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MASTER'S THESIS

Title:

**Feasibility study of green hydrogen production using
renewable energy source solar-energy: A case study of
Khenchela, Algeria**

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Abstract

The global transition toward carbon neutrality has positioned green hydrogen as a promising energy carrier capable of supporting renewable energy integration and contributing to the decarbonization of hard-to-abate sectors. In this context, this study investigates the feasibility of green hydrogen production using solar photovoltaic energy in Khenchela, Algeria, through a 3E concept: Energy, Economy, and Environment.

The proposed system consists of a utility-scale photovoltaic plant directly coupled to a Proton Exchange Membrane PEM electrolyzer, supported by hydrogen compression and storage units. A Python-based hourly simulation model was developed and applied over a 25-year project lifetime using photovoltaic generation data obtained from the System Advisor Model SAM. The analysis incorporates system operation, hydrogen production, energy curtailment, component replacement, discounted cash flow modeling, and environmental impact assessment.

The results indicate that the system can produce approximately 15.43 million kg of green hydrogen over its lifetime, with an average annual production of about 617,000 kg. The electrolyzer operates with a capacity factor of 34.84%, while the overall solar-to-hydrogen efficiency reaches approximately 56.3%. The Levelized Cost of Hydrogen LCOH is estimated at 7.68 USD/kg, with capital expenditures representing the largest cost contribution. Financial analysis shows that project profitability is achieved only under higher hydrogen selling prices, highlighting the strong influence of market conditions on economic viability. Sensitivity analysis identifies electrolyzer energy consumption and capacity factor as the most influential parameters affecting hydrogen production costs.

From an environmental perspective, the proposed system avoids approximately 390,706 tonnes of CO₂ emissions over the project lifetime compared with electricity supplied by the Algerian grid. Overall, the findings confirm the technical feasibility and environmental benefits of solar-based green hydrogen production in northeastern Algeria, while emphasizing the need for cost reductions and supportive policies to improve economic competitiveness.

Keywords: Green hydrogen, PEM electrolysis, photovoltaic energy, stand-alone system, oversizing strategy, Solar-to-Hydrogen STH, techno-economic analysis, LCOH, decarbonization, Algeria, Khenchela.

Résumé

La transition mondiale vers la neutralité carbone a placé l'hydrogène vert au cœur des solutions énergétiques durables en raison de sa capacité à favoriser l'intégration des énergies renouvelables et à contribuer à la décarbonation des secteurs difficiles à électrifier. Dans ce contexte, cette étude évalue la faisabilité de la production d'hydrogène vert à partir de l'énergie solaire photovoltaïque à Khenchela, en Algérie, selon une approche 3E : Énergie, Économie et Environnement.

Le système proposé est constitué d'une centrale photovoltaïque de grande capacité couplée directement à un électrolyseur à membrane échangeuse de protons PEM, complété par des unités de compression et de stockage de l'hydrogène. Un modèle de simulation horaire développé sous Python a été appliqué sur une durée de vie du projet de 25 ans en utilisant les données de production photovoltaïque obtenues à partir du logiciel System Advisor Model SAM. L'analyse prend en compte le fonctionnement du système, la production d'hydrogène, les pertes par écrêtement énergétique, le remplacement des composants, l'analyse financière basée sur les flux de trésorerie actualisés ainsi que l'évaluation des impacts environnementaux.

Les résultats montrent que le système peut produire environ 15,43 millions de kg d'hydrogène vert sur toute sa durée de vie, soit une production annuelle moyenne d'environ 617 000 kg. Le facteur de capacité de l'électrolyseur atteint 34,84 %, tandis que le rendement global de conversion solaire-hydrogène est d'environ 56,3 %. Le coût actualisé de l'hydrogène LCOH est estimé à 7,68 USD/kg, les dépenses d'investissement représentant la part la plus importante du coût total. L'analyse financière indique que la rentabilité du projet n'est atteinte qu'à des prix de vente élevés de l'hydrogène, mettant en évidence l'influence déterminante des conditions du marché sur la viabilité économique. L'analyse de sensibilité révèle également que la consommation énergétique de l'électrolyseur et son facteur de capacité sont les paramètres les plus influents sur le coût de production de l'hydrogène.

Sur le plan environnemental, le système proposé permet d'éviter environ 390 706 tonnes de CO₂ sur la durée de vie du projet par rapport à une alimentation électrique issue du réseau algérien. Globalement, les résultats confirment la faisabilité technique et les bénéfices environnementaux de la production d'hydrogène vert à partir de l'énergie solaire dans le nord-est de l'Algérie, tout en soulignant la nécessité de réduire les coûts et de mettre en place des politiques de soutien afin d'améliorer sa compétitivité économique.

Mots-clés : Hydrogène vert, électrolyse PEM, énergie photovoltaïque, Système autonome, Stratégie de surdimensionnement oversizing, Rendement de conversion solaire-hydrogène STH analyse technico-économique, LCOH, décarbonation, Algérie, Khenchela.

الملخص

أدى التوجه العالمي نحو تحقيق الحياد الكربوني إلى جعل الهيدروجين الأخضر ناقلاً واعداً للطاقة، قادرًا على دعم دمج الطاقات المتجددة والمساهمة في إزالة الكربون من القطاعات التي يصعب خفض انبعاثاتها. وفي هذا السياق، تهدف هذه الدراسة إلى تقييم جدوى إنتاج الهيدروجين الأخضر باستخدام الطاقة الشمسية الكهروضوئية في ولاية خنشلة بالجزائر، وفق مقارنة ثلاثية الأبعاد تشمل الطاقة والاقتصاد والبيئة (3 E) .

يتكون النظام المقترح من محطة كهروضوئية واسعة النطاق مقترنة مباشرة بمحلل كهربائي من نوع غشاء تبادل البروتونات (PEM)، ومدعومة بوحدات ضغط وتخزين الهيدروجين. وقد تم تطوير نموذج محاكاة ساعي باستخدام لغة Python وتطبيقه على مدى عمر مشروع قدره 25 سنة، اعتمادًا على بيانات إنتاج الكهرباء الكهروضوئية المستخرجة من برنامج System Advisor Model (SAM). وتشمل الدراسة تشغيل النظام، وإنتاج الهيدروجين، وفائض الطاقة غير المستغل، واستبدال المكونات، والتحليل المالي باستخدام التدفقات النقدية المخصومة، بالإضافة إلى تقييم الأثر البيئي.

أظهرت النتائج أن النظام قادر على إنتاج حوالي 15.43 مليون كغ من الهيدروجين الأخضر خلال عمر المشروع، بمتوسط إنتاج سنوي يقارب 617 ألف كغ. كما يعمل المحلل الكهربائي بمعامل استخدام قدره 34.84٪، بينما تبلغ الكفاءة الإجمالية لتحويل الطاقة الشمسية إلى هيدروجين حوالي 56.3٪. وقد قُدرت التكلفة المستوية للهيدروجين (LCOH) بنحو 7.68 دولار أمريكي/كغ، حيث تمثل تكاليف الاستثمار الأولية أكبر مساهمة في التكلفة الإجمالية. وأظهر التحليل المالي أن ربحية المشروع تتحقق فقط عند أسعار بيع مرتفعة للهيدروجين، مما يبرز التأثير الكبير لظروف السوق على الجدوى الاقتصادية. كما بين تحليل الحساسية أن استهلاك الطاقة في المحلل الكهربائي ومعامل استخدامه يمثلان أكثر العوامل تأثيرًا على تكلفة إنتاج الهيدروجين.

ومن الناحية البيئية، يساهم النظام المقترح في تجنب انبعاث ما يقارب 390,706 طن من ثاني أكسيد الكربون خلال عمر المشروع مقارنة بالكهرباء الموردة من الشبكة الجزائرية. وبشكل عام، تؤكد النتائج الجدوى التقنية والفوائد البيئية لإنتاج الهيدروجين الأخضر اعتمادًا على الطاقة الشمسية في شمال شرق الجزائر، مع التأكيد على ضرورة خفض التكاليف وتوفير سياسات داعمة لتعزيز القدرة التنافسية الاقتصادية لهذا القطاع.

الكلمات المفتاحية: الهيدروجين الأخضر، التحليل الكهربائي PEM ، الطاقة الكهروضوئية، نظام مستقل، استراتيجية الإفراط في التحجيم ، (Oversizing) (STH) كفاءة تحويل الطاقة الشمسية إلى هيدروجين، التحليل التقني والاقتصادي، التكلفة المستوية للهيدروجين، إزالة الكربون، الجزائر، خنشلة.

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List of abbreviations

Abbreviation	Full Term
H ₂	Hydrogen
H ₂ O	Water
LHV	Lower Heating Value
HHV	Higher Heating Value
LNG	Liquefied Natural Gas
CH ₄	Methane
P2E	Power-to-Energy
AWE	Alkaline Water Electrolysis
PEM	Proton Exchange Membrane
AEM	Anion Exchange Membrane
SOEC	Solid Oxide Electrolysis Cell
DNI	Direct Normal Irradiance
DHI	Diffuse Horizontal Irradiance
GHI	Global Horizontal Irradiance
PV	Photovoltaic
DC	Direct Current
AC	Alternating Current
MPPT	Maximum Power Point Tracking
SAM	System Advisor Model
SEC	Specific Energy Consumption
STH	Solar-to-Hydrogen
CAPEX	Capital Expenditure
OPEX	Operating Expenditure
O&M	Operation and Maintenance
LCOH	Levelized Cost of Hydrogen
DCF	Discounted Cash Flow
NPV	Net Present Value

IRR	Internal Rate of Return
CO ₂	Carbon Dioxide
PR	Performance Ratio
CF	Capacity Factor

Introduction

The global energy sector is undergoing a profound transformation driven by the need to reduce greenhouse gas emissions, enhance energy security, and achieve long-term carbon neutrality objectives. In this context, renewable energy technologies have experienced significant development worldwide. However, the intermittent nature of renewable resources such as solar and wind energy remains a major challenge for the large-scale integration of clean energy into modern energy systems.

