and analysis of the proposed energy system.

Hydrogen demand is usually expressed in mass units (kg/year or tonnes/year), while PyPSA operates using power units (MW). Therefore, it is necessary to convert the hydrogen demand into an equivalent electrical power in order to integrate it into the model.

Convert annual hydrogen to hourly flow

$$1000 \text{ tonnes/year} = 1000000 \text{ kg/year} \quad (3.17)$$

So

$$\dot{m}_{H_2} = \frac{1000000}{8760} \approx 114.16 \text{ kg/h} \quad (3.18)$$

The Lower Heating Value (LHV) of hydrogen is equal to 33.33 kWh/kg

So the hydrogen energy demand is:

$$P_{H_2} = 114.16 \times 33.33 \approx 3805 \text{ kW} \approx 3.81 \text{ MW} \quad (3.19)$$

▪ Photovoltaic Capacity Factor

For the selected site of M'sila (Algeria), the PV capacity factor time series was derived from site-specific solar irradiation data and spans one full year with hourly resolution (8760 hours). The data reflects the local climatic conditions, including seasonal and diurnal variations in solar availability.

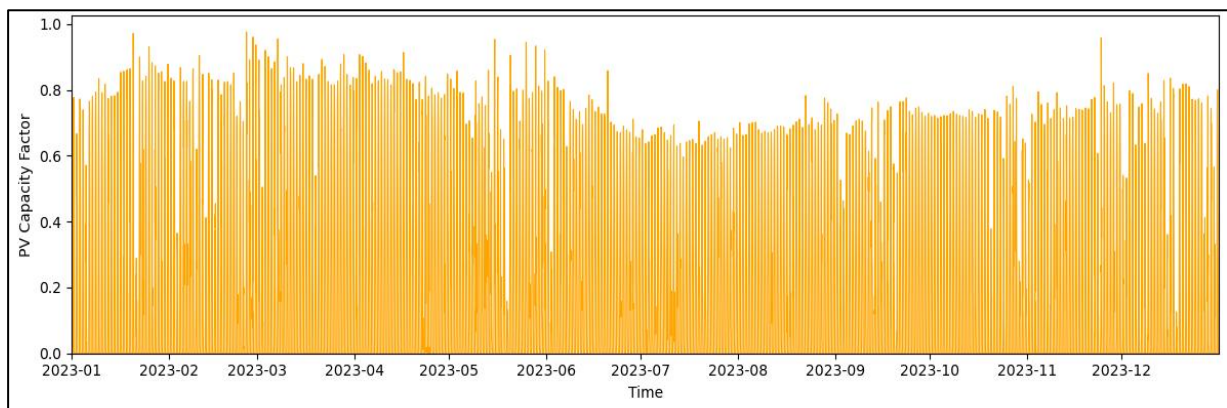


Figure 3.7. Capacity Factor in M'sila for the Year 2023 (Average 20.32%).

Unlike theoretical estimates, the Capacity Factor (CF) used in this study was obtained from real-world station measurements (Ain El-Melh station with latitude and longitude of 34°51" N, and 04°11" E, respectively, while the height above sea level is 910 m) [44]. Consequently, site-specific losses, including soiling (dust accumulation), thermal degradation, and system inefficiencies, are implicitly integrated into the dataset, providing a high degree of reliability for the M'Sila region case study.

▪ **Techno-economic data:**

Table 3.3. Techno-economic modelling for the PtH system.

	Value	Ref
Photovoltaic		
CAPEX	650 €/kW	[42], [45]
OPEX (annual)	1.9% (% of CAPEX)	[45]
Lifetime	Project lifetime	[42]
Battery storage (Li-ion)		
CAPEX (module +BOP)	306 €/kWh	[42]
OPEX (annual)	2 % of CAPEX	[42], [29]
Lifetime of the module	10 years	[42], [29]
Replacement cost (module)	50% (% of CAPEX)	[42]
Lifetime of BOP	Project lifetime	[42]
Self-discharge rate	0.007%/h	[42]
Charging efficiency	95%	[42]
Discharging efficiency	95%	[42]
Min. SOC	20%	
Max. SOC	100%	
Electrolyser (PEM)		
Efficiency	64.1% (52kWh/Kg _{H2})	[45]
CAPEX (stack +BOP)	1000 €/kW	[46]
Replacement cost (stack)	25% (% of CAPEX)	[47]
OPEX (annual)	2% (% of CAPEX)	[42],[45],[46]
Lifetime of the stack	9 years	
Lifetime of the BOP	Project lifetime	[42]
Hydrogen storage		
CAPEX	500 €/kg _{H2} LPST	[42], [45]
OPEX (annual)	2% (% of CAPEX)	[42]
Lifetime	Project lifetime	[42]
Min. SOC	0%	
Max. SOC	100%	
Other assumptions		
Electricity purchase price	0.030€/KWh	[48]
Electricity sale price	Sensitivity analysis(0% to 60% of electricity purchase price)	
Project lifetime	25 y	[45]
Discount rate	7%	[45]

-The residential electricity price in Algeria is DZD 5.650 per kWh or USD 0.042. The electricity price for businesses is DZD 4.680 kWh or USD 0.035. These retail prices were collected in September 2025 and include the cost of power, distribution, and transmission, and all taxes and fees [48]. Currency converted from USD to EUR at an exchange rate of 0.857, based on market data from April 10, 2026 ($0.035\text{USD/kWh} = 0.030 \text{ €/kWh}$).

-The sensitivity analysis from 0% to 60% aims to cover all possible scenarios in terms of the electricity sale price.

3.2.2 Technical Assessment

The methodology adopted in this part is based on simulation and performance analysis of a photovoltaic-powered PEM electrolyzer system under Algerian climatic conditions using MATLAB/Simscape.

The layout of the developed model consists of several interconnected subsystems representing the different components of the hydrogen production chain. The system starts with the photovoltaic (PV) array, which converts solar energy into electrical power using irradiance and temperature data as inputs.

The PEM electrolyzer is the core component of the hydrogen production system. It uses the electrical energy produced by the PV generator to split water into hydrogen and oxygen through the electrolysis process. The electrolyzer model reproduces the electrical and electrochemical behavior of the stack during operation.

The water supply subsystem provides the required water input for the electrolysis process, while the produced hydrogen is transferred to the hydrogen storage tank for storage and further use.

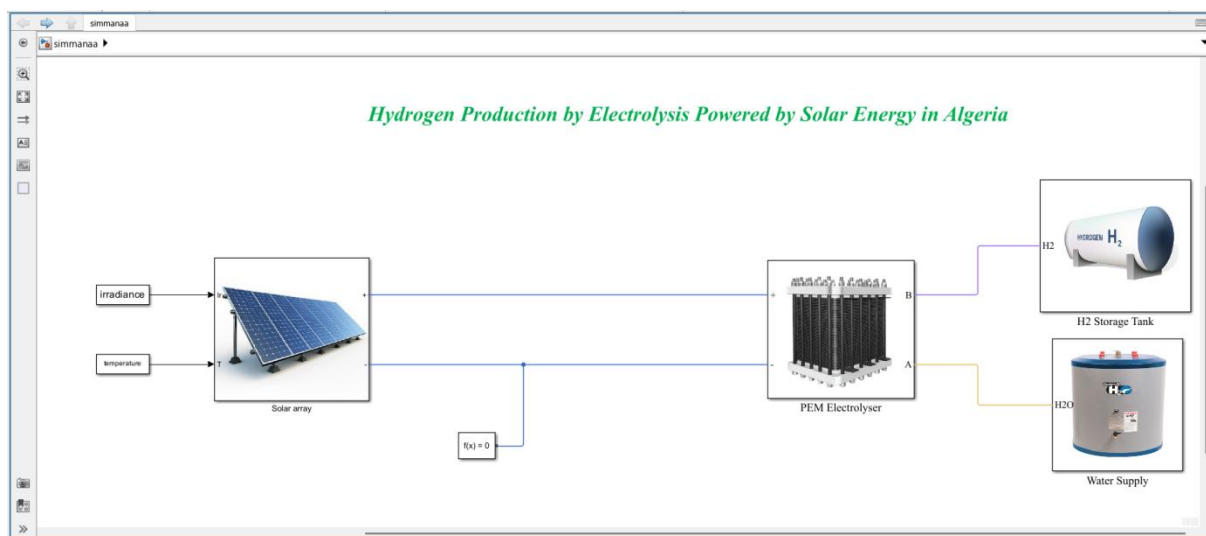


Figure 3.8. Simscape model layout of the PV-powered PEM electrolyzer system.

The interaction between the different subsystems enables the evaluation of the global performance of the proposed hydrogen production system.

3.2.2.1 Simulation Framework

▪ Introduction to Simscape modeling

Simscape is a physical modeling tool integrated within the MATLAB/Simulink environment, designed to simulate and analyze the behavior of physical systems. It offers an extensive library of predefined components representing various domains. Each library group contains ready-to-use components that directly represent real-world physical elements [49].

-The Foundation Library provides fundamental building blocks shared across multiple domains, including sources, sensors, passive elements, and initial condition settings. It serves as the core reference library upon which all other Simscape libraries are built [49].

-The Utilities Library offers complementary tools for managing physical units, configuring initial conditions, and automatically analyzing equations, thereby enhancing model accuracy and usability[49].

-The Battery Library is dedicated to energy storage systems. It includes models of individual cells, battery packs, and electro-thermal behaviors, making it essential for applications related to electromobility and energy management [49].

-The Driveline Library provides components for modeling and simulating rotational and translational mechanical systems. It includes elements such as worm gears, lead screws, and vehicle-related components like engines, tires, transmissions, and torque converters [49].

-The Electrical Library contains components for modeling and simulating electrical, electronic, and mechatronic systems. It includes semiconductor devices, electric machines, and components used in applications such as electromechanical actuation, smart grids, and renewable energy systems [49].

-The Fluids Library includes components designed for simulating hydraulic and pneumatic systems, such as pumps, tanks, pipelines, and valves. It is widely used in modeling industrial processes and systems like braking circuits [49].

-The Multibody Library provides a 3D mechanical simulation environment for complex systems such as robots, vehicle suspensions, construction equipment, and aircraft landing gear. Simscape Multibody formulates and solves the equations of motion for the entire mechanical system [49].

Figure 3.9 illustrates the Simulink Library Browser focused on Simscape and its main domains (Battery, Electrical, Fluids, Multibody, etc.), which serves as the primary interface for integrating physical components into a model.

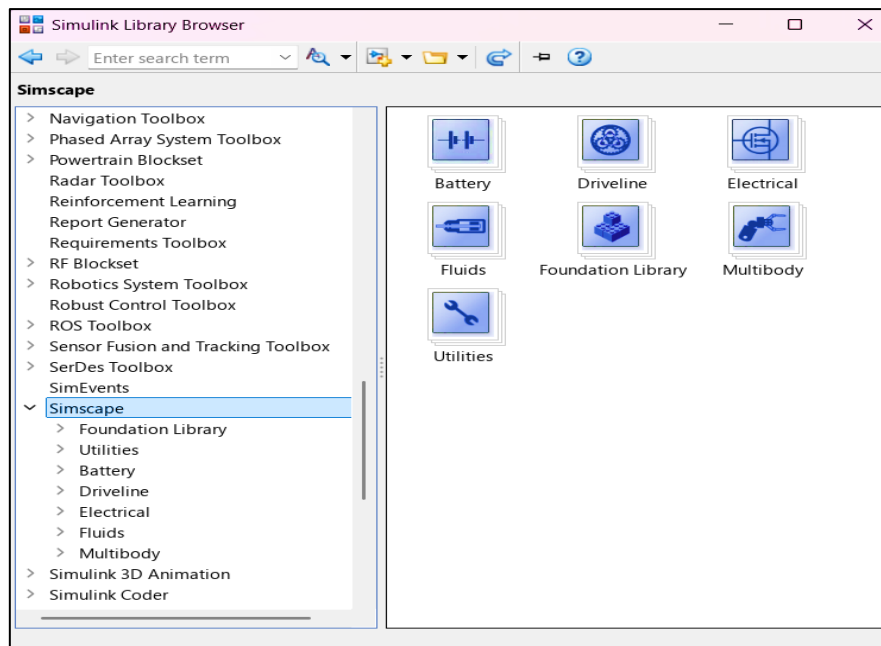


Figure 3.9. Simscape Block Libraries.

Simscape differs from Simulink in both its modeling approach and the way system components interact within the simulation environment, where Simulink is a graphical programming environment in which input and output blocks are connected to represent a dynamic system. In this approach, the mathematical equations of the system must first be derived and validated before being implemented in the form of block diagrams. Simulink mainly represents the flow of signals between blocks, leading to a unidirectional signal-based mathematical model. Therefore, it can be considered a traditional modeling environment where equations are translated into interconnected functional blocks [50].

Simscape adopts a physics-based modeling approach, relying on fundamental principles such as the conservation of energy and mass [49]. This approach enables the analysis of interactions between multiple physical domains, providing deeper insight into the behavior of complex systems [49].

Each physical domain is defined by two types of variables: across variables and through variables [49]. Across variables are measured using sensors connected in parallel, whereas through variables are measured using sensors connected in series [49].

The following table lists the Through and Across variables associated with each type of physical domain in Simscape software:

Table 3.4. Through and Across Variables of Simscape Physical Domains [49].