Among the solutions proposed to address this challenge, hydrogen has emerged as a strategic energy carrier capable of storing renewable electricity and providing energy flexibility across different sectors. In particular, green hydrogen, produced through water electrolysis powered by renewable energy sources, is increasingly recognized as a promising pathway for supporting the global energy transition and reducing dependence on fossil fuels.

The growing international interest in hydrogen has accelerated since the adoption of the Paris Agreement in 2015, leading many countries to establish hydrogen strategies and launch large-scale development initiatives. In parallel, several regional projects have been proposed to facilitate future hydrogen trade, including the SouthH2 Corridor initiative, which aims to strengthen energy cooperation between North Africa and Europe and highlights the strategic role that countries such as Algeria could play in the emerging hydrogen economy.

Algeria possesses favorable conditions for green hydrogen development due to its significant solar energy potential and its geographical proximity to potential future hydrogen markets. Within this national context, the Khenchela region offers an attractive case study for evaluating the feasibility of renewable hydrogen production under local climatic conditions.

The present study investigates the feasibility of a standalone photovoltaic-to-hydrogen system based on the direct coupling of a utility-scale photovoltaic plant with a PEM electrolyzer and a hydrogen compression and storage unit. The assessment is conducted through the 3E framework, which considers Energy, Economic, and Environmental dimensions simultaneously. A high-resolution simulation model is developed to evaluate system performance over a 25-year project lifetime, taking into account operational behavior, hydrogen production, economic performance, and environmental benefits.

This work is organized into five chapters. Chapter 1 presents an overview of hydrogen fundamentals, production pathways, storage technologies, and the hydrogen economy. Chapter 2 reviews the principles of water electrolysis, the main electrolyzer technologies, and their performance characteristics. Chapter 3 introduces solar energy fundamentals, photovoltaic technology, and the solar resource in Algeria. Chapter 4 describes the study area, system configuration, and simulation methodology adopted in this work. Finally, Chapter 5 presents and analyzes the technical, economic, and environmental results obtained from the proposed system.

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Chapter one: Overview on hydrogen

Chapter one: Overview on hydrogen

1.1 Introduction

The global transition toward carbon neutrality is driven by the growing need to balance economic development, energy security, and environmental protection. Within this context, hydrogen is no longer viewed simply as a chemical element, but as a strategic resource capable of reshaping energy systems and strengthening energy security.

The convergence of economic and energy interests has highlighted green hydrogen as a promising solution for integrating intermittent renewable energy into sectors with continuous and high energy demand, particularly those that are difficult to decarbonize, such as heavy industry, maritime transport, and petrochemicals.

Hydrogen functions as an energy carrier that allows energy to be stored, transported, and converted into other usable forms such as electricity, heat, or fuel. Its strategic importance lies in its ability to improve energy system flexibility, support carbon neutrality, and reduce dependence on fossil fuels.

The transition toward a hydrogen economy is therefore not simply a substitution of one fuel for another, but a structural transformation capable of redefining industrial value chains and creating new economic opportunities.

1.2 Hydrogen fundamentals

Hydrogen is considered one of the most promising energy carriers for the future due to its abundance, versatility, and potential to reduce greenhouse gas emissions. Its growing importance is closely linked to the global transition toward cleaner and more sustainable energy systems.

To better understand its role in this transition, it is necessary to go through the fundamental aspects of hydrogen, including its definition, properties, and its function as an energy carrier in decarbonization strategies.

1.2.1 Hydrogen definition & concept:

The term hydrogen originates from the Greek words: hydro (water) and gen (to generate), meaning “water-forming”. Henry Cavendish first identified it in 1776. Hydrogen is the simplest chemical element, consisting of a single proton and a single electron.

Under standard conditions, hydrogen exists as a diatomic molecule H_2 , commonly referred to as dihydrogen. It is the most abundant element in the universe, primarily found in combination with other elements such as in water H_2O and hydrocarbons.

Hydrogen is also a fundamental component of all living organisms. However, since it rarely exists in its pure form on earth, energy is required to extract it from its compounds. (DUMON, 2022). All methods for creating, storing, and transforming hydrogen for use as energy are referred to as hydrogen technology. (Batoul, et al., 2023)

1.2.2 Hydrogen properties:

Hydrogen is a colorless, odorless, and tasteless gas with distinctive properties that make it particularly attractive for energy applications, as summarized in Table 1. (International Energy Agency, IEA, 2019)

Table 1: Physical properties of hydrogen

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m ³ (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m ³ (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane

Auto ignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

One of the key characteristics that enhances its potential for decarbonizing various sectors of the economy is its high gravimetric energy density.

Figure 1 illustrates a comparison between specific energy and energy density for several fuels, based on their lower heating values. (Rivarolo, Riveros-Godoy, Magistri, & Massardo, 2019).

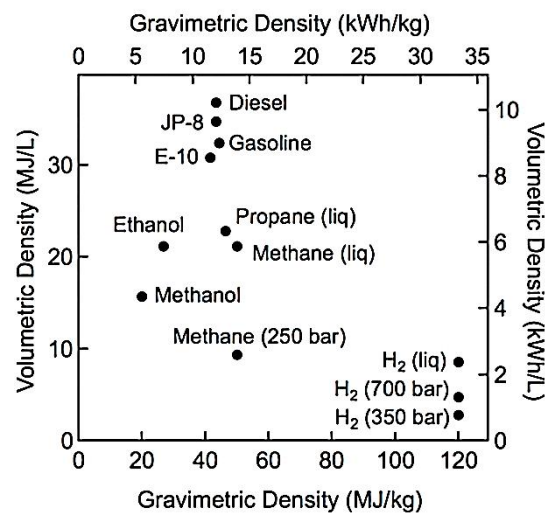


Figure 1: Gravimetric & volumetric density of hydrogen & other fuels.

Hydrogen exhibits the highest energy per unit mass among common energy carriers, with nearly three times the energy content of gasoline. However, despite this high gravimetric energy density, hydrogen has a relatively low volumetric energy density. For instance, liquid hydrogen has an energy density of approximately 8 MJ/L, compared to about 32 MJ/L for gasoline.

This contrast implies that, although hydrogen is highly efficient in terms of mass, larger volumes are required to store and transport it in order to meet the same energy demand as conventional fuels.

1.2.3 Hydrogen as an energy carrier & its role in decarbonization:

Hydrogen has recently emerged as a promising option in the global search for sustainable and low-carbon energy solutions. This increasing interest is not accidental, as hydrogen is the most abundant element in the universe, representing nearly 80% of its matter (Primerli, 2024). Its wide range of potential applications has strengthened the idea that it could serve as a clean alternative to fossil fuels and contribute to the development of sustainable energy systems.

Hydrogen is capable of storing energy within the molecular bonds between its atoms, similarly to other fuels such as methane CH_4 . This energy can be released through combustion or through electrochemical processes such as fuel cells. (Primerli, 2024; Moraga, 2022). However, unlike fossil fuels; hydrogen combustion does not produce greenhouse gases, generating only water vapor as a by-product.

Despite these advantages, hydrogen rarely exists in nature in its free form. Instead, it is typically found combined with other elements, such as in water molecules, which means it must be extracted through energy-intensive processes. For this reason, hydrogen is not considered a primary energy source like fossil fuels or renewable energy, but rather an energy carrier capable of storing and transporting energy produced from other sources (Primerli, 2024; Cercolani, 2022).

Hydrogen can store surplus electricity generated from renewable energy sources and release it when needed. It can also be used in several applications, including fuel cells, synthetic fuel production, and direct combustion in industrial processes. These characteristics allow hydrogen to play an important role in sectors where direct electrification is difficult, such as heavy industry and long-distance transport. (Cercolani, 2022; Moraga, 2022).

With the global transition toward low-emission energy systems, hydrogen technologies are receiving increasing attention. According to the hydrogen council, more than 350 large-scale hydrogen infrastructure projects are currently under development worldwide, reflecting the growing role of hydrogen in future energy strategies. (Primerli, 2024; Hydrogen Council, 2023).

1.3 Hydrogen economy: Market, policy, & challenges

The hydrogen economy represents a rapidly evolving sector that has the potential to transform energy systems worldwide. Understanding the hydrogen economy requires examining market dynamics, versatility and applications, as well as policy frameworks and collaborative initiatives, both globally and nationally, that support its development. Recognizing the challenges and considerations associated with hydrogen adoption is essential for assessing its economic, technological, and environmental feasibility

1.3.1 Hydrogen market:

The hydrogen market has historically been dominated by industrial applications, particularly ammonia production and oil refining. However, in recent years, global decarbonization policies have significantly reshaped market dynamics, accelerating investment in low-carbon hydrogen technologies.

Global hydrogen demand reached approximately 97 million tons annually in 2023 and projected to increase to between 130 and 150 million tons by 2030 due to expanding industrial activities and the global energy transition. (International Energy Agency. IEA, 2024; Hydrogen Council, 2023) .Currently, green hydrogen accounts for less than 1% of total market demand, corresponding to only a few hundred thousand tons per year, (International Energy Agency. IEA, 2024) .Nevertheless, green hydrogen demand is expected to grow at a compound annual growth rate CAGR of 30–40% until 2030, (Research and Markets, 2024; International Energy Agency. IEA, 2024). Depending on the implementation of decarbonization policies and investments in water electrolysis projects.

Low-emission hydrogen production could reach approximately 37 million tons annually by 2030 if planned projects are successfully implemented. (International Energy Agency. IEA, 2024) .This suggests that green hydrogen may evolve from a niche emerging market into a significant component of the global energy mix during this decade. Furthermore, its market value projected to reach tens of billions of dollars before 2030, with growth concentrated in Europe, Asia, and North America, particularly in the heavy transport, chemical, and power generation sectors.

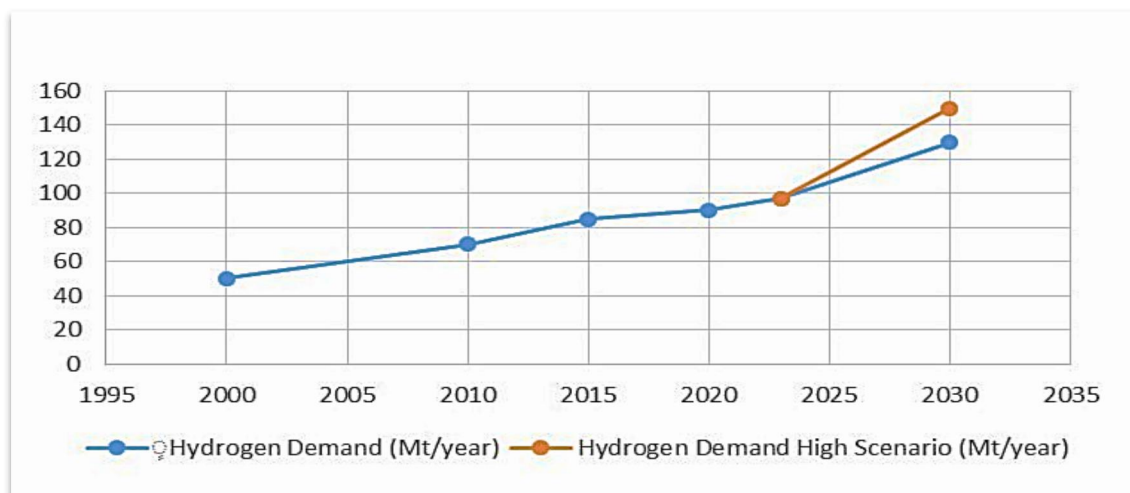


Figure 2: Global hydrogen demand growth scenarios up to 2030 Note. Created by the author based on data from Global Hydrogen Review 2024, by IEA (2024)

1.3.2 Hydrogen versatility & applications:

The growing interest in the hydrogen molecule creates an imperative for research and development in broad fields that require its presence as a fundamental element in industrial applications such as power generation and transportation.

Historically, hydrogen was primarily used for industrial purposes, particularly in ammonia production, oil refining, and petrochemical processes, relying heavily on grey hydrogen derived from natural gas.

In the 1990s and early 2000s, with the development of fuel cell technologies, attention began to shift towards considering hydrogen as an energy carrier. However, global demand remained largely focused on traditional industrial applications.

A major breakthrough occurred after the Paris agreement in 2015, when numerous countries adopted national hydrogen strategies and launched projects to develop hydrogen production. Investment in low-carbon hydrogen, including green and blue hydrogen, accelerated, supported by declining costs of renewable energy. This shift made hydrogen an economically viable and increasingly essential component of the global energy mix. (International Energy Agency. IEA, 2024) (Hydrogen Council, 2023).

Hydrogen is increasingly being applied in several sectors, including:

1.3.2.1 Industrial applications:

Hydrogen has been used in industry for decades, originally relying on grey hydrogen. Recent years have seen pilot projects using green hydrogen (International Energy Agency. IEA, 2024) (Staffell, et al., 2019).

Hydrogen played a critical role in industrial processes, and there is a growing shift toward using low-carbon hydrogen to reduce emissions (International Energy Agency. IEA, 2024; Staffell, et al., 2019).

- **Ammonia production:** Used extensively for fertilizers; pilot projects using green hydrogen are underway in Europe and the Middle East.
- **Oil refining (hydrocracking, desulfurization):** Hydrogen reduces sulfur content in fuels, with some refineries beginning to integrate blue or green hydrogen.
- **Petrochemical processes:** Hydrogen used in hydrogenation and chemical synthesis, low-carbon hydrogen increasingly considered to reduce the sector's carbon footprint.

1.3.2.2 Energy & power generation:

Initially limited, hydrogen use in energy systems has expanded since 2015 with renewable-powered electrolysis projects.

Hydrogen contributes to decarbonizing the energy sector and integrating renewable energy sources (International Energy Agency. IEA, 2024).

- **Electricity generation using fuel cells:** Deployed in micro grids, backup power systems, and experimental renewable-powered plants.
- **Power-to-gas storage systems:** Surplus renewable energy can be converted to hydrogen for storage and later reconversion to electricity.
- **Grid balancing in renewable energy systems:** Hydrogen provides flexibility to manage the variability of solar and wind energy.

1.3.2.3 Transportation:

Hydrogen offers a low-carbon alternative for mobility, especially in heavy-duty and long-range transport sectors (Hydrogen Council, 2023).

- **Fuel cell vehicles (cars, buses, trucks):** Deployment is increasing rapidly in Asia, Europe, and North America.
- **Hydrogen trains & ships:** Pilot projects in Germany, Japan, and Norway demonstrate feasibility for heavy transport applications.

1.3.2.4 Emerging & future applications:

While fuel cell vehicles emerged in the 1990s, large-scale deployment accelerated after 2015, especially in Europe and Asia (Hydrogen Council, 2023).

Emerging applications highlight hydrogen's strategic role in long-term decarbonization and the global energy transition (International Energy Agency. IEA, 2024).

- **Industrial decarbonization (steel, cement, chemicals):** Hydrogen replaces carbon-intensive processes, like direct reduced iron DRI in steelmaking.
- **Aviation & heavy-duty transport:** Research is ongoing for hydrogen-powered planes and trucks to reduce emissions in sectors that are difficult to electrify.
- **Integration with renewable energy for low-carbon energy systems:** Hydrogen acts as energy storage, grid stabilizer, and feedstock for synthetic fuels and chemicals.

1.3.3 Hydrogen Algeria's policy, support & collaboration:

Recent years have shown the Algerian government's growing interest in hydrogen production projects, particularly renewable hydrogen, as part of its strategy to reduce carbon emissions (CEREF, 2023; Mines, 2024) . In this context, national strategies have been developed to support the transition toward a low-carbon energy system, involving major public and private actors, such as Sonatrach and Sonelgaz (Sonatrach, 2024a; Sonatrach, 2024b).

In addition, Algeria has strengthened international cooperation with several European partners, including VNG, Snam, Verbund, within the South2Corridor initiative. These collaborations aim to facilitate technology exchange, develop hydrogen transportation infrastructure, attract investment, and integrate Algerian hydrogen into the European market (SouthH2 Corridor, 2024; Hubilo., 2024).

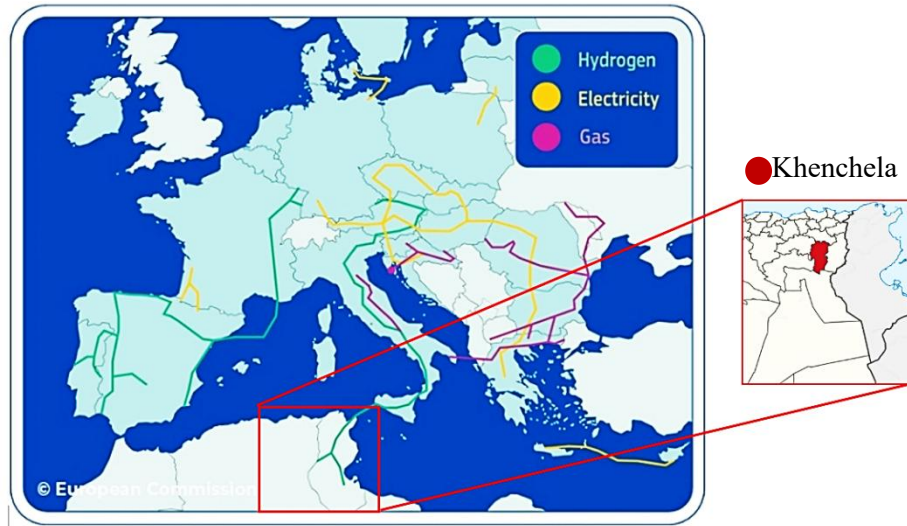


Figure 3: Planned route of the SouthH2 Corridor from North Africa to Europe showing the case study location.

The figure shows the planned SouthH2 Corridor extending near the Algerian-Tunisian border through Tunisia, Italy, Austria, and Germany. The corridor is intended to transport renewable hydrogen from North Africa to European industrial markets. (SouthH2 Corridor, 2024).

The map illustrates a European proposal for energy transit corridors linking North Africa to Europe, including hydrogen, natural gas, and electricity networks. Hydrogen corridors are highlighted in green and extend from the eastern Algerian border near the study case region Khenchela through Tunisia to Italy and Central Europe. Although Algeria is not directly connected to the hydrogen pipelines shown on the map, its proximity to Tunisia and its extensive experience in natural gas transport provide a strategic advantage, emphasizing the importance of integrating Algeria into future hydrogen distribution routes to Europe.