Physical Domain	Across Variable	Through Variable
Electrical	Voltage	Current
Gas	Absolute pressure and temperature	Mass flow rate and energy flow rate
Isothermal liquid	Absolute pressure	Mass flow rate
Magnetic	Magnetomotive force (mmf)	Flux
Mechanical rotational	Angular velocity	Torque
Mechanical translational	Translational velocity	Force
Position-based mechanical translational	Position and translational velocity	Force
Moist Air	Absolute pressure, temperature, specific humidity (water vapor mass fraction), mass ratio of water droplets to moist air, and trace gas mass fraction	Mixture mass flow rate, mixture energy flow rate, water vapor mass flow rate, water droplet mass flow rate, and trace gas mass flow rate
Thermal	Temperature	Heat flow
Thermal liquid	Absolute pressure and temperature	Mass flow rate and energy flow rate
Two-phase fluid	Absolute pressure and specific internal energy	Mass flow rate and energy flow rate

▪ Creation of a Custom Component in Simscape

To create a new custom component in Simscape, a component model class must be defined by writing a component file with the “.ssc” extension. The file starts with the “component” keyword followed by the component name and ends with the “end” keyword. The component file can contain several sections arranged in any order. The declaration section is used to define the component elements such as parameters, variables, nodes, inputs, and outputs, with each declaration block beginning with its corresponding keyword and ending with end. The branches section establishes the relationship between the component variables and the physical nodes by connecting the Through and Across variables [49]. For composite models, the structure section is used to specify the internal component connections. The equation section contains the mathematical equations that describe the physical behavior of the component during simulation, including conditional equations when necessary. The events section allows the implementation

of discrete event behavior and state updates, while the annotations section is used to customize the appearance and properties of the generated Simscape block [49].

Table 3.5. Simscape Language Syntax [49].

Keyword	Description
annotations	Control the appearance of the Simscape block based on the component
branches	Establish a relationship between components through variables and nodes
component	Component model class definition
Faults	Faults interface annotation for custom component (depuis R2024b)
inputs	Define component inputs, that is, physical signal input ports of the block
nodes	Define component nodes, that is, conserving ports of the block
outputs	Define component outputs, that is, physical signal output ports of the block
parameters	Declare domain or component parameters
variables	Declare domain or component variables

The Simscape Component block allows the direct generation of a Simscape block from a textual component file without requiring the library build process. Although the `ssc_build` command can be used to create a custom block library from all Simscape component files within a namespace, the Simscape Component block provides an alternative approach by enabling on-the-fly conversion of a component file directly into a custom block inside the Simulink model[49].

To deploy a Simscape component file directly into a block diagram, “the Simscape Component” block is first added from the Simscape > Utilities library into the Simulink model. By default, the block is not associated with any component file. The block dialog box is then opened by double-clicking the block [49].

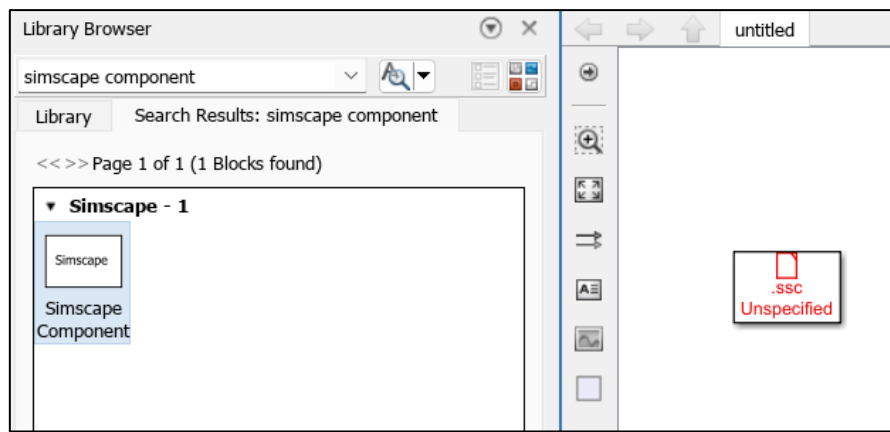


Figure 3.10. Implementation of a custom Simscape component.

After that, the Select component file button is used to open a browser that displays only files with ‘.ssc’ or ‘.sscp’ extensions from the current working directory. The required Simscape language component file is then selected, while ensuring that its folder, or the namespace parent folder if applicable, is included in the MATLAB path. Once the file is opened, the source file name appears in the dialog box together with the block description and source code link. The selected component is immediately applied to the block, and the block icon, ports, parameters, and variables are automatically updated according to the selected component [49].

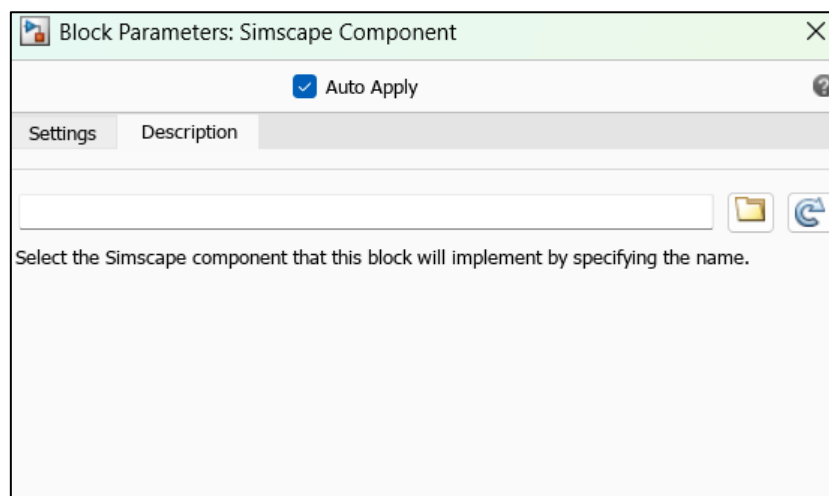


Figure 3.11. Simscape Component Block Parameters Configuration Window.

3.2.2.2 System Modeling and Simscape Implementation

▪ Photovoltaic subsystem

○ Model Description

The semiconductor operation of a photovoltaic cell can be represented with the equivalent circuit shown in Figure 3.12.

where the PV parameters are defined as follows:

I_L is the photo-generated current, I_d is the diode current, I_p is the current through the parallel resistor, V_d is the diode voltage, R_s is the series resistance, and R_p is the parallel resistance.

Based on Kirchhoff's current law, the output current is represented by [51]:

$$I = I_L - I_d - I_p \quad (3.20)$$

The diode current is expressed as [51]:

$$I_d = I_0 \left(e^{\frac{qV_d}{nN_s kT}} - 1 \right) \quad (3.21)$$

The shunt current is [51]:

$$I_p = \frac{V_d}{R_p} \quad (3.22)$$

By substitution, the output current becomes [51]:

$$I = I_L - I_0 \left(e^{\frac{q(V+IR_s)}{nN_s kT}} - 1 \right) - \frac{V+IR_s}{R_p} \quad (3.23)$$

Where I_0 is the reverse saturation current of the diode, T is cell temperature (K), n is diode ideality factor, N_s is the number of cells in series, k is Boltzmann constant (1.38×10^{-23} J/K), and q represents the electron charge (1.60×10^{-19} C) [51].

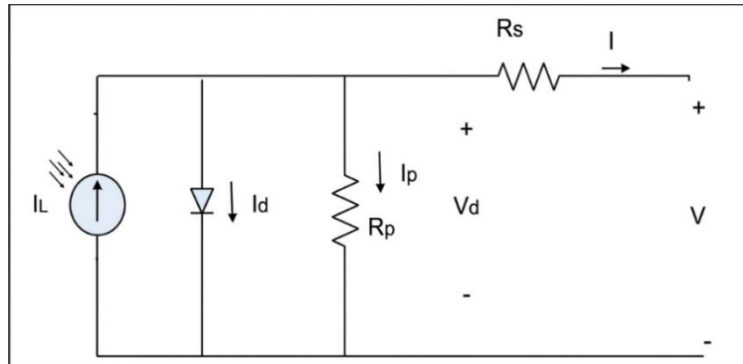


Figure 3.12. Equivalent circuit of a PV cell [51].

The photocurrent depends on irradiance and temperature [51]:

$$I_L = (I_{sc} + \mu_{sc}(T - T_{ref})) \frac{G}{G_{ref}} \quad (3.24)$$

$$I_0 = I_{0-ref} \left(\frac{T}{T_{ref}} \right)^3 \exp \left[\frac{qE_g}{nk} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \quad (3.25)$$

$$I_{0-ref} = \frac{I_{sc}}{\frac{qV_{oc}}{e n N_s k T} - 1} \quad (3.26)$$

Where I_{0-ref} is the cell's reverse saturation current at reference conditions, I_{sc} is the short-circuit current, V_{oc} is the open-circuit voltage, G is the irradiance input, $G_{STC} = 1000 \text{ W/m}^2$ is the irradiance at Standard Test Conditions (STC), $T_{STC} = 25^\circ\text{C}$ is the temperature at STC, μ_{sc} is the temperature coefficient of the short-circuit current, and E_g is the material band-gap energy [51].

DC-DC converters provide high efficiency and flexibility for regulating power in DC-based systems. In the proposed solar green hydrogen production system, a buck–boost converter is integrated with an MPPT controller using the Perturb and Observe (P&O) technique [52]. This configuration enables the photovoltaic system to efficiently supply the PEM electrolyzer with the required electrical power for hydrogen generation [52]. In addition, the control system allows continuous tracking of the maximum power point under varying irradiance and temperature conditions, thereby enhancing the utilization of renewable solar energy [52]. The DC-DC buck-boost converter can be represented with the equivalent circuit shown in Figure 3.13.

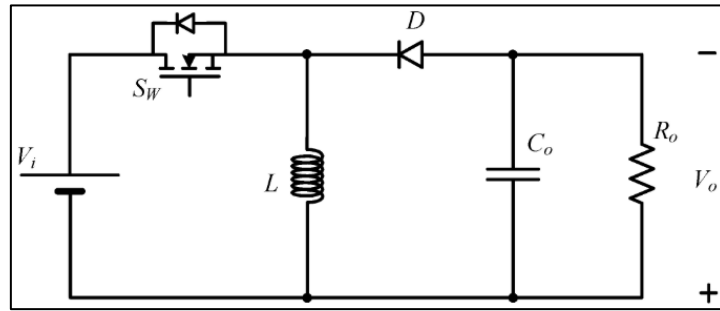


Figure 3.13. Conventional DC-DC buck-boost converter [53].

The conventional buck–boost converter output voltage V_o can theoretically vary from zero to infinity as the duty cycle D changes from 0 to 1. The relationship between the input voltage V_i , output voltage V_o , and duty cycle D is given by [53]:

$$V_o = \frac{D}{1-D} V_i \quad (3.27)$$

For switch ON [54]:

$$\begin{cases} v_L = v_i \\ \frac{di_L}{dt} = \frac{v_i}{L} \end{cases} \quad (3.28)$$

$$\begin{cases} i_C = -\frac{v_o}{R} \\ \frac{dv_o}{dt} = \frac{v_o}{RC} \end{cases} \quad (3.29)$$

For switch OFF [54]:

$$\begin{cases} v_L = -v_o \\ \frac{di_L}{dt} = -\frac{v_o}{L} \end{cases} \quad (3.30)$$

$$\begin{cases} i_C = i_L - i_o \\ \frac{dv_o}{dt} = \frac{i_L}{C} - \frac{v_o}{RC} \end{cases} \quad (3.31)$$

The Maximum Power Point Tracking (MPPT) method adopted in this work is the Perturb and Observe (P&O) algorithm. If the power increases, the duty cycle of the DC-DC converter is adjusted in the same direction to reach the maximum power point (MPP). Otherwise, the direction is reversed. Although the method is simple and effective, it causes oscillations around the MPP. A large step size provides a faster response to changes in irradiance and temperature, while a small step size reduces oscillations but slows the tracking speed [55].

Figure 3.14 illustrates the flowchart of the Perturb and Observe (P&O) algorithm used for Maximum Power Point Tracking (MPPT) in the photovoltaic system.

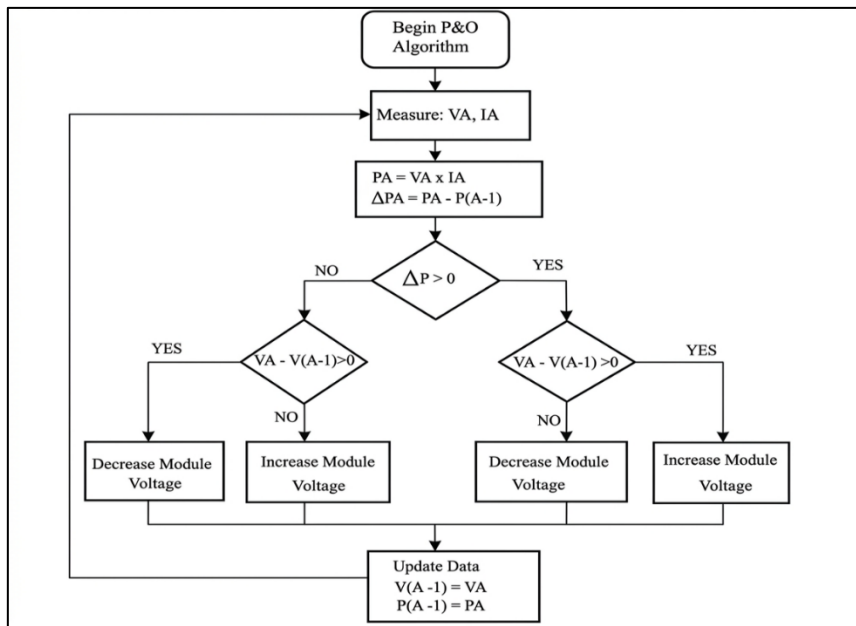


Figure 3.14. Flow chart of the P&O Algorithm [55].

○ Implementation in Simscape

The photovoltaic subsystem was implemented in Simscape using a solar cell block whose output depends on irradiance and temperature inputs.

Voltage and current sensors were used to measure the electrical output of the PV system and provide feedback to the MPPT controller. The MPPT algorithm generates the duty cycle required to control the DC-DC converter and ensure operation at the maximum power point. The converter adapts the variable PV output to the operating requirements of the PEM electrolyzer, enabling efficient hydrogen production under varying environmental conditions.

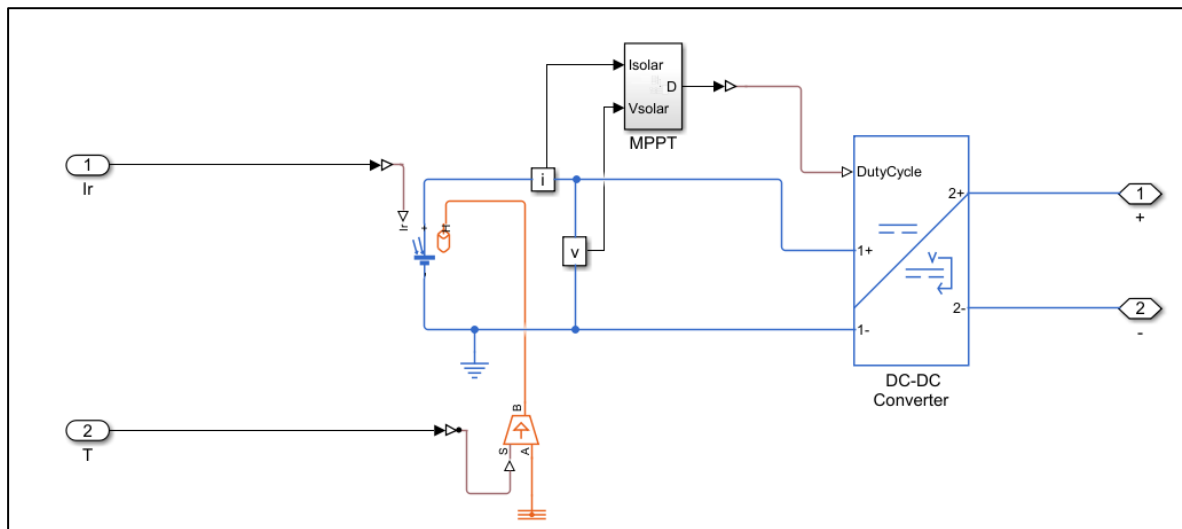


Figure 3.15. Simscape model of the PV subsystem.

The photovoltaic system considered in this study has a total installed power of 70 kW. The PV module used in the simulation is the AS_6M30_HC_320W module, selected directly from the parameterization manager available in Simscape.

Table 3.6. Characteristics of the PV Panel

Parameter	Value	Unit
Maximum Power ($P_{\max}$)	320	W
Open Circuit Voltage (V_{OC})	40.20	V
Short Circuit Current (I_{SC})	10.14	A
Voltage at Maximum Power (V_{mp})	33.40	V
Current at Maximum Power (I_{mp})	9.59	A
Number of series-connected cells per string	60	-
Number of parallel-connected strings	1	-
Module efficiency	18.96	%
Module area	1.69	m ²

The temperature and irradiance data used in this study were obtained from real-world measurements recorded at the Ain El-Melh station in M'sila. The dataset includes values over two days in July and December for the year 2023 in order to evaluate the system's dynamic response under different seasonal conditions. The corresponding temperature and irradiance profiles are presented in Figures 3.16 and 3.17, respectively.

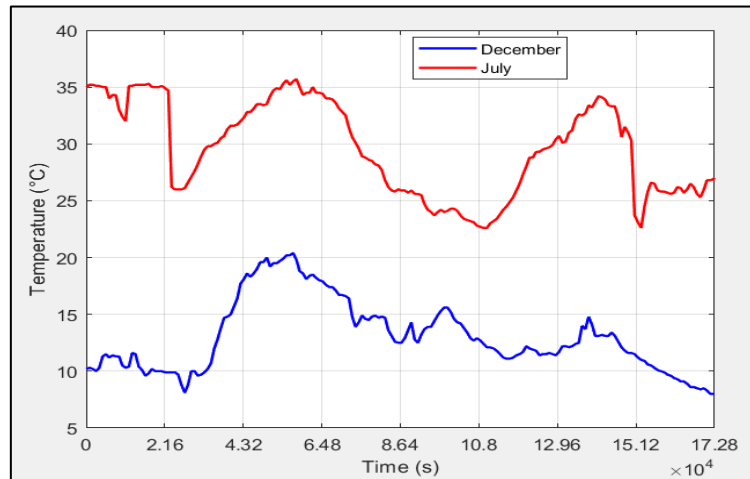


Figure 3.16. Ambient temperature variation during two days in December and July.

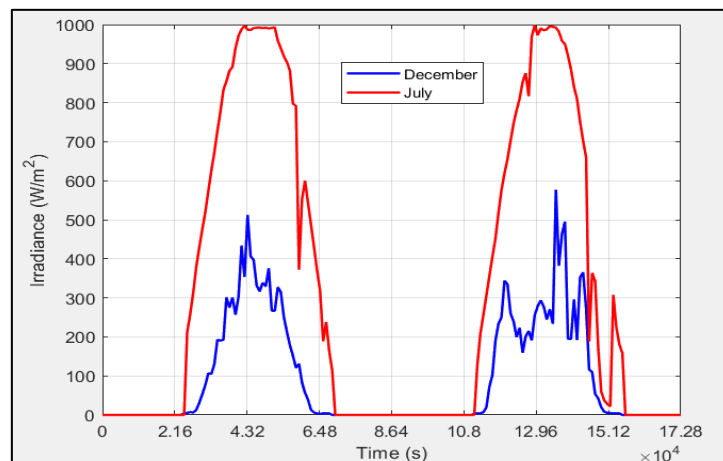


Figure 3.17. Solar irradiance variation during two days in December and July.

It is very important to import the irradiance and temperature data as time-series signals rather than constant variables, because both parameters vary continuously with time.

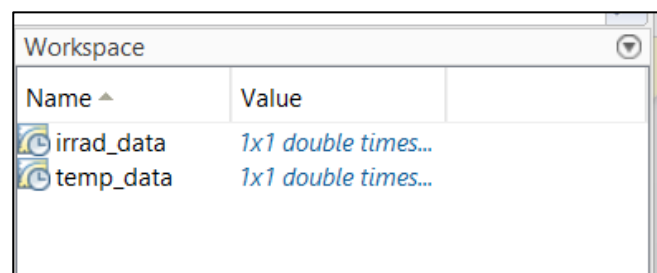
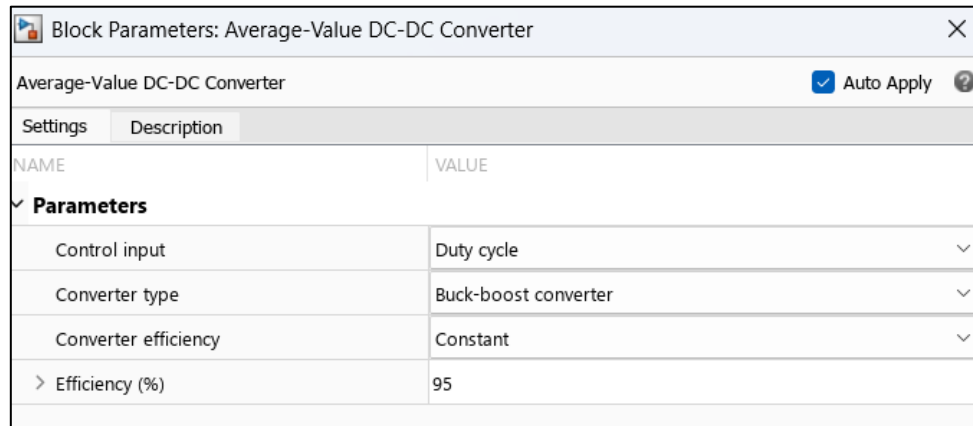


Figure 3.18. MATLAB workspace illustrating the imported solar irradiance and temperature time-series data.

The DC-DC converter does not maintain constant hydrogen production. The produced hydrogen still varies with the photovoltaic power since the PEM electrolyzer operation mainly depends on the supplied current.

The operational parameters of the DC-DC buck-boost converter are displayed in Figure 3.19.



Block Parameters: Average-Value DC-DC Converter	
Average-Value DC-DC Converter ☒ Auto Apply ?	
Settings Description	
NAME	VALUE
Parameters	
Control input	Duty cycle
Converter type	Buck-boost converter
Converter efficiency	Constant
> Efficiency (%)	95

Figure 3.19. Block Parameters for the DC-DC Converter.

▪ PEM Electrolyser

The developed model is mainly centered around the PEM electrolyser stack, which represents the core component of the entire hydrogen production system. All auxiliary components are connected to this central block in order to reproduce the real operating conditions of the electrolyser.

The model is composed of the electrolyser stack, including the anode channels, membrane electrode assembly (MEA), and cathode channels, together with several auxiliary components such as the recirculation subsystem, heat exchanger, dehumidifier, and thermal mass. These components ensure proper water circulation, heat dissipation, thermal regulation, and hydrogen conditioning, allowing a more realistic simulation of the electrolyser's dynamic and thermal behavior [56].

A simplified MATLAB/Simulink model of a proton exchange membrane electrolyzer, originally introduced in [57], was adopted in this work. The model formulation and implementation details are described in [58] and [59]. It has been extensively validated and applied in several previous research studies [60]- [61]- [62].

A reference operating condition of 70 kW electrical input was defined for the PEM electrolyzer to evaluate its characteristics, and this value was also used as the maximum operating limit for system-level analysis.

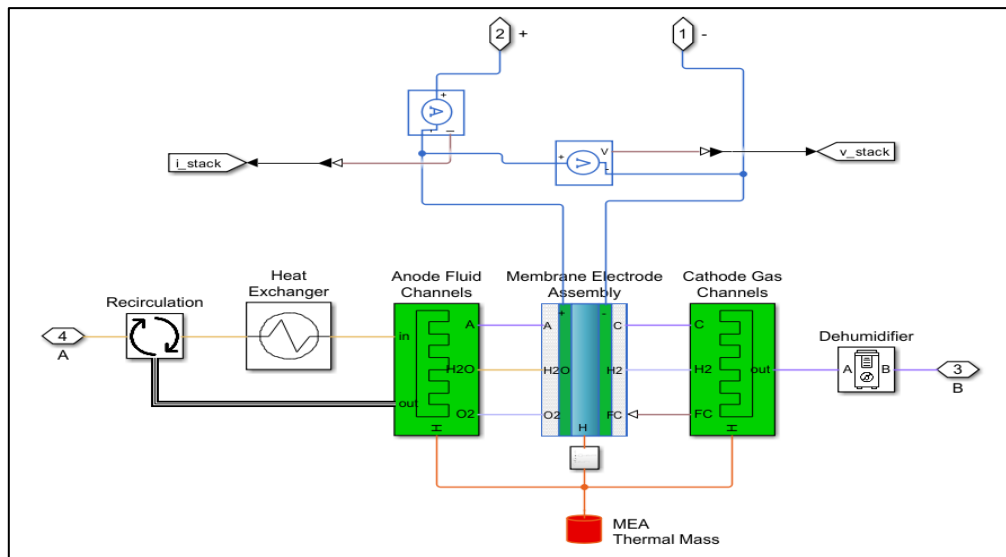


Figure 3.20. PEM Electrolyzer Stack model with Auxiliary Components for Thermal and Fluid Management.

Table 3.7 presents the operating parameters of the PEM electrolyser.

Table 3.7. PEM electrolyzer stack parameters

Parameter	Value	Unit
Maximum power	70	KW
Number of cells	50	-
Cell area	280	cm ²
Maximum operating current density	2.77	A/cm ²
Maximum operating cell voltage	1.8	V
Cathode pressure	30	bar
Operating temperature	80	°C
H ₂ max generation rate	1.45	Kg/h
Stack efficiency based on LHV	69	%

○ Anode and Cathode Channels

To simulate the anode and cathode channels, basic pipe elements were used, where the anode channels include three main pipes: two thermal liquid pipes dedicated to water management and one moist air pipe for oxygen transport. The moist air pipe was connected to a cap, which acts as a terminal point in a moist air network.

The system communicates with the external model through three thermal liquid ports: “1-in” for water entry, “2-out” for water and oxygen exit, and “4-H₂O” for water removal due to electrochemical consumption and internal transport mechanisms. Port 3 (A) is not a flow port; it serves as a thermodynamic coupling interface for the anode moist air domain, exchanging state variables to ensure consistency of the gas properties across the model, without allowing

any actual mass flow through it. Port 5 (O_2) is the oxygen outlet port, where oxygen produced in the MEA is injected into the oxygen channels using a controlled trace gas source and then transported through the channel before leaving the system. Port 6 (H) is the thermal port, representing the heat exchange between the anode channels and their surroundings.

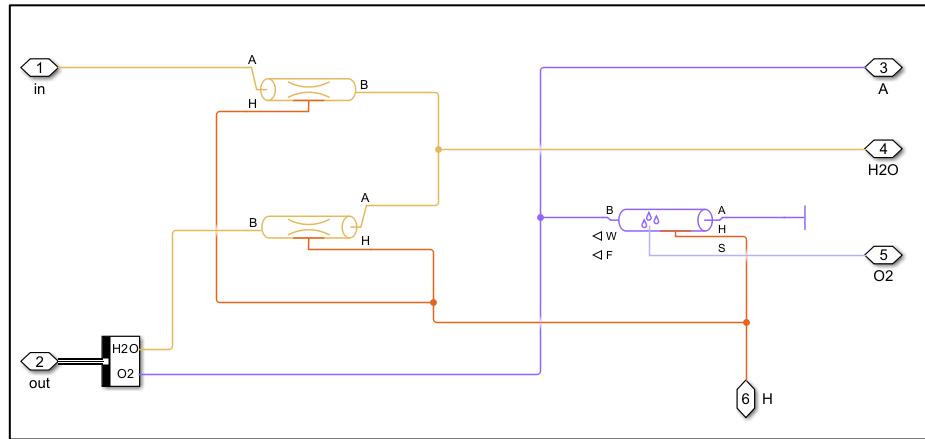


Figure 3.21. Anode channel model.