Overall, these national policies and international partnerships are intended to support Algeria's energy decarbonization objectives, strengthen its export potential, and position

the country as a regional leader in the emerging low-carbon hydrogen economy (ERRANET, 2024).

1.3.4 Hydrogen challenges & considerations:

Hydrogen as a potential alternative to fossil fuels and a key component of future sustainable energy systems, its large-scale deployment still faces several technical, economic, and regulatory challenges. That must be addressed to develop and deploy it more widely. One of the economic challenges lies in production costs, specifically green hydrogen compared to conventional hydrogen, where current production costs range between 3.8 and 11.9 US dollars per kilogram, mainly due to high renewable electricity prices and the costs of electrolysis equipment, which remain technically complex and expensive. (IRENA, 2022).

Additional costs are required for the hydrogen value chain, including massive investments in infrastructure such as storage systems, transportation networks, and conversion technologies, these processes introduce additional costs and energy losses, making large-scale hydrogen trade economically challenging. (UNFCCC, 2022).

The availability of renewable electricity represents another challenge, as hydrogen production requires enormous amounts of renewable energy to supply sufficient electricity for large-scale electrolysis systems, competing with other sectors that use electricity directly in industry and transport. (International Energy Agency. IEA, 2024; UNFCCC, 2022).

Investment in hydrogen projects still faces uncertainty regarding regulations and public policies in many countries, because these countries are still working on establishing regulatory frameworks, safety standards, and market mechanisms for its production, storage, transport, and trade. (International Energy Agency. IEA, 2024; Hydrogen Council, 2023).

Moreover, the development of the hydrogen market depends on creating stable demand. Without long-term purchase agreements and clear industrial demand, investors remain hesitant to finance such large-scale projects. (Hydrogen Council, 2023; International Energy Agency. IEA, 2024).

It is also important to accelerate the global hydrogen transition and expand its adoption through the development of low-emission production technologies.

1.4 Hydrogen production technologies

Hydrogen can be produced using a wide range of technologies and industrial processes. These methods mainly differ in their environmental impact and carbon emissions. Although hydrogen production and utilization are not new concepts, its growing role as a clean energy carrier aimed at reducing greenhouse gas emissions has recently attracted significant attention.

Based on the environmental footprint of the production pathway, hydrogen is commonly classified using a color-coding system. Each color represents a specific production method and its associated carbon intensity, although the final product remains the same: a colorless hydrogen molecule H_2 . In general, this classification depends primarily on two factors: the energy source used and the production technology employed.

There are two main categories of energy sources: Fossil fuels and Electricity. Fossil fuels are non-renewable, carbon-rich materials capable of storing energy in their natural state. In contrast, electricity is not a physical fuel but a flow of electrons that must generally be used at the moment it is generated, as large-scale storage remains challenging. For this reason, electricity is often converted into other energy carriers, such as hydrogen. (National Geographic Society, n.d; Primerli, 2024).

1.4.1 Fossil fuels as an energy source:

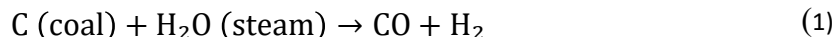
Fossil fuels are hydrocarbon-based energy resources, mainly including coal, oil, and natural gas. They are formed from the remains of ancient plants and microorganisms that were buried and transformed through geological processes over millions of years. (National Geographic Society, n.d).

1.4.1.1 Coal gasification:

Coal gasification is a thermo-chemical process used to convert coal into synthesis gas (syngas), a mixture primarily composed of hydrogen H_2 , carbon monoxide CO , and carbon dioxide CO_2 . In this process, coal is heated at high temperatures in the presence of

controlled amounts of oxygen and steam. This reaction breaks down the carbon-based material and produces syngas containing hydrogen along with other gaseous compounds.

The simplified gasification reaction is as follows:



Hydrogen yield can be further increased through the water–gas shift reaction:



After these reactions, hydrogen is separated from the gas mixture for further use. Coal gasification is considered economically attractive due to the relatively low cost and global availability of coal, as well as technological advancements in gasification systems. However, this process generates large amounts of carbon dioxide CO_2 , making it one of the most carbon-intensive hydrogen production pathways.

Hydrogen produced from coal gasification is commonly referred to as black hydrogen when derived from bituminous coal (Laboratory Notes, 2025; Awan & Al-Hamed, 2023). A similar process using lignite coal produces brown hydrogen. Both types are associated with high carbon emissions and are considered among the most polluting forms of hydrogen production. (Awan & Al-Hamed, 2023).

1.4.1.2 Catalytic reforming & steam methane reforming:

- **Catalytic reforming :**

Catalytic reforming is a petroleum refining process primarily used to convert low-octane naphtha into high-octane gasoline components. During this process, hydrocarbons undergo catalytic reactions that rearrange their molecular structure and release hydrogen as a byproduct. The hydrogen generated can be recovered and reused in various refinery operations, such as hydrocracking and hydro treating. However, the hydrogen produced through catalytic reforming is generally insufficient to meet the high hydrogen demand in modern refineries. (Gary, Kaiser, & Handwerk, 2007).

- **Steam methane reforming SMR :**

Steam methane reforming SMR is currently the most widely used commercial process for hydrogen production. Methane CH_4 , the principal component of natural gas, reacts with steam at high temperatures 650–1000 °C and pressures 5–40 bar in the presence

of a nickel-based catalyst. This endothermic reaction produces carbon monoxide and hydrogen:



The water-gas shift reaction further converts $CO + H_2O \rightarrow CO_2 + H_2$, increasing hydrogen yield. Finally, hydrogen is purified using pressure swing adsorption PSA, achieving purity levels of up to 99.9%. (Begum, 2020).

SMR and catalytic reforming typically produce inexpensive gray hydrogen, which nevertheless emits greenhouse gases. A mitigation technique called carbon capture and storage CCS can lower CO_2 emissions from fossil fuel-based hydrogen production. By capturing CO_2 during manufacture and storing it in geological formations, blue hydrogen can be produced, offering a substantially lower carbon footprint than traditional gray, black, or brown hydrogen. (European Commission, 2020; International Energy Agency., 2023)

Methane pyrolysis is another technology used to reduce emissions and is considered less harmful than conventional fossil fuel-based hydrogen production. In the absence of oxygen, this process involves the thermal decomposition of carbon-containing materials, such as biomass, polymers, or other organic waste.

Unlike traditional fossil fuel processes, carbon is not released as gaseous CO_2 but is produced as carbon black, a solid that is easier to store and has a lower impact on greenhouse gas emissions. Hydrogen produced via this method is commonly referred to as turquoise hydrogen. (Begum, 2020).

1.4.2 Electricity as an energy source:

Since electricity is difficult to store directly, it is often converted into chemical energy carriers for medium-to long-term storage. This approach is particularly useful for utilizing excess electricity when generation exceeds demand or when the grid's capacity is limited.

The main method for achieving this is water electrolysis, in which an electrolyzer splits water molecules into hydrogen and oxygen. When electricity generated from fossil fuels, the resulting hydrogen classified as gray or blue, depending on whether carbon capture is applied. Electricity from renewable sources produces green hydrogen. This process, known

as power-to-energy conversion P2E, is one of the most suitable methods for producing hydrogen with low emissions. (Eltrop, 2013).

1.4.2.1 Electrolysis using nuclear power:

Electricity from nuclear power can drive water electrolysis to produce hydrogen in a carbon-free manner. Hydrogen produced with nuclear electricity is commonly called pink hydrogen. One advantage is the continuous and stable electricity supply, enabling consistent hydrogen production.

Some nuclear plants also generate high-temperature heat, which can be used in high-temperature electrolysis (HTE) to produce red hydrogen. Both pink and red hydrogen are considered low-carbon alternatives to fossil-fuel-based production. (NexantECA, n.d).

1.4.2.2 Electrolysis using renewable energy wind & hydropower:

Electricity from renewable sources such as wind or hydropower can be used to drive water electrolysis. Wind turbines convert kinetic energy from wind into electricity, while hydroelectric dams harness flowing water. This electricity is then used to produce hydrogen directly.

Hydrogen produced in this way is known as green hydrogen, a clean and sustainable fuel since it generates almost no CO₂ emissions (Nuttall, Powell, J. B, Bakenne, A. T, Anaya-Stucchi, K. L., & Wilson, A, 2024). The color designation reflects the electricity source, not the electrolysis process

1.4.2.3 Electrolysis using solar energy:

Hydrogen produced via solar-powered electrolysis commonly referred to as yellow hydrogen. Technologies such as photovoltaic cells or concentrated solar power are used to generate the electricity for this process.

Yellow hydrogen is a sub-classification of green hydrogen, emphasizing the solar energy source. These color classifications are primarily used in media and public discourse to simplify hydrogen sources, not as strict scientific categories. (Nuttall, Powell, J. B, Bakenne, A. T, Anaya-Stucchi, K. L., & Wilson, A, 2024).

Another relatively recent and largely theoretical discovery for obtaining hydrogen

Naturally occurring hydrogen, sometimes called handout or giveaway hydrogen, formed at high temperatures and pressures in the earth's crust when water reacts with iron-rich rocks. While largely theoretical at present, this hydrogen could potentially be harvested using drilling techniques. Existing oil and gas infrastructure may provide suitable locations. Handout hydrogen represents a possible future low-carbon hydrogen source, albeit mostly speculative. (De Blasio, 2024).