It is important to note that the water flow is not split by the stack into separate inlet and outlet nodes. Rather, the incoming flow, outgoing flow, and water consumption all meet at a single node, where mass and energy may be removed from the loop according to the reactions modeled in the MEA block.

On the other hand, the cathode channels are modeled using a moist air pipe because the produced hydrogen is not completely pure and contains water vapor generated during the electrolysis process. This approach allows the model to represent both hydrogen flow and humidity effects inside the cathode side. The port H2 represents the hydrogen inlet, while the port out corresponds to the hydrogen outlet directed toward the humidifier. The port C is used to share the cathode fluid properties. The thermal port H represents the heat exchange between the cathode channels and the surrounding environment, whereas FC contains the internal flow and thermodynamic state variables used in the dynamic simulation of the gas channels.

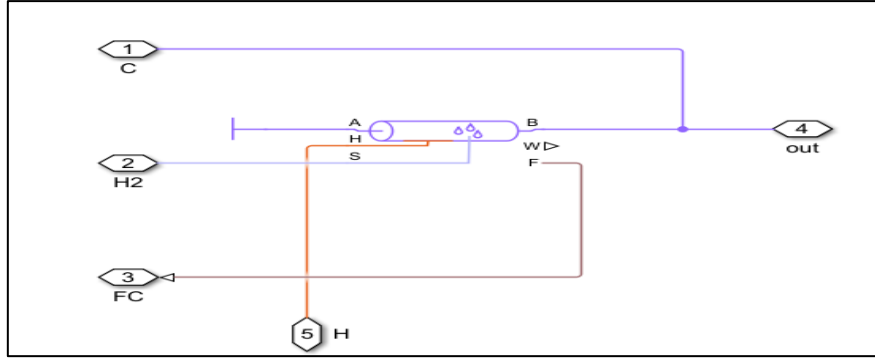


Figure 3.22. Cathode channels model.

○ Membrane Electrode Assembly

The Membrane Electrode Assembly (MEA) is the central component of a PEM electrolyser. It is composed of three main layers: the proton exchange membrane, the catalyst layers, and the gas diffusion layers. Each layer plays a specific role in enabling the electrochemical reactions involved in hydrogen production [63].

Since a complete PEM electrolyser MEA model is not directly available in the Simscape library, the MEA is modeled based on a model that reproduces the electrical, thermal, and chemical phenomena occurring inside the electrolyser stack. Using the operating parameters and the current measured in the electrical circuit, the model calculates the stack voltage as well as the associated mass and energy flow rates at the different ports.

✓ Electrochemical model

The electrical power at the stack ($P_{DC, stack}$ [W]) is expressed as follows:

$$P_{DC, stack} = V_{stack} \cdot I_{stack} \quad (3.32)$$

$$V_{stack} = N_{cells} \cdot V_{cell} \quad (3.33)$$

$$I_{stack} = A_{cell} \cdot j_{cell} \quad (3.34)$$

$$P_{DC, stack} = N_{cells} \cdot V_{cell} \cdot A_{cell} \cdot j_{cell} \quad (3.35)$$

Where I_{stack} [A] and j_{cell} [A/cm^2] are the current and the current density, which are directly proportional to the area of the cell A_{cell} [cm^2], V_{cell} [V] is the voltage of a single cell, V_{stack} [V] is the overall voltage of the stack, and N_{cells} is the number of cells in the stack.

Cell voltage

The cell voltage is the sum of the open-circuit voltage (V_{rev}), the activation overvoltage (V_{act}), the ohmic overvoltage (V_{ohm}), and the concentration overvoltage (V_{con}) [64], and it is expressed as follows:

$$V_{\text{cell}} = V_{\text{rev}} + V_{\text{act}} + V_{\text{ohm}} + V_{\text{conc}} \quad (3.36)$$

Open-circuit voltage

A minimum voltage is required to initiate the water electrolysis process. This minimum value, known as the reversible or open-circuit voltage, depends on the operating conditions of the electrolyzer, particularly temperature and pressure [64]. However, in practical operation, a higher voltage must be applied to drive the electrochemical reactions due to the presence of various internal losses within the cell. These losses are mainly associated with reaction kinetics at the electrodes, ionic and electronic resistances, and mass transport limitations [64]-[65]. The open-circuit voltage is defined as:

$$V_{\text{rev}} = E^0 + \frac{R_u T_{\text{cell}}}{2F} \ln \left(\frac{a_{\text{H}_2} \cdot \sqrt{a_{\text{O}_2}}}{a_{\text{H}_2\text{O}}} \right) \quad (3.37)$$

$$E^0 = 1.229 - 0.9 \times 10^{-3} (T_{\text{cell}} - 298) \quad (3.38)$$

Where R_u is the universal gas constant ($R_u = 8.314 \text{ J/mol.K}$), F is the Faraday constant ($F = 96485.332 \text{ C/mol}$), T_{cell} is the cell temperature, a_{H_2} activity of hydrogen, a_{O_2} activity of oxygen, and $a_{\text{H}_2\text{O}}$ is the activity of water in liquid state.

The activities are approximated by the partial pressures [60].

The pressure ratio at the anode is defined as:

$$p_{\text{ws ratio an}} = \frac{p_{\text{an}}}{p_{\text{sat}}(T_{\text{cell}})} \quad (3.39)$$

Where p_{an} is the anode pressure, $p_{\text{sat}}(T_{\text{cell}})$ is the saturation pressure of water at the cell temperature.

The water mass fraction at the anode is calculated by:

$$y_{\text{H}_2\text{O an}} = \begin{cases} \frac{1}{p_{\text{ws ratio an}}}, & p_{\text{ws ratio an}} > 1 \\ 1, & \text{otherwise} \end{cases} \quad (3.40)$$

This means that when the anode pressure exceeds the saturation pressure, the water fraction decreases inversely with the pressure ratio; otherwise, the gas is considered fully saturated with water vapor.

The water activity at the anode is then determined from:

$$a_{\text{H}_2\text{O an}} = y_{\text{H}_2\text{O an}} \cdot p_{\text{ws ratio an}} \quad (3.41)$$

which gives:

$$a_{H_2O\ an} = \begin{cases} 1, & p_{ws\ ratio\ an} > 1 \\ p_{ws\ ratio\ an}, & \text{otherwise} \end{cases} \quad (3.42)$$

The oxygen mass fraction at the anode is obtained using:

$$y_{O_2\ an} = 1 - y_{H_2O\ an} \quad (3.43)$$

$$a_{O_2\ an} = y_{O_2\ an} \cdot \frac{p_{an}}{p_{std}} \quad (3.44)$$

Wich becomes:

$$a_{O_2\ an} = \begin{cases} \frac{p_{an}-p_{sat}}{p_{std}}, & p_{ws\ ratio\ an} > 1 \\ 0, & \text{otherwise} \end{cases} \quad (3.45)$$

Where $p_{std} = 1\ atm$ is the standard pressure.

Finally, at the cathode side, the hydrogen mass fraction is measured directly from the MEA block through the FC port, and the hydrogen activity is calculated as:

$$a_{H_2\ cat} = y_{H_2\ cat} \cdot \frac{p_{cat}}{p_{std}} = \frac{p_{H_2}}{p_{std}} \quad (3.46)$$

Activation overvoltage

Activation overvoltage represents the extra voltage needed to overcome the activation energy associated with the electrochemical reactions taking place at the electrodes of the PEM electrolyzer [64]. This overvoltage is commonly determined by the following equation:

$$V_{act} = V_{act,an} + V_{act,ca} \quad (3.47)$$

$$V_{act,an} = \frac{R_u T_{cell}}{\alpha_{an} F} \operatorname{arcsinh} \left(\frac{j_{cell}}{2j_{0,an}} \right) \quad (3.48)$$

$$V_{act,ca} = \frac{R_u T_{cell}}{\alpha_{ca} F} \operatorname{arcsinh} \left(\frac{j_{cell}}{2j_{0,ca}} \right) \quad (3.49)$$

Where α_{an} and α_{ca} are the charge transfer coefficients of the anode and cathode, assumed equal to 0.5, $j_{0,an}$ and $j_{0,ca}$ are the anode and cathode exchange current densities, respectively, assumed to be constant and equal to $8 \times 10^{-5}\ A/cm^2$ for the anode.

Ohmic Overpotential

The ohmic voltage is dependent on the membrane thickness δ_{mem} fixed equal to $125\ \mu m$, and the membrane conductivity σ_{mem} [S/m] [64], it is dominated by ionic loss predominantly in the membrane :

$$V_{ohm} = R_{ohm} \cdot j_{cell} \quad (3.50)$$

$$R_{ohm} = \frac{\delta_{mem}}{\sigma_{mem}} \quad (3.51)$$

The membrane conductivity can be assumed fully hydrated since it is in direct contact with water:

$$\sigma_{\text{mem}} = (0.005139\lambda_{\text{mem}} - 0.00326) \cdot \exp \left[1268 \left(\frac{1}{303.15} - \frac{1}{T_{\text{cell}}} \right) \right] \quad (3.52)$$

λ_{mem} is the membrane water content (hydration level), the model uses the Springer/Dutta correlation to calculate it:

For $0 \leq a_{H_2O} \leq 1$:

$$\lambda_{\text{mem}} = 0.043 + 17.81a_{H_2O} - 39.85a_{H_2O}^2 + 36a_{H_2O}^3 \quad (3.53)$$

For $a_{H_2O} > 1$:

$$\lambda_{\text{mem}} = 14.003 + 1.4(a_{H_2O} - 1) \quad (3.54)$$

Concentration overvoltage

The concentration (or diffusion) overvoltage occurs because of mass transport limitations within the electrolyte or near the electrode surface [64]; it is evaluated by considering only the anode side, where the main contribution occurs :

$$V_{\text{conc}} = \frac{RT_{\text{cell}}}{2\alpha_{\text{an}}F} \ln \left(\frac{j_L}{j_L - j_{\text{cell}}} \right) \quad (3.55)$$

where: j_L is the limiting current density.

The activation and ohmic overvoltages dominate the overall voltage losses. Therefore, the concentration overvoltage can be reasonably neglected in this model.

✓ Fluid dynamic model

The fluid dynamic model performs the mass balance calculations to determine the amount of water removed at the anode side and the hydrogen and oxygen generated and introduced into the system through mass sources. The overall mass balance is mainly influenced by two mechanisms: electrochemical production and mass transport [60]. The production and consumption rates associated with the water electrolysis reaction are calculated using Faraday's law, which requires the molar masses of the species M_i [60].

$$\eta_{\text{Faraday}} = \frac{j_{\text{useful}}}{j_{\text{input}}} = 100\% \quad (3.56)$$

$$\dot{m}_{H_2O, \text{cons}} = \frac{N_{\text{cells}} A_{\text{cell}} j_{\text{input}} \eta_{\text{Faraday}}}{2F} M_{H_2O} \quad (3.57)$$

$$\dot{m}_{O_2, \text{prod}} = \frac{N_{\text{cells}} A_{\text{cell}} j_{\text{input}} \eta_{\text{Faraday}}}{4F} M_{O_2} \quad (3.58)$$

$$\dot{m}_{H_2, \text{prod}} = \frac{N_{\text{cells}} A_{\text{cell}} j_{\text{input}} \eta_{\text{Faraday}}}{2F} M_{H_2} \quad (3.59)$$

The water transport process consists of three different mechanisms, each characterized by a distinct physical contribution [60].

The total water transport rate through the membrane is determined by the combined effects of diffusion, electro-osmotic drag, and hydraulic transport :

$$\dot{m}_{H_2O,trans} = (\dot{n}_{H_2O,Diff} + \dot{n}_{H_2O,drag} + \dot{n}_{H_2O,hyd})M_{H_2O} \quad (3.60)$$

-The first contribution corresponds to the water flux caused by diffusion, which results from the difference in reactant concentration across the membrane electrode assembly (MEA) [60]. Assuming a linear water concentration profile between the anode and cathode catalyst layers, the diffusion transport can be expressed :

$$\dot{n}_{H_2O,Diff} = D_{H_2O,mem} \frac{(C_{H_2O,ACL} - C_{H_2O,CCL})}{\delta_{mem}} A_{cell} N_{cells} \quad (3.61)$$

$$D_{H_2O} = 1.25 \times 10^{-10} \exp \left[2416 \left(\frac{1}{303.15} - \frac{1}{T_{cell}} \right) \right] \quad (3.62)$$

where $D_{H_2O,mem} \left[\frac{m^2}{s} \right]$ is the membrane water diffusion coefficient, $C_{H_2O,ACL}$ and $C_{H_2O,CCL} \left[\frac{mol}{m^3} \right]$ represent the water concentrations at the anode and cathode catalyst layers, respectively .

The water concentrations at the anode and cathode catalyst layers are expressed as follows:

$$C_{H_2O,ACL} = \frac{\rho_{mem}}{M_{mem}} \lambda_{ACL} \quad (3.63)$$

$$C_{H_2O,CCL} = \frac{\rho_{mem}}{M_{mem}} \lambda_{CCL} \quad (3.64)$$

where ρ_{mem} is the dry membrane density equal to 2000 kg/m³, M_{mem} is the equivalent weight of the membrane equal to 1.1kg/mol, λ_{ACL} and λ_{CCL} are the membrane water content at the anode and cathode catalyst layer, respectively, obtained from the Springer/Dutta hydration correlation.

-The second mechanism is the Electro-Osmotic Drag, which represents the transport of water molecules carried by the H^+ ions through the membrane. This mechanism depends directly on the useful current density [60].

$$\dot{n}_{H_2O,drag} = \frac{n_d j_{useful} A_{cell} N_{cells}}{F} \quad (3.65)$$

The electro-osmotic drag coefficient is given by:

$$n_d = 0.0029 \lambda_{mem}^2 + 0.05 \lambda_{mem} - 3.4 \times 10^{-19} \quad (3.66)$$

where n_d is the electro-osmotic drag coefficient

-The last one is Pressure-driven transport is generated by the pressure difference between the anode and cathode sides of the membrane and is modeled using Darcy's law [60].

$$\dot{n}_{H_2O,hyd} = \frac{K_{Darcy} A_{cell} \rho_{H_2O} (p_{an} - p_{cat})}{\delta_{mem} \mu_{H_2O} M_{H_2O}} \quad (3.67)$$

K_{Darcy} is the Darcy permeability constant equal to $1.58 \times 10^{-14} \text{ cm}^2$, and μ_{H_2O} is the dynamic viscosity of water.

✓ Thermodynamic model

The thermal power output Q_{out} is calculated as the difference between the electrical power entering the stack $P_{DC,stack}$ and the net internal power requirement P_{net} [60].

The net power represents the thermodynamic demand of the internal processes and is defined as the reaction power P_{rxn} , minus two contributions: the power associated with bringing reactants and products to standard conditions $P_{\Delta std}$, and the power associated with water transport across the membrane P_{trans} . The reaction term is computed from the higher heating value (HHV) of hydrogen, taken as 285.9 kJ/mol [60].

$$Q_{out} = P_{DCstack} - P_{net} = P_{DCstack} - (P_{rxn} - P_{\Delta std} - P_{trans}) \quad (3.68)$$

with:

$$P_{rxn} = \dot{n}_{H_2,prod} \cdot HHV_{H_2} \quad (3.69)$$

$$P_{\Delta std} = \dot{m}_{H_2O,cons} \cdot [(\Delta h_{H_2O,A} - \Delta h_{H_2O,vap}) - (\Delta h_{H_2O,std} - \Delta h_{H_2O,vap,std})] \\ + \dot{m}_{O_2,prod} \cdot (\Delta h_{O_2,A} - \Delta h_{O_2,std}) + \dot{m}_{H_2,prod} \cdot (\Delta h_{H_2,C} - \Delta h_{H_2,std}) \quad (3.70)$$

$$P_{trans} = \dot{m}_{H_2O,trans} \cdot (\Delta h_{H_2O,A} - \Delta h_{H_2O,vap} + \Delta h_{H_2O,C}) \quad (3.71)$$

The terms $P_{\Delta std}$ and P_{trans} are evaluated using the thermodynamic properties of water, hydrogen, and oxygen provided by the Simscape physical property libraries. The specific enthalpies are automatically calculated as functions of the operating temperature, pressure, and species composition and are subsequently used in the stack energy balance.

The thermal power generated in the MEA is transferred through the thermal port H, which is connected to the thermal ports of the flow channels and to the thermal mass of the stack [60], as illustrated in Figure 3.20.

The stack temperature is dynamically calculated from the thermal energy balance according to:

$$Q_{out} = mc_p \frac{dT_{stack}}{dt} \quad (3.72)$$

where Q_{out} is the generated heat power, m is the equivalent mass of the stack, c_p is the specific heat capacity, and T_{stack} is the stack temperature.

The thermal mass block receives the heat flow from the electrolyzer and computes the temperature evolution over time. This temperature is then used internally by the PEM electrolyzer model to determine several temperature-dependent parameters such as membrane conductivity, activation losses, Nernst voltage, and water transport phenomena.

The stack temperature is therefore not imposed as a constant value but obtained dynamically from the balance between generated heat and the thermal inertia of the stack.

The thermal mass of the electrolyzer stack is calculated by summing the volumes of the main solid components (membrane and gas diffusion layers) for one cell, multiplied by the material density and the total number of cells. It is expressed as:

$$m = \rho_{mem} \cdot A_{stack} \cdot 10^{-4} \cdot (\delta_{mem} + t_{GDL,A} + t_{GDL,C}) \cdot 10^{-6} \cdot N_{cells} \quad (3.73)$$

Where $t_{GDL,A}$, $t_{GDL,C}$ are the anode and cathode GDL (Gas Diffusion Layer) thicknesses equal to 25 μm and 250 μm , respectively, and ρ_{mem} is the dry membrane density equal to 2000 kg/m^3 .

NAME	VALUE
Parameters	
Mass type	Constant
Mass	stack_me_rho * stack_area * 1e-4 * (sta... kg
Configurability	Compile-time
Specific heat	stack_me_cp 870 J/kg/K
Configurability	Compile-time
Number of graphical ports	1
Initial Targets	
> ☒ Temperature	
> ☐ Heat flow rate	
Nominal Values	

Figure 3.23. MEA thermal mass block parameters.

The thermal port H of the electrolyser is connected to a temperature sensor to measure the stack temperature and to a heat flow rate sensor to measure the generated thermal power Q_{out} .

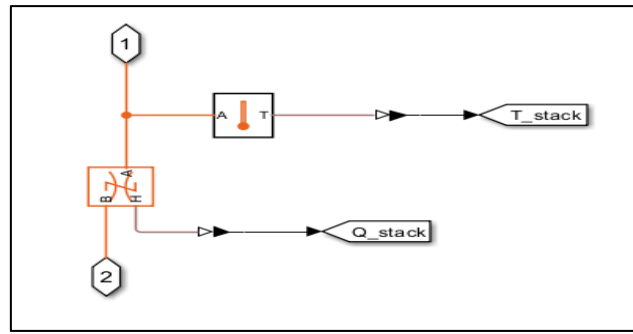


Figure 3.24. Thermal Measurement of the MEA.

○ Heat exchanger

The implementation of the heat exchanger is modeled using a simple Thermal Liquid (TL) pipe configuration.

This system does not require a separate cooling network, where the heat generated by the electrolyzer is removed by the excess water flow and subsequently rejected to the environment through convective heat transfer between the circulating fluid and the surrounding environment.

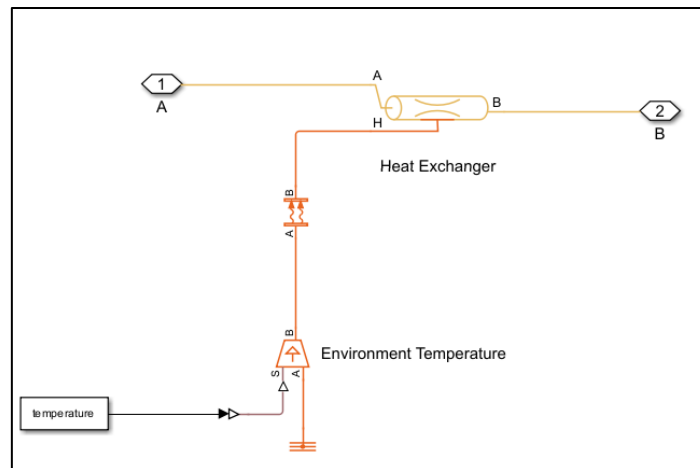


Figure 3.25. Heat exchanger model

○ Recirculation subsystem

This part is designed to ensure water recirculation, oxygen separation, and temperature regulation in the PEM electrolyzer system. Fresh water enters the subsystem through Port 1 to compensate for the water consumed during electrolysis.

The outlet mixture from the electrolyzer stack enters through Port 3, containing excess liquid water and oxygen gas generated at the anode side. This mixture is directed to a separator tank, where the oxygen is separated from the water and discharged to the environment through the moist air network.

The remaining water is then mixed with the incoming fresh water and sent to a circulation pump. The pump flow rate is controlled by a PI controller to maintain the stack temperature close to the optimal operating value of 80°C. Finally, the conditioned water is recirculated back to the electrolyzer stack through Port 2.

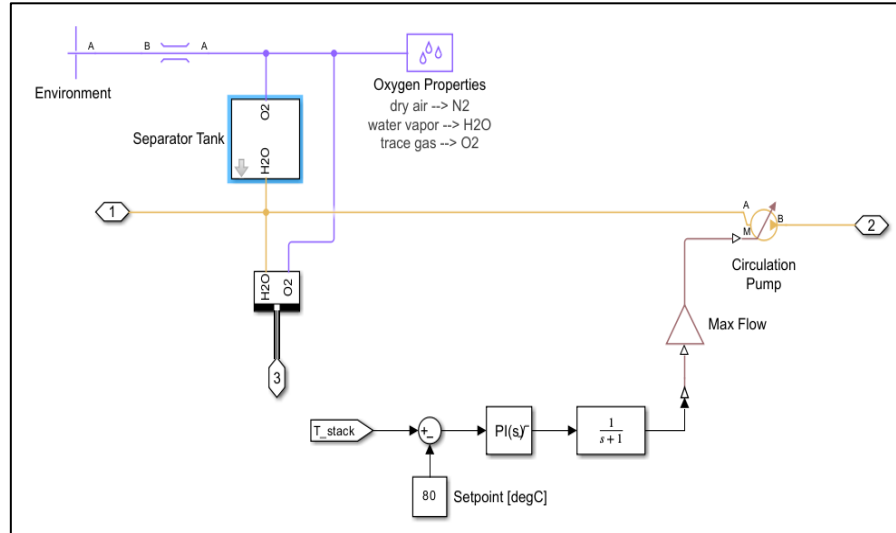


Figure 3.26. Anode recirculation and thermal control model.

The separator tank consists of two variable volumes: a lower volume containing the oxygen-rich water and an upper volume containing the separated oxygen gas. The oxygen-rich water leaving the electrolyzer enters the separator through Port 2 and is connected to the liquid chamber through a Translational Mechanical Converter (TL), which allows the liquid volume to vary with the position of the piston. As gravitational separation takes place, oxygen accumulates in the upper chamber and is discharged through Port 1. The gas chamber is connected to a Mechanical Translational Converter (MA), which represents the variation of the gas volume and couples the gas pressure to the piston movement.

The separated water is collected at the bottom of the tank and is subsequently directed to the heat exchanger before being recirculated to the anode side of the electrolyzer.

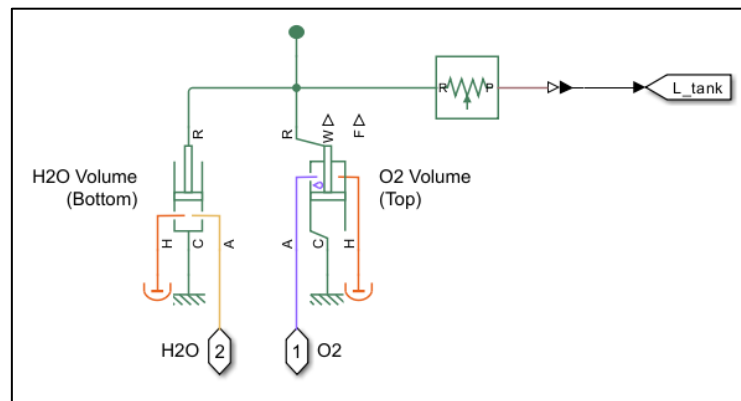


Figure 3.27. Separator tank model.

○ Water Supply

The water supply sub-system is used to feed the electrolyser stack. It consists of a water reservoir, a controlled pump, and a feedback control loop that maintains a desired water level.

The water reservoir is modeled using a Controlled Reservoir (TL) block with defined liquid water properties using the Thermal Liquid Settings block (the default liquid is water, so we don't need to change its parameters), and its temperature is set by the physical signal port T [K].

A closed-loop control system is implemented to regulate the water level inside the separator tank, ensuring a stable and continuous water supply to the electrolyser. For realistic operating conditions, the maximum water flow rate is set to 0.02 kg/s, which accounts not only for the theoretical water consumption but also for additional requirements such as circulation and cooling

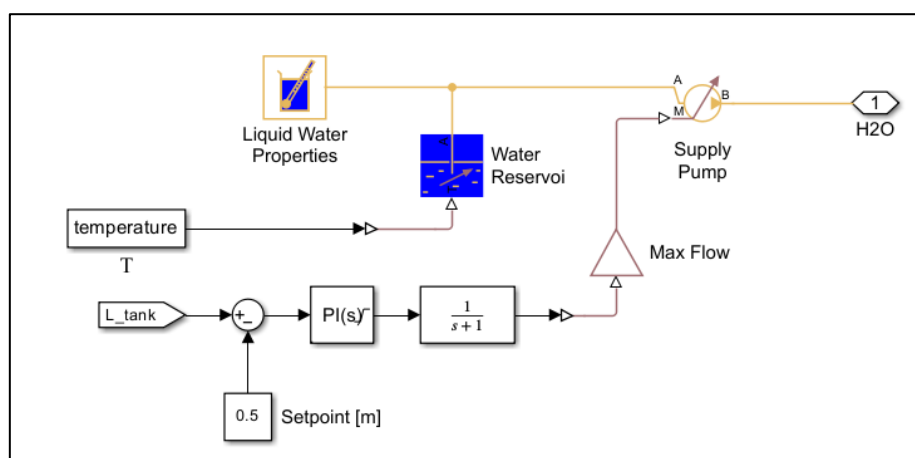


Figure 3.28. Water supply model

○ Dehumidifier Subsystem

This subsystem represents a simplified model of the actual hydrogen drying section, which in a real system would typically be based on a pressure swing adsorption (PSA) unit. The main objective of this block is to achieve a hydrogen purity level of 99.99% by removing residual water vapor from the gas stream.

The dryer is modeled as an ideal constant-volume chamber representing the PSA system volume. Its function is to temporarily store the moist hydrogen gas and subsequently remove the contained water using a controlled moisture source, as illustrated in Figure 3.29. The amount of water to be removed is determined using a mass flow sensor, which provides the corresponding physical signal for closed-loop control of the dehydration process.