1.5 Hydrogen storage technologies

The hydrogen energy infrastructure is fundamentally dependent on efficient storage technologies. The chosen storage method directly influences hydrogen applications as well as transportation strategies.

Due to its chemical properties 'being the smallest element' hydrogen exhibits high permeability it can diffuse through materials, flammability, and can cause material embrittlement. These characteristics create significant challenges in increasing energy density and ensuring safe and practical storage, transport, and utilization.

Hydrogen storage methods can be broadly classified into three main categories:

1.5.1 Compressed gas storage:

Compressed hydrogen storage is the simplest and most mature method. After production, hydrogen is initially stored at low pressure and then compressed using a compressor to higher pressures for efficient storage.

Hydrogen is stored in pressure vessels, which are classified into four types depending on their material composition, pressure resistance, and application. (U.S. Department of Energy, n.d).

- **Type I vessels** are made entirely of metal (steel or aluminum). They are easy to manufacture and relatively inexpensive, but heavy. These vessels can typically withstand pressures up to 50 MPa and are mainly used in stationary industrial applications where weight is not a critical factor.
- **Type II vessels** consist of a metal liner reinforced with composite materials

such as resin-impregnated fibers. This reinforcement improves strength while slightly reducing weight compared to Type I vessels.

- **Type III vessels** have a metal liner fully wrapped with carbon fiber composites. These vessels are significantly lighter and can withstand higher pressures, making them suitable for more advanced applications.

- **Type IV vessels** use a polymer liner instead of metal and are fully wrapped with carbon fiber. They are lightweight and capable of withstanding very high pressures up to 700 bar, making them ideal for mobile applications such as hydrogen-powered vehicles.

In general, increasing storage pressure improves hydrogen density, allowing more hydrogen to be stored in a smaller volume. However, higher pressures also increase system complexity, cost, and safety requirements. (Friman, 2020) .

1.5.2 Liquid hydrogen:

Liquid hydrogen storage is characterized by a significantly higher volumetric density compared to gaseous hydrogen, reaching approximately 70.8 kg/m³. The conversion of hydrogen from gas to liquid achieved by lowering the temperature to around -253°C, at atmospheric pressure 1 atm.

However, the liquefaction process is energy-intensive and technically complex, requiring long cooling times. As a result, approximately 30–40% of the initial energy content may be lost during the liquefaction process.

Liquid hydrogen storage is mainly used in medium- and large-scale applications, particularly for distribution and long-distance or intercontinental transport. It is also widely applied in aerospace industries, such as rocket propulsion systems. (Friman, 2020).

1.5.3 Material-Based storage:

Material-based hydrogen storage involves storing hydrogen within materials through chemical interactions, allowing higher storage densities and improved safety compared to physical methods.

- **Metal hydrides** store hydrogen in solid form within metal lattices, forming strong chemical bonds that enable storage at moderate pressure and near room

temperature. Hydrogen can be released either by thermolysis an endothermic process or hydrolysis an exothermic reaction with water. Although this method considered safe, it is limited by the high weight of metallic materials.

- **Chemical hydrides** store hydrogen in compounds such as methanol and ammonia, which are generally in liquid form. This facilitates transportation and handling due to their lower weight and higher gravimetric density. However, hydrogen extraction requires additional chemical reactions, often involving heat or catalysts, which increases system complexity. (Begum, 2020).

Despite their advantages, material-based storage methods are still under development due to challenges related to weight, cost, and hydrogen release efficiency

1.5.4 Advanced storage methods:

Advanced hydrogen storage methods include emerging technologies such as adsorption in porous materials, liquid organic hydrogen carriers LOHC, and nanostructured materials. Adsorption-based storage relies on materials with high surface area, such as activated carbon or metal–organic frameworks, where hydrogen is physically adsorbed at low pressures. LOHC systems store hydrogen in liquid organic compounds, enabling easier transport and handling using existing fuel infrastructure. Additionally, novel approaches such as nanomaterials and glass microspheres are being investigated for their potential to enhance storage capacity. Despite their promising advantages, these technologies are still under development and face challenges related to efficiency, cost, and scalability (Schlapbach, L & Züttel, A., 2001)

1.6 Conclusion

Hydrogen plays a central role in the transition to cleaner and more sustainable energy systems. Its ability to store, transport, and deliver energy makes it essential for decarbonizing sectors that are hard to electrify. The environmental and economic value of hydrogen depends on its production method, with green hydrogen offering the most sustainable pathway.

Achieving a hydrogen-based economy requires not only cost reduction but also adaptable networks and efficient storage and transport infrastructure. Deploying green hydrogen

production facilities is essential for enabling innovative industrial chains and meeting global decarbonization targets.

Since water electrolysis is the main method for producing green hydrogen, the next chapter focuses on this process, examining its principles, technologies, and performance as the foundation for a sustainable hydrogen economy.

Chapter two: Overview on water electrolysis

Chapter two: Overview on water electrolysis

2.1 Introduction

In the previous chapter, hydrogen was explored as a clean energy carrier, highlighting green hydrogen as a sustainable alternative produced from renewable resources. Its production relies fundamentally on water electrolysis, a process in which electrical energy splits water into hydrogen and oxygen.

Invented in the early 19th century, electrolysis was long the dominant method for industrial hydrogen production. However, the rise of natural gas in the 1920s led to the widespread adoption of steam methane reforming as a more economical alternative. Today, with renewable energy's increasing share in electricity generation and stricter limits on greenhouse gas emissions, water electrolysis is regaining importance. It remains the only known method to produce sustainable hydrogen using renewable electricity.

Linking hydrogen production to renewable energy offers a crucial opportunity to decarbonize heavy industry and transport sectors, traditionally reliant on fossil fuels. Water electrolysis is thus a decisive factor in the energy transition. This chapter examines the historical evolution, theoretical and technical principles, and types of water electrolysis technologies, efficiency analyses, applications, and obstacles that hinder large-scale adoption

2.2 Water electrolysis

Water electrolysis is a fundamental process in physics and chemistry, dating back to the late 18th century. It uses a direct electric current to drive non-spontaneous chemical reactions and enabling applications from green hydrogen production to metal extraction.

2.2.1 Water electrolysis history:

The development of water electrolysis dates back to the early 19th century, during the first industrial revolution. In 1800, William Nicholson and Anthony Carlisle demonstrated for the first time that water could be decomposed into hydrogen and oxygen using an electric current, laying the foundation for modern electrochemistry.

Over the following decades, electrolysis technology gradually evolved, leading to its industrial adoption in the early 20th century. By 1939, more than 400 industrial water electrolysis units had been established worldwide, reflecting its growing importance in hydrogen production.

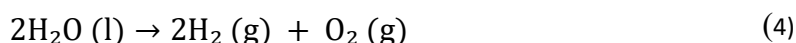
The scale of electrolysis systems continued to expand, and large-scale plants were developed, including facilities capable of producing up to 10000 m³H₂/h. In 1948, the first compact industrial electrolyzer was introduced, marking a significant step toward more efficient and practical system designs.

Technological advancements accelerated in the second half of the 20th century. In 1966, General Electric developed the first solid polymer electrolyte SPE system, which later evolved into modern proton exchange membrane PEM technology. In 1972, the first solid oxide-based electrolysis systems were introduced, followed by improvements in alkaline electrolysis systems in 1978.

Today, research continues to focus on enhancing electrolyzer performance, particularly through the development of advanced membrane materials and high-temperature systems. Companies such as DuPont play a key role in advancing membrane technologies, while ongoing innovations aim to improve efficiency, durability, and large-scale deployment of hydrogen production systems. (Zoulias, Varkaraki, Lymberopoulos, & Christodoulou, 2005)

2.2.2 Water electrolysis definition & concept:

Water electrolysis is an electrochemical process in which water molecules H₂O are decomposed into hydrogen gas H₂ and oxygen gas O₂ using electrical energy. The overall reaction can be expressed as follows:



This process considered a clean method for hydrogen production, particularly when powered by renewable energy sources, as it does not involve direct carbon dioxide emissions.

Electrolysis requires a direct current DC power supply to drive the reaction within an electrochemical cell.

In practice, pure water exhibits very low electrical conductivity, which limits its ability to carry electric current. Therefore, an electrolyte is added to enhance ionic conductivity. Common electrolytes include alkaline solutions such as potassium hydroxide KOH and sodium hydroxide NaOH, as well as acidic solutions such as sulfuric acid H₂SO₄. These substances dissociate into ions that facilitate charge transport between the electrodes.

The electrolysis of water involves two coupled half-reactions occurring at the electrodes.

At the cathode, the hydrogen evolution reaction HER takes place, where electrons are consumed to reduce protons or water molecules and produce hydrogen gas. At the anode, the oxygen evolution reaction OER occurs, involving the oxidation of water and the release of oxygen gas along with electrons.

These reactions are driven by the flow of electrons through the external circuit and the movement of ions within the electrolyte, ensuring charge balance in the system. The overall process is governed by thermodynamic and kinetic factors, which determine the energy required to initiate and sustain the reactions. (Rashid, Al Mesfer, Naseem, & Danish, M, 2015).

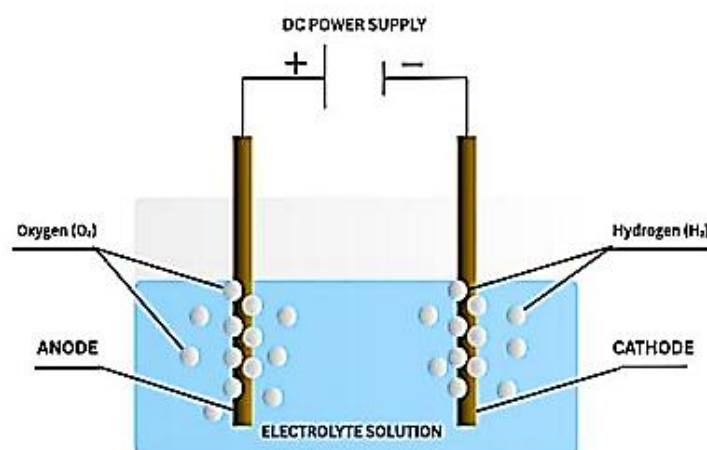
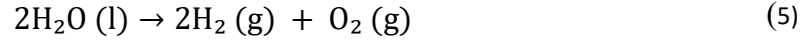


Figure 4: Schematic representation of the water electrolysis process (Rashid, Al Mesfer, Naseem, & Danish, M, 2015)

2.2.3 Water electrolysis electrochemical & energy principles:

The electrochemical basis of water electrolysis is based on converting electrical energy into chemical energy stored in hydrogen. In an electrolyzer, water is decomposed according to the overall reaction:



As a result, hydrogen and oxygen gases are produced separately. According to the electrochemical principle, the production of one mole of hydrogen requires two electrons, because each hydrogen molecule contains two protons H^+ , and each proton requires one electron to form a hydrogen atom.

Therefore, the amount of electricity required is equal to $2F$, where F is Faraday's constant:

$$F = 96485 \text{ (C/mole)}$$

Thus, the charge required to produce one mole of hydrogen is approximately 192970C .

One normal cubic meter Nm^3 of hydrogen contains about 44.6 moles. Therefore, the amount of electricity required to produce 1 Nm^3 of hydrogen is about 89.3 F , which is approximately 2400 Ah . Due to the high current efficiency of water electrolysis, this value is commonly used in practical calculations.

Thermodynamically, the total energy required for water electrolysis is represented by the enthalpy change ΔH , which is equal to the sum of the Gibbs free energy change ΔG and the thermal contribution, $T\Delta S$:

$$\Delta H = \Delta G + T\Delta S \quad (6)$$

This means that the energy required for electrolysis is not entirely electrical, since part of it may be supplied as heat.

The minimum voltage required to initiate electrolysis called the reversible voltage:

$$E_{\text{rev}} = \frac{\Delta G}{nF} \quad (7)$$

Under standard conditions (25°C & 1 bar), this reversible voltage is:

$$E_{\text{rev}}(0) = 1.23 \text{ V} \quad (8)$$

This is the minimum theoretical voltage required for water electrolysis.

However, there is another important voltage called the thermoneutral voltage, which corresponds to the total energy requirement ΔH :

$$E_H = \frac{\Delta H}{2F} \quad (9)$$

Under standard conditions, its value is:

$$E_H(0) = 1.48 \text{ (V)} \quad (10)$$

The difference between these two voltages is important. The reversible voltage of 1.23 V represents the minimum electrical energy theoretically required, whereas the thermoneutral voltage of 1.48 V corresponds to thermal equilibrium without the need for heat exchange with the surroundings.

If the operating voltage is below 1.48 V, the electrolyzer must absorb heat from the surroundings. On the other hand, if the voltage is above 1.48 V, part of the supplied electrical energy is dissipated as heat.

Finally, at 1.23 V, the minimum electrical energy required to produce 1 Nm³ of hydrogen is 2.94 kWh/Nm³, whereas at 1.48 V, the energy requirement increases to 3.54 kWh/Nm³.

In practical systems, electrolyzers usually operate between 1.8 and 2.2 V because of activation losses, ohmic resistance, and mass transport limitations. (Hou & Yang, M, 2025).

2.3 Electrolysers technologies

Water electrolysis technologies can be categorized based on the type of electrolyte used, which separates the anodic and cathodic half-reactions in the electrolyzer. The main types of water electrolysis systems for hydrogen production are as follows

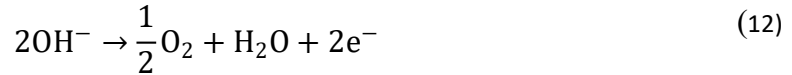
2.3.1 ALK Alkaline water electrolysis:

Alkaline Water Electrolysis AWE, also referred to as Alkaline Electrolysis AEL, is the oldest and most established technology for hydrogen production. It operates by immersing two electrodes in a liquid alkaline electrolyte, typically potassium hydroxide

KOH at a concentration of 25–30 wt%, which ensures efficient transport of hydroxide ions OH^- and high ionic conductivity at operating temperatures between 70 and 90°C. During the process, water reduced at the cathode to produce hydrogen gas and hydroxide ions according to the reaction:



At the anode, hydroxide ions are oxidized to form oxygen gas, water, and electrons:



The overall reaction can be written as:



A diaphragm separates the cathode and anode compartments, preventing the mixing of hydrogen and oxygen while allowing ion migration. The electrodes are generally made of nickel or nickel-coated stainless steel, which eliminates the need for precious metals, while the diaphragm is often composed of porous materials such as Zirfon. In addition, bipolar plates are used to connect the cells within the stack and distribute current efficiently.

AWE systems are typically constructed in a monopolar arrangement for low-pressure operation, whereas bipolar configurations are preferred in pressurized systems to reduce space requirements and optimize material usage.

AWE is considered a highly mature and cost-effective technology due to its reliance on abundant materials and the absence of expensive catalysts.

Large-scale alkaline electrolysis plants have been in operation since the 1920s, such as the Rjukan plant in Norway. The technology offers a long operational lifetime of 20–30 years, high hydrogen production capacity suitable for gigawatt-scale projects, and relatively low capital costs. However, AWE systems operate at relatively low current densities, typically between 0.2 and 0.4 A/cm², respond more slowly to fluctuations in renewable electricity, and most conventional systems operate at atmospheric pressure, requiring additional compression equipment, although modern pressurized AWE units are increasingly being developed. (Rouwenhorst, 2026).

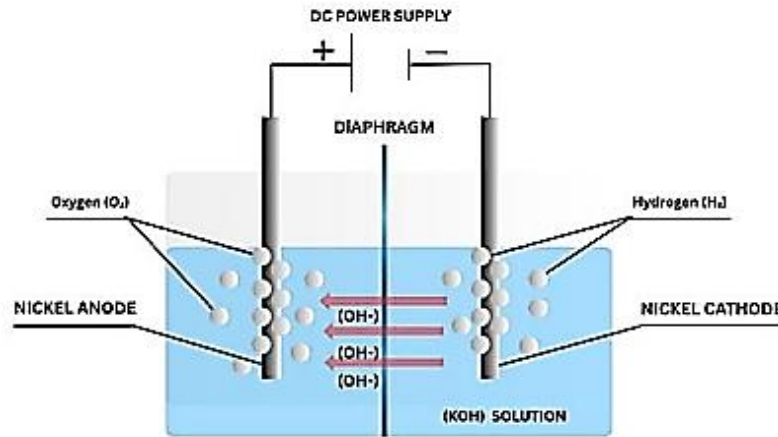


Figure 5: Schematic of ALK Alkaline water electrolysis (Rouwenhorst, 2026)

2.3.2 PEM Proton Exchange Membrane water electrolysis:

Proton Exchange Membrane PEM electrolysis uses a solid polymer membrane as both an electrolyte and a gas separator. During operation, water at the anode is split into oxygen gas, protons H^+ ions, and electrons. The protons migrate through the proton-conducting membrane to the cathode, where they combine with electrons supplied via an external circuit to produce high-purity hydrogen gas.

PEM electrolysis relies on advanced and expensive materials. The membrane is typically a Nafion fluoropolymer, while the catalysts require precious metals, such as iridium Ir at the anode and platinum Pt at the cathode. The bipolar plates are generally made of titanium-coated materials to resist corrosion in the acidic environment. The scarcity of iridium poses a limitation to large-scale deployment of this technology.

The main advantages of PEM include its dynamic response, enabling rapid start-up, shutdown, and load following, making it ideal for integration with intermittent

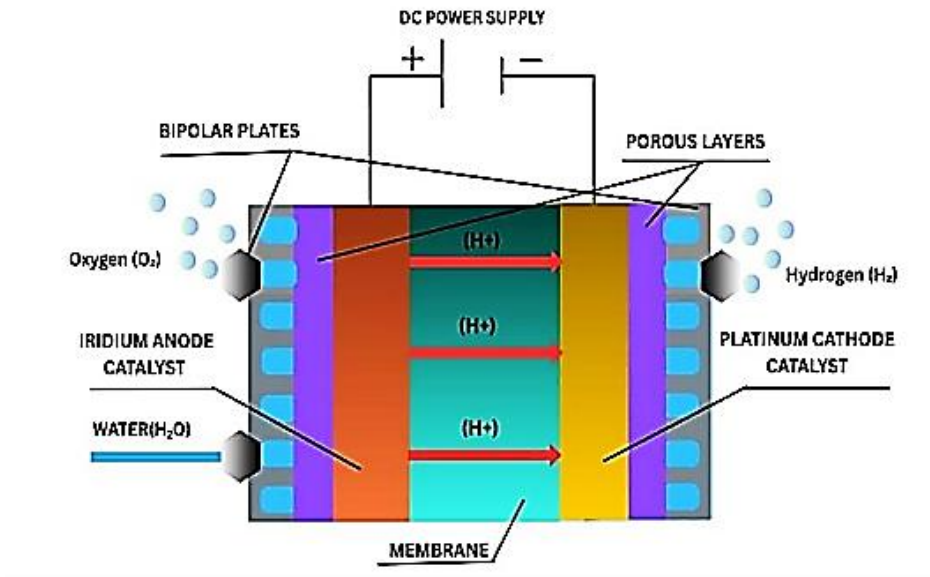


Figure 6: Schematic of PEM Proton Exchange Membrane water electrolysis (Rouwenhorst, 2026)

Renewable energy sources. It operates at high current densities above 2.0 A/cm^2 , allowing compact and space-saving designs. Hydrogen can be produced directly at elevated pressures typically 30–70 bar, reducing the need for subsequent compression, and the resulting gas is extremely pure due to the membrane's effective gas separation.