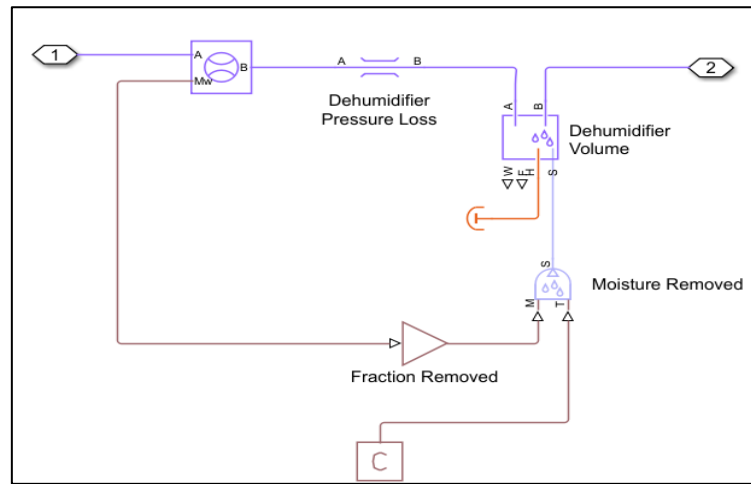


Figure 3.29. Dehumidifier model.

○ Hydrogen Storage Tank

The hydrogen storage subsystem shown in Figure 12 uses a local restriction to model the pressure regulator valve, which maintains the cathode pressure at 3 MPa while the anode operates at atmospheric pressure. The regulator is controlled by a PI controller that adjusts the valve opening area according to the pressure error in order to ensure stable operation of the storage system. The pressure difference across the membrane electrode assembly (MEA) promotes hydraulic water transport from the cathode to the anode side, helping to compensate for electro-osmotic drag and reduce water accumulation at the cathode. The hydrogen then flows through a pipe component where the flow and thermal effects are considered before entering the hydrogen reservoir, representing the storage tank. In addition, a mass flow rate sensor is used to measure the hydrogen flow rate ($\dot{m}_{H_2}$), while the hydrogen properties block defines the gas composition and thermodynamic properties of the stored hydrogen.

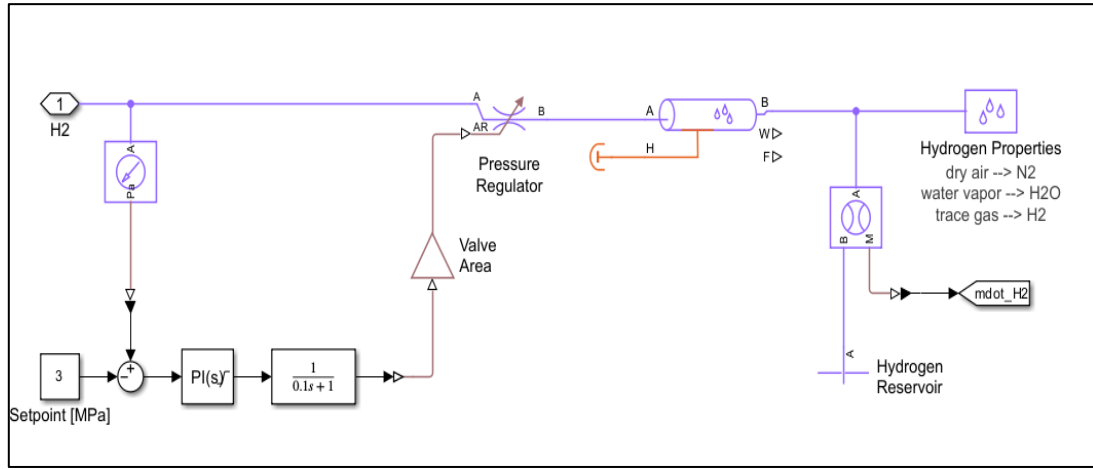


Figure 3.30. Hydrogen storage tank model.

▪ Photovoltaic Conversion Efficiency

The instantaneous photovoltaic conversion efficiency represents the ratio of the electrical power generated by the PV array to the incident solar power on the active module surface area and is expressed as [66] [67]:

$$\eta_{PV}(t) = \frac{P_{PV}(t)}{G(t) A_{PV}} \times 100 \quad (3.74)$$

Where $\eta_{PV}(t)$ is the instantaneous photovoltaic efficiency (%), $P_{PV}(t)$ is the electrical power output of the PV array at time t (W), $G(t)$ is the solar irradiance incident on the PV surface at time t ($\text{W} \cdot \text{m}^{-2}$), and A_{PV} is the total effective area of the PV array (m^2).

While the average photovoltaic efficiency over the simulation period is calculated as:

$$\eta_{PV,avg} = \frac{1}{N} \sum_{i=1}^N \eta_{PV,i} \quad (3.75)$$

▪ PEM Electrolyzer Efficiency

The instantaneous efficiency of the PEM electrolyzer is defined as the ratio between the chemical energy stored in the produced hydrogen and the electrical energy consumed by the electrolyzer. Based on the Lower Heating Value (LHV) of hydrogen, it is expressed as [68]:

$$\eta_{PEM}(t) = \frac{\dot{m}_{H_2}(t) LHV_{H_2}}{P_{EL}(t)} \times 100 \quad (3.76)$$

Where $\eta_{PEM}(t)$ is the instantaneous PEM electrolyzer efficiency (%), $\dot{m}_{H_2}(t)$ is the hydrogen production rate ($\text{kg} \cdot \text{s}^{-1}$), LHV_{H_2} is the lower heating value of hydrogen ($\approx 33.33 \text{ kWh} \cdot \text{kg}^{-1}$ or $120 \text{ MJ} \cdot \text{kg}^{-1}$), and $P_{EL}(t)$ is the electrical power consumed by the electrolyzer (W).

▪ Total system efficiency

The formula for PV-to-hydrogen efficiency (η_S) is as follows:

$$\eta_S(t) = \eta_{PV}(t) \times \eta_{PEM}(t) \times \eta_c(t) \quad (3.77)$$

Where η_c is the power conditioning efficiency assumed to be constant and equal to 95%.

Alternatively, the total system efficiency can be directly expressed in a unified energy-based form as [67]:

$$\eta_S(t) = \frac{\dot{m}_{H_2}(t) LHV_{H_2}}{G(t) A_{PV}} \times 100 \quad (3.78)$$

3.3 Results and discussion

3.3.1 Economic Assessment

▪ Design Indicators

Figure 3.31 presents the design indicators for the first scenario, where the system is fully based on PV generation without any battery or grid support. The PV system is sized at 37.5 MW and the electrolyser at 22.8 MW, giving a PV-to-electrolyser ratio of 1.64. The electrolyser ratio of 3.84 means that, under rated conditions, it can produce almost four times more hydrogen than the demand. The hydrogen storage has a capacity of 280.72 MWh (about 8.422 tonnes) and provides 73.78 hours of autonomy. This indicates that the 100% PV-based system is oversized to ensure a continuous and reliable hydrogen supply, which is essential for industrial-scale hydrogen use.

=====	
SYSTEM DESIGN -100%PV- M'SILA	
=====	
Optimal PV Capacity	: 37.50 MW
Optimal Electrolyzer Capacity	: 22.80 MW
Optimal H2 Storage Capacity	: 280.72 MWh
PV Ratio (R_PV)	: 1.64
Electrolyzer Ratio (R_EL)	: 3.84
Storage Autonomy (A_HS)	: 73.78 hours

=====	

Figure 3.31. Optimal system design for scenario 1.

In Scenario 2 (Figure 3.32), the introduction of battery storage does not modify the optimal configuration, as the battery capacity remains zero. This indicates that the model does not find economic value in allocating capacity to electrical storage under the given cost and operational assumptions. From a cost-optimal perspective, this outcome suggests that system flexibility is

more efficiently achieved through hydrogen storage rather than battery storage. This result is consistent with findings from the Italian Ministry of Environment and Energy Security and the Polytechnic University of Turin, which developed a model showing that battery integration does not improve the levelized cost of hydrogen. Similarly, Garud et al. (2023) demonstrated that hydrogen storage is economically more advantageous than battery storage when comparing different sizing configurations. Furthermore, Superchi et al. (2023) showed that batteries only become competitive when their cost falls below 100 €/kWh, a value that remains optimistic even in long-term cost projections (Cole et al., 2021).

SYSTEM DESIGN - PV+BESS - M'SILA	
Optimal PV Capacity	: 37.50 MW
Optimal Electrolyzer Capacity	: 22.80 MW
Optimal H2 Storage Capacity	: 280.72 MWh
Optimal Battery Capacity	: -0.00 MWh
PV Ratio (R_PV)	: 1.64
Electrolyzer Ratio (R_EL)	: 3.84
Hydrogen Storage Autonomy	: 73.78 hours
Battery Autonomy	: -0.00 hours

Figure 3.32. Optimal system design for scenario 2.

In Scenario 3, the system operates by primarily relying on PV generation, with an installed capacity of 36.39 MW, to supply the electrolyzer during daytime hours, while the grid is used during periods of insufficient solar production, such as at night or during low irradiance. Despite the presence of the grid, the PV system remains significantly oversized relative to the electrolyzer capacity of 6.53 MW, resulting in a high PV ratio of 5.57. This oversizing is necessary to ensure compliance with the monthly energy balance constraint, whereby total imported electricity must be compensated by exporting surplus PV generation. Consequently, excess PV energy is frequently injected into the grid to offset imports. The availability of grid flexibility allows a substantial reduction in electrolyzer capacity compared to the fully autonomous case, leading to a more balanced electrolyzer ratio of 1.10, which is close to the average hydrogen demand. However, the electrolyzer remains partially oversized, as it must produce additional hydrogen during its operational periods to compensate for non-operational hours caused by maintenance and downtime. In this configuration, hydrogen storage is drastically reduced to 21.69 MWh, providing a limited autonomy of 5.7 hours, and is no longer used as a primary balancing mechanism. Instead, it mainly serves as a backup during electrolyzer downtime.

System Design with Grid Interaction - M'SILA	
PV Capacity	: 36.39 MW
Electrolyzer Capacity	: 6.53 MW
H2 Storage Capacity	: 21.69 MWh
Battery Capacity	: -0.00 MW

PV Ratio (R_{PV})	: 5.57
Electrolyzer Ratio (R_{EL})	: 1.10
H2 Storage Autonomy	: 5.70 h
Battery Autonomy	: -0.00 h
=====	

Figure 3.33. Optimal system design for scenario 3.

Table 3.8 summarizes the optimal design indicators for the three scenarios. The comparison shows that the off-grid configuration requires higher PV and electrolyser capacities and larger hydrogen storage to ensure full autonomy, leading to a more overdimensioned system. In contrast, the grid-connected scenario with constraints reduces both electrolyser and storage requirements, improving economic performance due to increased flexibility. In all scenarios, the battery does not participate in the optimal configuration, as its capacity remains zero, indicating that it is not economically competitive under the considered assumptions.

Table 3.8. Optimal system design for the three scenarios.

Indicator	Scenario 1	Scenario 2	Scenario 3
PV Capacity [MW]	37.50	37.50	36.39
Electrolyser Capacity [MW]	22.80	22.80	6.53
PV ratio (R_{PV}) [-]	1.64	1.64	5.57
Electrolyser ratio (R_{EL}) [-]	3.84	3.84	1.10
Hydrogen Storage Capacity [MWh]	280.72	280.72	21.69
Hydrogen Autonomy [h]	73.78	73.78	5.7
Battery Storage Capacity [MWh]	-	0	0
Battery Autonomy [h]	-	0	0

▪ Economic Indicators

The economic results presented in Figure 3.34 indicate that photovoltaic-based hydrogen production in Algeria is feasible and cost-competitive within the context of green hydrogen markets, providing a clear answer to the first research question. Scenarios 1 and 2 exhibit identical costs, with a total CAPEX of 56.17 M€, annual OPEX of 1.003 M€/year, and a net present cost (NPC) of 67.86 M€, resulting in an LCOH of 5.823 €/kg.

FINANCIAL RESULTS - M'SILA	
Total Effective CAPEX	: 56,167,300.07 €
Total Annual OPEX	: 1,003,247.56 €/year
Net Present Cost (NPC)	: 67,858,729.02 €

LCOE	: 38.26 €/MWh
LCOH	: 5.823 €/kg

Figure 3.34. Economic indicators for scenarios 1 and 2.

In contrast, Scenario 3, which integrates grid interaction under a monthly balance constraint, significantly reduces CAPEX to 31.88 M€ and NPC to 49.14 M€, despite a higher OPEX of 1.48 M€/year due to grid electricity imports. This leads to a lower LCOH of 4.216 €/kg, highlighting the economic advantage of grid-assisted operation, largely driven by the relatively low cost of grid electricity in Algeria.

FINANCIAL RESULTS - M'SILA	
Total CAPEX	: 31,881,759.41 €
Total Annual OPEX	: 1,480,511.73 € /year
Grid Cost (annual)	: 893,949.26 €
Net Present Cost (NPC)	: 49,135,026.00 €

LCOE	: 38.26 €/MWh
LCOH	: 4.216 €/kg

Figure 3.35. Economic indicators for scenario 3.

The Levelized Cost of Electricity (LCOE) is estimated at 38.26 €/MWh, reflecting Algeria's high solar potential and its contribution to reducing hydrogen production costs, as electricity constitutes the dominant cost component of LCOH. Comparing the LCOH calculated in this study with values reported in other regions highlights the economic feasibility of PV-based hydrogen production in Algeria. Bhandari and Shah (2021) reported LCOH ranging from 6.2 to 57.6 €/kg for different PtH configurations (off-grid and grid-connected) using PEM and alkaline electrolyzers, while Tang et al. (2022) found LCOH of 7.1–15.3 €/kg for off-grid and 3.5–7.3 €/kg for on-grid systems in Sweden. Marocco et al. (2023) reported an LCOH of 8.2 €/kg for an off-grid PV hydrogen system in Italy. This positions Algeria within the lower-to-mid cost range globally, confirming the strong economic potential of PV-based hydrogen production using PEM electrolysis with storage. It should also be noted that the cost

assumptions are based on 2020–2023 data; therefore, further reductions in technology costs are expected to lower the LCOH even more under current conditions.

Table 3.9. Economic indicators for the three scenarios.

Indicator	Scenario 1	Scenario 2	Scenario 3
Total Capex [M€]	56.17	56.17	31.88
Total Opex [M€/year]	1.003	1.003	1.48
Total Net Present Cost [M€]	67.86	67.86	49.14
LCOE [€/MWh]	38.26	38.26	38.26
LCOH €/kg	5.823	5.823	4.216

▪ Energy Indicators

The results in Table 3.10, for the first and second scenarios, show a mismatch between the photovoltaic (PV) generation and the demand of the electrolyser. The PV system generates about 66.8 GWh per year, but only 77.9% of this energy is consumed, generating an excess of around 22.13% per year, mainly in periods of high irradiation. This excess energy is curtailed or exported, demonstrating that the PV capacity is oversized with respect to the electrolyser. On the other hand, the electrolyser is operated with a low utilization factor of 26% due to the limited availability of electricity in times of low PV generation. Such seasonal imbalance of overgeneration in summer and lack of supply in winter leads to energy curtailment and underutilization of system components, which ultimately reduces the overall system efficiency and increases the cost of hydrogen production.

Table 3.10. Energy indicators for scenarios 1 and 2.

Indicator	Value	Unit
Total energy produced	66774.772	MWh/year
Total energy consumed	51996.879	MWh/year
Electrolyser Utilization	26.036	%

Figure 3.36 presents the monthly grid energy balance under the imposed constraint ensuring that grid imports are equal to or limited by exports over the optimization horizon. The optimization process identifies December as the most critical month due to the lowest PV production. In this month, the grid exchange is balanced, and this condition propagates to the remaining months, ensuring that grid imports do not systematically exceed exports. As a result,

the grid is primarily utilized as a balancing resource, covering periods where PV generation is insufficient, such as nighttime hours or low-irradiation conditions.

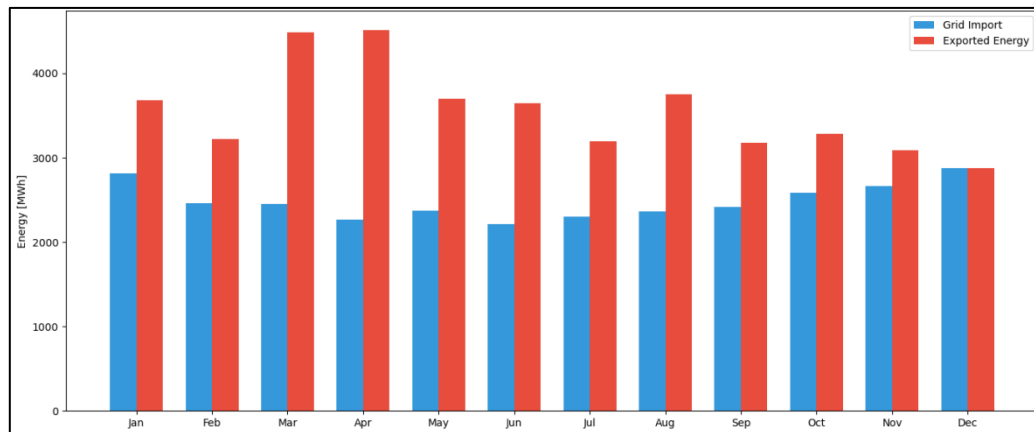


Figure 3.36. Monthly Grid Energy Balance (Import vs Exported Energy).

The results illustrated in Figure 3.37 show the monthly energy source distribution for the electrolyser, where PV and grid electricity jointly ensure the required demand. Although the PV share varies seasonally due to solar resource availability, the grid share remains dominant on an annual basis, contributing 57.31% of the total electricity supply, while PV contributes 42.69%.

Despite this, the electrolyser operates with a high utilization factor of 90.91%, indicating that it is supplied with electricity for most of the year. However, this does not correspond to continuous full-capacity operation. The utilization is limited by several operational constraints, including downtime, as well as system management strategies related to hydrogen storage (When the storage system approaches its maximum capacity, the electrolyser output is curtailed because the electrolyser is slightly oversized with a design ratio of 1.1, which leads to periods of surplus hydrogen production to prevent overfilling, resulting in reduced operation even if electricity is available).

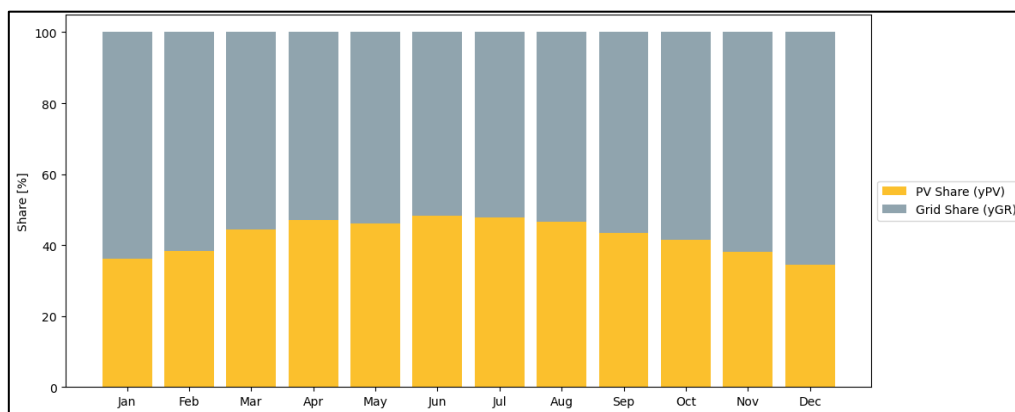


Figure 3.37. Monthly Energy Source Share for Electrolyser.

▪ Sensitivity analysis

The results presented in Figures 3.38 and 3.39 show a clear linear relationship between electricity sale price (from excess electricity of PV) and the levelized cost of hydrogen.

For the first and second scenarios, the sensitivity analysis shows that monetizing PV curtailment provides a modest reduction in LCOH ($\approx 4\text{--}5\%$). Although increasing the electricity sale price improves economic performance, the impact remains limited, indicating that hydrogen production cost is primarily driven by capital expenditures rather than curtailment management.

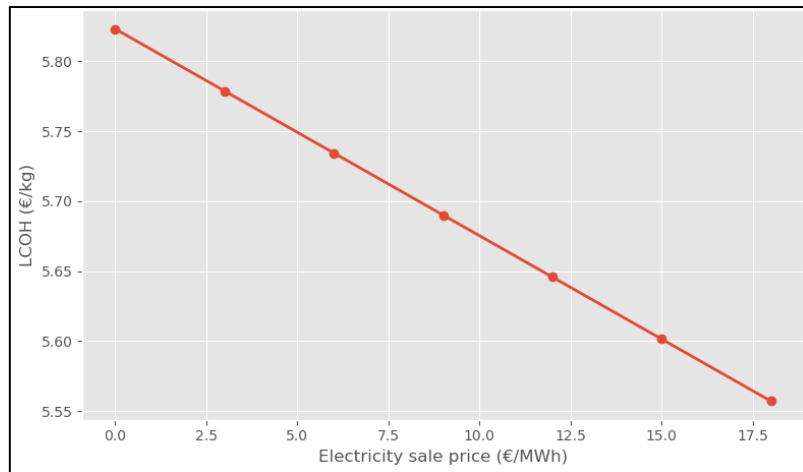


Figure 3.38. Sensitivity of LCOH to Electricity Selling Price for Scenarios 1 and 2.

For the last scenario, the recovery and sale of excess electricity significantly improve system economics. With a higher level of exported energy, the impact on LCOH becomes much more pronounced compared to previous scenarios. As the electricity selling price increases from 0 to 18 €/MWh, the LCOH decreases from 4.216 €/kg to 3.449 €/kg. This highlights that systems with high excess strongly benefit from electricity market participation, making energy valorization a key lever for cost reduction in hydrogen production systems.

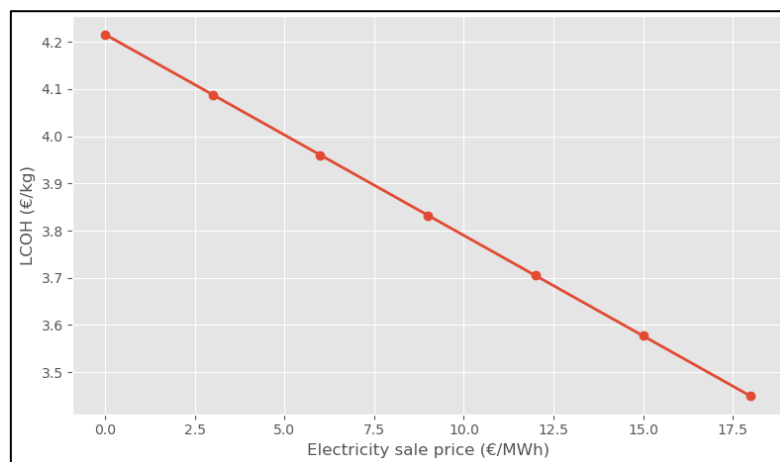


Figure 3.39. Sensitivity of LCOH to Electricity Selling Price for Scenario 3.

It is difficult to give a definitive answer to the second question of the research (Under which strategy is hydrogen cheapest in Algeria?), as the optimal strategy depends not only on techno-economic performance but also on future regulatory frameworks and market conditions.

From a purely economic perspective, integrating the system with the grid and valorizing excess electricity (through export or sale) leads to the lowest LCOH, even under the monthly operational constraint, because grid electricity prices in Algeria are currently lower than the LCOE of renewable generation. This strategy reduces curtailment losses and generates additional revenue, thereby improving overall system profitability. However, this approach may not be aligned with future European regulations for green hydrogen. The European Union has established strict criteria for renewable hydrogen, including additionality, geographical correlation, and especially temporal correlation. From 2030 onward, hydrogen production must be matched with renewable electricity generation on an hourly basis, significantly limiting the use of grid electricity and excess energy that is not directly linked to renewable production.

These constraints reduce operational flexibility and may increase hydrogen production costs, as electrolyzers can no longer operate freely based on grid availability but must strictly follow renewable generation profiles.

3.3.2 Technical Assessment

▪ Electrical power

Figure 3.40 illustrates the power profile supplied to the PEM electrolyzer; it can be clearly observed that the power delivered in July is significantly higher than in December over the entire operating period. This difference is mainly due to the higher solar irradiance available during summer, which increases the PV generation potential and therefore enhances the power available for the electrolyzer.

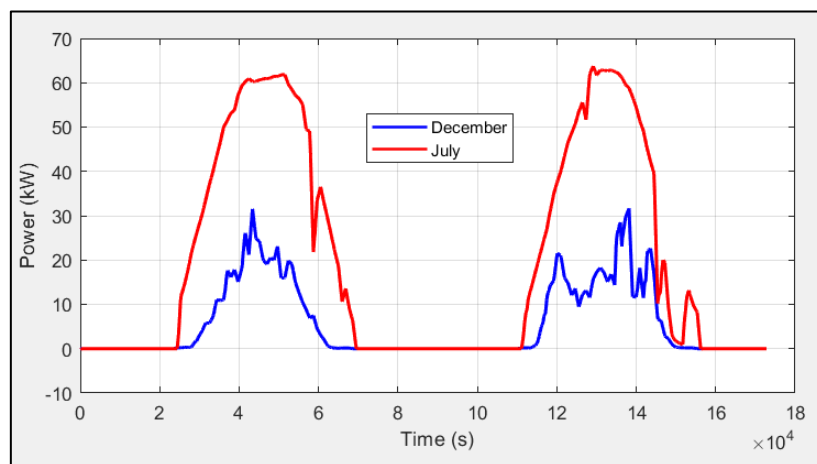


Figure 3.40. Power supplied to the PEM electrolyzer.

However, in both cases, the supplied power never reaches the installed PV capacity of 70 kW. This limitation can be explained by two main factors. First, the PV module efficiency decreases at higher temperatures, which is typical in July, leading to thermal losses that reduce the effective electrical output despite high irradiance levels. Second, the DC-DC converter introduces additional conversion losses (with an efficiency of 95%), which further reduce the power delivered to the PEM electrolyzer.

▪ Hydrogen production

Figure 3.41 presents the hydrogen production rate of the PEM electrolyzer during the representative days in July and December. The hydrogen production profile closely follows the electrical power supplied to the electrolyzer, demonstrating the dependence of hydrogen generation on the available photovoltaic power. Higher production rates are observed in July due to the greater solar irradiance and longer daylight duration, whereas lower production rates are obtained in December. The fluctuations observed in the hydrogen production rate reflect the intermittent nature of the solar resource, resulting in a non-continuous hydrogen generation profile.

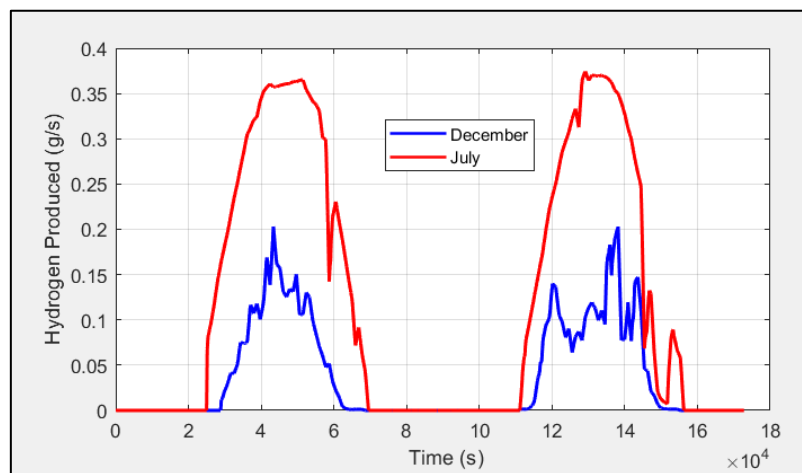


Figure 3.41. The mass flow rate of hydrogen production in July and December.