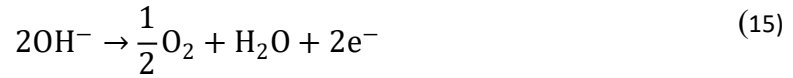
However, PEM electrolysis faces economic and operational challenges, including higher capital costs CAPEX due to precious metals and titanium components, and longevity concerns compared to the well-established alkaline systems. Despite these limitations, PEM is considered a high-performance and flexible technology for modern hydrogen production. (Rouwenhorst, 2026).

2.3.3 AEM Anion Exchange Membrane water electrolysis:

Anion Exchange Membrane AEM electrolysis is an emerging hydrogen production technology that combines the advantages of both Alkaline Water Electrolysis AWE and Proton Exchange Membrane PEM electrolysis. Similar to PEM systems, AEM uses a solid polymer membrane; however, instead of conducting protons H^+ , the membrane transports hydroxide ions OH^- . During operation, water reduced at the cathode to produce hydrogen gas and hydroxide ions according to the reaction:



The hydroxide ions then migrate through the membrane to the anode, where they are oxidized to form oxygen gas, water, and electrons:



The overall reaction is therefore identical to other electrolysis technologies:



One of the main advantages of AEM electrolysis is its ability to operate in an alkaline environment while using a compact membrane-based design. This allows the use of low-cost, non-precious metal catalysts such as nickel, iron, manganese, or cobalt instead of expensive platinum and iridium catalysts required in PEM systems. In addition, AEM systems can use stainless steel components, further reducing capital costs. The solid membrane also prevents gas crossover, enables the production of high-purity hydrogen, and allows operation under elevated pressures. AEM electrolyzers are compact, respond rapidly to fluctuations in renewable electricity, and considered highly suitable for coupling with intermittent energy sources such as solar and wind power.

Despite these advantages, AEM technology is still in the early stages of development and has not yet reached the commercial maturity of AWE or PEM systems. Current challenges include the limited chemical and mechanical stability of the membrane under alkaline conditions, lower hydroxide ion conductivity compared to proton conductivity in PEM membranes, and shorter stack lifetimes. Nevertheless, AEM is widely regarded as one of the most promising next-generation electrolysis technologies due to its potential to combine high performance with low cost. (Rouwenhorst, 2026).

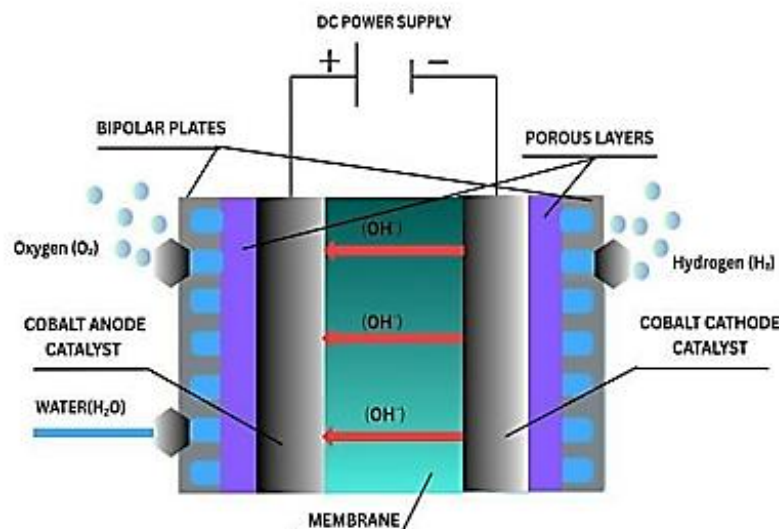


Figure 7: Schematic of AEM Anion Exchange Membrane water electrolysis (Rouwenhorst, 2026)

2.3.4 SOEC Solid Oxide water electrolysis cell:

Solid oxide electrolysis cells SOEC are considered the most thermodynamically efficient water electrolysis technology. Unlike AEL and PEM systems, SOEC operates at very high temperatures, typically between 600–850°C. In this process, steam H_2O is supplied to the cathode, where it dissociates into hydrogen gas and oxygen ions O^{2-} . The oxygen ions migrate through a solid ceramic electrolyte to the anode, where they release electrons and form oxygen gas. The electrolyte is usually made of yttria-stabilized zirconia YSZ, which conducts oxygen ions but not protons. Electrodes are composed of ceramic or cermet materials, such as nickel mixed with zirconia, eliminating the need for precious metals.

SOEC offers several key advantages. Its high operating temperature allows part of the required electrical energy to be replaced with thermal energy, significantly improving overall efficiency compared to low-temperature systems. It also supports co-electrolysis of steam and carbon dioxide CO_2 to produce syngas, which is a critical feedstock for sustainable fuels for aviation and shipping. Furthermore, SOEC can be integrated with industrial processes that generate excess heat, reducing electricity consumption.

However, SOEC faces notable challenges. Thermal stress from high temperatures accelerates material degradation and limits the lifespan of the cell. Its operational flexibility is lower, with long start-up times, making it less suitable for direct integration

with intermittent renewable energy sources. Additionally, systems are still in advanced experimental or limited-production stages, and their capital costs remain high due to the engineering complexity required for high-temperature operation. Despite these limitations, SOEC is described as a highly promising technology for future industrial applications, particularly where combined heat and electricity integration desired to produce carbon-neutral fuels. (Rouwenhorst, 2026).

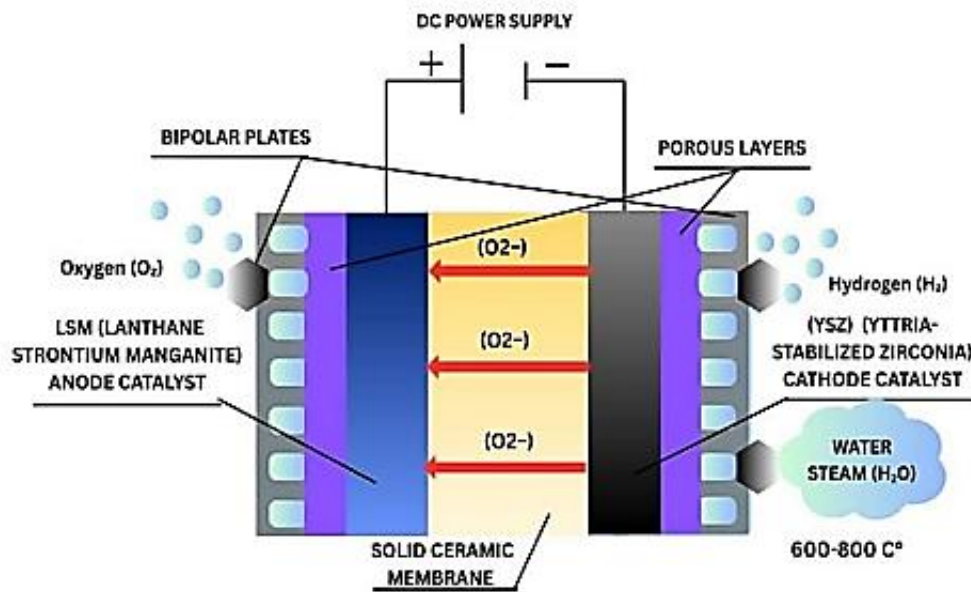


Figure 8: Schematic of SOEC Solid Oxide water electrolysis cell (Rouwenhorst, 2026)

2.4 Performance & applications of electrolyzers

To understand the applications of electrolyzers, it is first necessary to understand the thermodynamics and efficiency of each technology. A deeper understanding of these aspects inevitably requires considering economic and technical constraints.

2.4.1 Energy, voltage, & efficiency considerations in green hydrogen production:

Efficiency reflects the ability of an electrolyzer to convert electrical energy into the chemical energy stored in hydrogen and is generally categorized into current faradaic efficiency and voltage efficiency.

For systems operating below 100 °C, voltage efficiency η_v can be calculated using the thermoneutral benchmark of 1.48 V:

$$\eta_v = \frac{1.48}{E_{cell}} \quad (17)$$

Where E_{cell} is the actual operating voltage of the electrolyzer. To translate cell voltage into specific DC power consumption, the electrochemical constant of 2.393 Ah/Nm³ for H₂ is used. In practice, the stack's power consumption can be estimated as 2.393 x E_{cell} . For example, a stack operating at 1.8 V consumes approximately 4.30 kWh/Nm³.

Benchmarking in industry also requires distinguishing between Higher Heating Value HHV and Lower Heating Value LHV. The HHV includes the latent heat of water vaporization, which is important for fairly comparing technologies that use liquid water versus steam. Achieving cost-competitive hydrogen production requires minimizing over potentials, which drive E_{cell} above the thermodynamic potential E_0 .