Figure 3.42 presents the cumulative hydrogen stored in the tank during the same representative days in July and December. The amount of stored hydrogen increases progressively whenever the electrolyzer is operating, with the storage level reflecting the cumulative effect of hydrogen production over time. At the end of the two representative days, the total hydrogen stored reaches 21.21 kg in July, compared with only 6.42 kg in December. This significant difference highlights the strong influence of seasonal solar resource availability on the overall hydrogen yield. Although hydrogen storage mitigates short-term fluctuations in production, the

intermittent nature of photovoltaic-powered electrolysis may still pose challenges for industrial applications requiring a continuous and stable hydrogen supply.

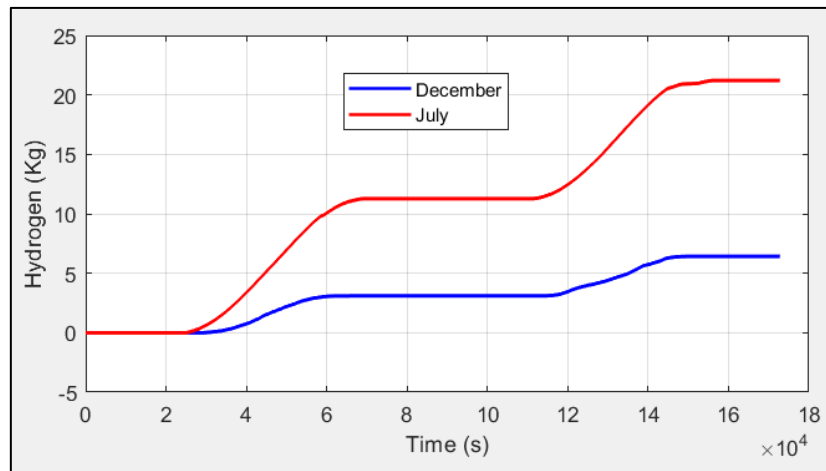


Figure 3.42. The stored hydrogen masses.

- **Performance and Efficiency Evaluation**
 - **Photovoltaic System Efficiency**

Figure 3.43 illustrates the variation of photovoltaic modules' efficiency. Although summer conditions provide higher solar irradiance, the elevated ambient temperatures in July lead to an increase in PV cell temperature, which negatively affects the semiconductor performance and reduces the conversion efficiency due to the negative temperature coefficient of PV modules. In contrast, during December, the lower ambient temperatures help maintain reduced cell temperatures, allowing the PV modules to operate closer to their optimal efficiency levels.

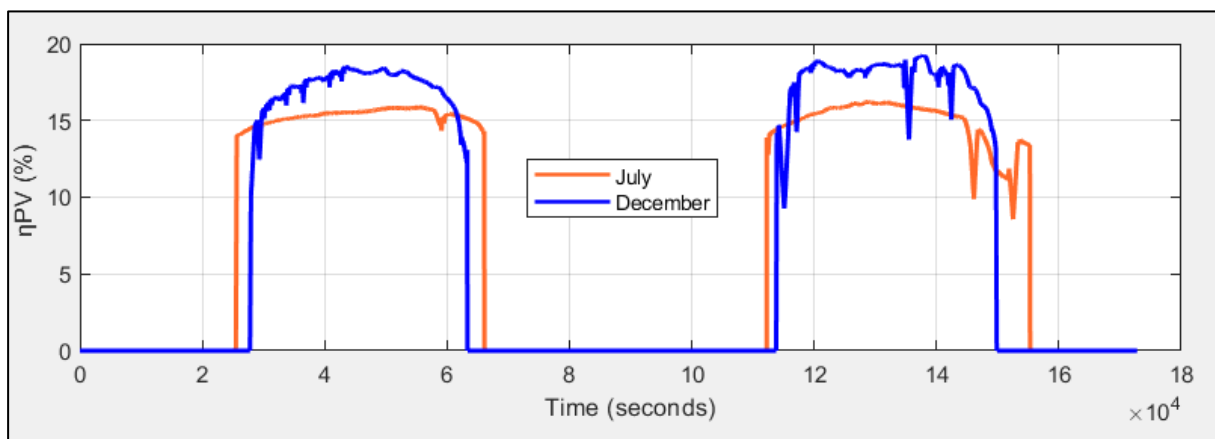


Figure 3.43. Photovoltaic system efficiency profile.

- **PEM Electrolyser stack Efficiency**

Figure 3.44 illustrates the dynamic variation of the PEM electrolyzer efficiency over a two-day operating period. The figure clearly demonstrates that the electrolyzer operates with higher

efficiency during July, maintaining a baseline of approximately 68% to 72% during peak hours, compared to December, where efficiency drops to around 65% to 67%.

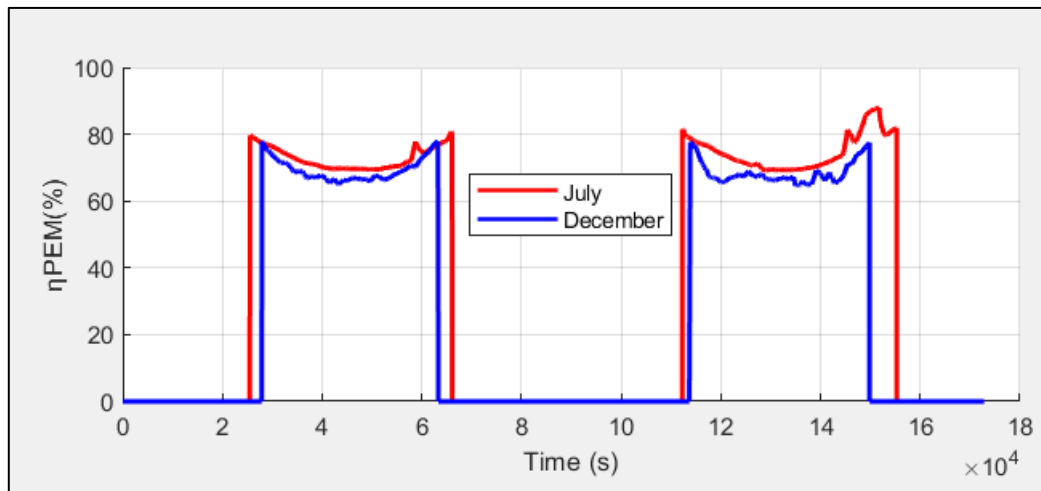


Figure 3.44 PEM electrolyzer stack efficiency based on the Lower Heating Value (LHV) of hydrogen.

The system will generally operate at a higher efficiency than its design efficiency during partial-load conditions, such as in the morning and evening periods [56].

The better performance observed in July can be explained by the higher solar irradiance in M'Sila, which provides greater and more stable electrical power from the PV generator. This allows the PEM electrolyzer to operate closer to its optimal operating region. In addition, the higher operating temperature during summer reduces the electrochemical losses, leading to lower cell voltage and improved conversion efficiency.

It is also worth noting that, although the PEM electrolyzer exhibits higher efficiency in July, the difference between July and December remains relatively small. This can be explained by the climatic conditions of M'Sila, where winter temperatures are moderate and do not reach very low values. Therefore, the increase in electrochemical losses caused by lower temperatures is limited, allowing the PEM electrolyzer to maintain relatively high efficiency even during December.

It is important to note that these values represent the stack efficiency only, without accounting for the Balance of Plant (BoP) components; therefore, the overall system efficiency of the full PEM electrolyzer would be lower.

○ System-Level Overall Efficiency

Figure 3.45 illustrates the overall PV-to-hydrogen system efficiency for July and December. The system efficiency varies throughout the day according to the available solar irradiance and

the operating conditions of both the PV array and the PEM electrolyzer. The maximum efficiency reaches approximately 12–12.3% in July and 11.5–12% in December.

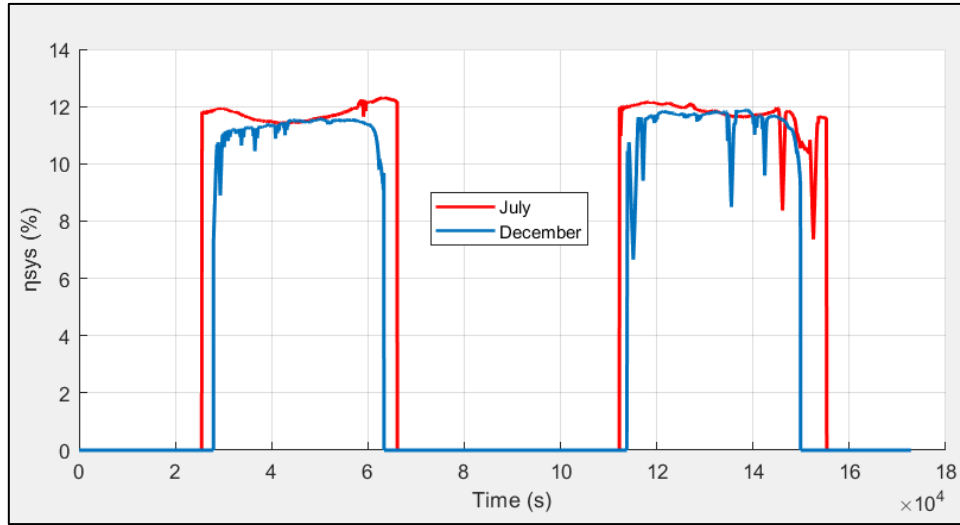


Figure 3.45. Overall PV-to-hydrogen efficiency of the proposed system.

The obtained results are consistent with values reported in the literature for integrated PV–PEM electrolyzer systems. Wang et al. [64] reported solar-to-hydrogen efficiencies of up to 14.9% for a 20 kW-class direct-coupled PV–electrolyzer system. Niederhofer et al. [65] reported overall PV-to-hydrogen efficiencies in the range of 12–14% for practical direct-coupled PV–PEM systems. Boretti [56] estimated annual PV-to-hydrogen efficiencies of approximately 13–15% for a large-scale PV-powered PEM electrolyzer system in NEOM City. Furthermore, recent studies have reported overall PV-to-hydrogen efficiencies ranging from 7.78% to 8.81% depending on operating conditions [66], while comprehensive reviews indicate that practical commercial PV–electrolyzer systems typically achieve efficiencies between 5% and 16% [67].

The agreement between the obtained efficiencies and those reported in previous studies confirms the reliability of the proposed model and indicates that the system can effectively convert Algeria's abundant solar resource into green hydrogen. Although the inclusion of Balance of Plant (BoP) energy consumption would reduce the overall system efficiency, the obtained performance remains within the range reported for commercially viable PV-to-hydrogen systems, further supporting the suitability of this technology for large-scale deployment in Algeria.

It should be noted that there is no universal rule stating that the electrolyzer efficiency must be higher in one month compared to another. The seasonal variation of efficiency depends on several operating parameters, including the stack temperature, current density, load profile, and system operating conditions. Therefore, a slightly higher efficiency in July or December can be

both physically acceptable depending on the specific configuration and control strategy of the electrolyzer system.

3.4 Conclusion

The obtained results from the two analyses confirm that green hydrogen production in Algeria is technically feasible and economically viable under the studied conditions. The strong solar resource availability combined with suitable electrolyzer performance demonstrates the country's significant potential to develop a competitive and sustainable hydrogen production pathwa

Conclusion and Perspectives

Conclusion and Perspectives

The economic analysis performed demonstrated that Algeria possesses favorable conditions for cost-competitive green hydrogen production due to its high solar potential and the resulting low photovoltaic electricity cost. The obtained LCOE of 38.26 €/MWh and LCOH of 5.823 €/kg place the proposed PV-based hydrogen production system within the lower range of costs reported in international studies. The techno-economic optimization further indicated that the introduction of battery storage does not modify the optimal configuration, as the battery capacity remains zero under the considered cost and operational assumptions. This result suggests that, from a cost-optimal perspective, system flexibility is more efficiently achieved through hydrogen storage rather than electrical storage, as hydrogen offers a more suitable solution for managing long-duration energy variability. This finding is consistent with previous studies reporting that battery integration does not significantly improve the levelized cost of hydrogen and that hydrogen storage is generally more economically advantageous across different system configurations. Batteries become competitive only under significantly reduced investment costs, which remain challenging under current and near-future projections. The results also showed that grid integration and the valorization of excess electricity can further reduce hydrogen production costs by minimizing renewable energy curtailment and generating additional revenues. Nevertheless, the long-term viability of such strategies remains dependent on future regulatory frameworks, particularly the European requirements for Renewable Fuels of Non-Biological Origin (RFNBO), which impose strict temporal matching between renewable electricity generation and hydrogen production.

From a technical perspective, the obtained results demonstrate the feasibility and robustness of green hydrogen production in Algeria using a photovoltaic-powered PEM electrolyzer system. The dynamic simulations carried out in Simscape confirm that the system is capable of producing hydrogen under varying climatic conditions, while maintaining stable operation across different seasonal profiles.

Several perspectives can be considered to extend and improve the present work. From an optimization standpoint, future studies could move from a linear programming (LP) formulation in PyPSA to a mixed-integer linear programming (MILP) approach. This extension would allow the explicit modeling of unit commitment constraints, including start-up and shut-down events of the electrolyzer, minimum operating times, and cycling limitations. Such an approach would provide a more realistic representation of operational behavior and enable a more accurate assessment of system flexibility and degradation impacts.

From a dynamic modeling perspective, the Simscape model could be further developed into a more detailed industrial-scale electrolyzer representation. This would include a more advanced description of auxiliary systems, degradation phenomena, thermal effects, and realistic Balance of Plant consumption, allowing for a closer representation of real-world industrial operation.

Finally, future research could explore the integration of multiple renewable energy sources, such as photovoltaic and wind energy, to form a hybrid generation system. This approach would improve resource complementarity, reduce intermittency, and increase the electrolyzer capacity factor, thereby enhancing hydrogen production stability. Such hybrid configurations are also aligned with the Algerian national energy strategy, which promotes diversified renewable energy integration for large-scale green hydrogen production.

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