The operating voltage of an electrolyzer can be expressed as:

$$E_{cell} = E_0 + E_{act} + E_{ohm} + E_{mass} \quad (18)$$

Where:

- **Activation over potential E_{act} :** Determined by catalytic kinetics, representing the energy required to initiate the reaction at the triple-phase interface (solid catalyst, liquid electrolyte, and gas product).
- **Ohmic over potential E_{ohm} :** Arises from internal resistances, including ionic resistance of membranes and electronic resistance of electrodes and bipolar plates. In AWE, parasitic shunt currents further reduce efficiency.
- **Mass transport over potential E_{mass} :** Mainly due to gas bubble accumulation on electrode surfaces, obstructing active sites and increasing liquid resistance, especially at high current densities (0.5–2 A/cm²).

The operating current density is the main parameter for balancing capital expenditure CAPEX against stack efficiency. No single electrolysis technology is universally optimal; strategic diversification helps mitigate risks related to material supply or operational constraints. (Hou & Yang, M, 2025).

The main technical features of the four water electrolysis technologies are summarized in table below:

Table 2: Main parameters for electrolysis technologies (Hou & Yang, M, 2025)

Performance Indicators	Alkaline Water Electrolysis (AWE)	Proton Exchange Membrane Water Electrolysis (PEMWE)	Anion Exchange Membrane Water Electrolysis (AEMWE)	Solid Oxide Electrolysis cell (SOEC)
Operating temperature (°C)	50–90	20–90	20–70	600–1000
Current density (A/cm ²)	0.2–0.6	1–3	0.2–1.5	0.3–2
Energy consumption (kWh/Nm ³)	4.2–5.0	4.2–5.0	≈4.8	2.5–4.0
Charge carrier	OH ⁻	H ⁺	OH ⁻	O ²⁻
Capital cost (USD/kW)	200–800	700–1400	(Prototype phase)	(Laboratory phase)

2.4.2 Industrial applications for electrolyzer:

The use of an electrolyzers is not limited to the production of oxygen and hydrogen gases; in addition, there are industrial applications that involve the use of electrolyzers, including:

Electrolyzers are not only used for the production of hydrogen and oxygen gases, but also in several important industrial applications, including:

- **Purification by electrolysis:**

Electrolysis can be used to purify metals. A piece of pure metal, such as copper, is used as the cathode, while the impure metal is used as the anode. When the electric circuit is closed, only the pure metal dissolves from the anode, forming metal ions that move toward the cathode and are deposited as pure metal.

- **Electroplating:**

Electrolysis is used in electroplating to deposit a thin layer of metal on another material. Electroplating can be used for rust prevention and decorative finishes. The electrolyte contains the cations of the metal to be deposited. The cathode is the object to be plated, while the anode is the metal used for coating. (Fongrsy, 2019).

- **Chlor-Alkali production:**

In this process, electrolysis of brine is used to produce chlorine gas, hydrogen gas, and sodium hydroxide. These products are widely used in water treatment, soap manufacturing, paper production, and many other industrial processes. (O'Brien, T. F, Bommaraju, T. V., & Hine, F, 2005).

- **Metal extraction from Ores:**

Some reactive metals, such as aluminum, sodium, and magnesium, are extracted from their ores by electrolysis. An electric current passes through the molten metal compound, causing metal ions to gain electrons and form pure metal. For example, aluminum is extracted from alumina by electrolysis. (Hassell, 2025).

2.4.3 Economic & technical barriers:

The energy transition, within the framework of visions for a carbon-neutral future, relies on electrolysis as a cornerstone of green hydrogen production. However, economic and technological realities impose constraints that slow down this transition.

Economically, between 2020 and 2024, financial investments increased significantly, rising sevenfold from 90€ billion to 680€ billion. Nevertheless, the expected objectives have not yet been achieved, as actual low-carbon hydrogen production has reached only 2 to 3 million tons, compared with the 100 million tons of hydrogen consumed globally by industry. Several factors explain this situation. (Techniques de l'Ingénieur, 2026).

- **Electricity cost:** Electricity is the most influential factor, representing approximately 75% of the total cost of hydrogen production through electrolysis.
- **Competitiveness gap:** Hydrogen produced by electrolysis remains significantly more expensive than hydrogen produced through conventional methods. Its production cost ranges between €4.0 and €4.9 per kilogram, compared with €1.5 to €2.0 per kilogram for hydrogen produced from natural gas.
- **Fierce international competition:** China currently controls around 60% of the global electrolyzer manufacturing capacity and applies a low-price strategy compared with European manufacturers.
- **Financing & investment:** There is considerable difficulty in reaching a Final Investment Decision. Of the more than 1500 projects announced in 2024, around 70% did not progress beyond the initial announcement stage because of economic and regulatory uncertainty. (Techniques de l'Ingénieur, 2026).

Technically, the choice of technology directly influences the cost of hydrogen production. The main challenge lies in minimizing the gap between operating costs and investment costs in strategic projects such as green hydrogen production and the associated infrastructure. Key technical challenges include:

- **Energy efficiency:** Water electrolysis still faces performance limitations, with maximum technical efficiency generally not exceeding 65%.

- **Reliance on critical materials:** Current technologies depend heavily on precious and rare metals such as platinum, which are expensive and difficult to supply. This has encouraged research into alternatives such as conductive polymers.
- **Water consumption:** Electrolyzers require large quantities of water. For example, hydrogen production in Tunisia alone is expected to require 248 million cubic meters of desalinated water by 2050, placing additional pressure on water resources.
- **Infrastructure & connectivity:** Electrolyzers often lack dedicated pipeline networks and storage facilities, such as salt caverns, to connect production sites with industrial consumption centers.
- **Technological differences:** There is strong competition between alkaline electrolyzers, which are mass-produced in China and are cheaper but slower to operate, and proton exchange membrane PEM electrolyzers, which are faster and more efficient but also more expensive. (Techniques de l'Ingénieur, 2026).

2.5 Conclusion

Water electrolysis is the fundamental process for hydrogen production and the basis for green hydrogen technologies. Mastering its thermodynamic and electrochemical principles is essential to understand its efficiency and scalability. A key consideration for sustainable hydrogen production is the source of electricity: hydrogen cannot be considered environmentally friendly if it relies solely on conventional grid power. The next chapter will therefore focus on renewable energy, exploring how solar electricity can provide a clean and sustainable power source for water electrolysis.

Chapter three: Overview on solar energy

Chapter three: Overview on solar energy

3.1 Introduction

Having discussed the principles and operation of electrolyzers for hydrogen production, it is essential to consider the renewable energy sources capable of supplying the required electrical power. Among the various renewable options, solar energy represents one of the most promising and widely available resources for driving water electrolysis and producing green hydrogen. The sun continuously emits an enormous amount of energy toward the earth, estimated at approximately 1.73×10^{17} W, which far exceeds current global energy demand. This vast and virtually inexhaustible resource represents one of the most promising solutions to the growing challenges associated with energy security and environmental sustainability (Hurley, 2025).

Solar energy refers to the fraction of this incoming radiation that can be captured and converted into useful forms of energy, such as thermal and electrical power. Through a range of technologies. Unlike conventional fossil fuels, solar energy is renewable, widely available, and environmentally friendly, as it does not produce harmful emissions during operation.

The efficiency of solar energy systems depends on several factors, including solar irradiance, geographic location, and system design. Understanding the fundamental characteristics of solar radiation and its interaction with the earth's atmosphere is therefore essential for optimizing energy conversion processes and improving system performance.

Algeria possesses exceptional solar potential due to its geographical location within the global solar belt, characterized by high levels of solar irradiance and extended sunshine duration throughout the year. This significant natural advantage positions the country as a key player in the development of solar energy technologies. The transition toward solar-based systems represents a strategic opportunity to not only meet increasing energy demands but also to reduce greenhouse gas emissions, diversify the national energy mix, and support sustainable economic development.

3.2 Solar energy fundamentals

Understanding solar energy requires a comprehensive analysis of its fundamental principles, including concepts of solar energy, the nature of solar radiation, the main solar energy technologies and the distribution of solar resources. In this context, particular attention is given to Algeria, which possesses significant solar potential due to its geographical location.

3.2.1 Solar energy concept:

Solar energy is the primary source of energy on earth, driving most natural processes and sustaining life. The earth receives a significant amount of solar radiation, with an average value of approximately 1000 W/m^2 at the surface under optimal conditions. This energy is transmitted in the form of electromagnetic radiation and is absorbed by the atmosphere, oceans, and land surfaces.

Solar energy originates from nuclear fusion reactions occurring in the sun's core, where hydrogen nuclei combine to form helium, releasing a large amount of energy where temperatures reach approximately 15 million degrees Celsius. This immense energy output plays a crucial role in maintaining the earth's temperature within a habitable range and supports essential natural processes such as the water cycle, photosynthesis, and climate regulation. As a result, solar energy is fundamental to life on earth and represents a key resource for sustainable energy production. (Lefèvre., 2026).

3.2.2 Solar radiation:

The efficiency of solar energy systems is strongly influenced by the geometry of the sun's position in the sky. The apparent motion of the sun results from the earth's rotation around its axis and its revolution around the sun. This motion leads to daily and seasonal variations in solar radiation.

During a typical day, the sun appears to move from east to west, forming an arc across the sky due to the earth's rotation. In addition, the sun's path changes throughout the year because of the tilt of the earth's axis approximately 23.5° . Consequently, in summer, the sun reaches a higher position in the sky, resulting in longer days and higher solar radiation,

whereas in winter, the sun remains lower, leading to shorter days and reduced radiation levels. (National Weather Service, n.d).

The position of the sun in the sky is commonly described using three fundamental angles. (Eopedia, 2025).

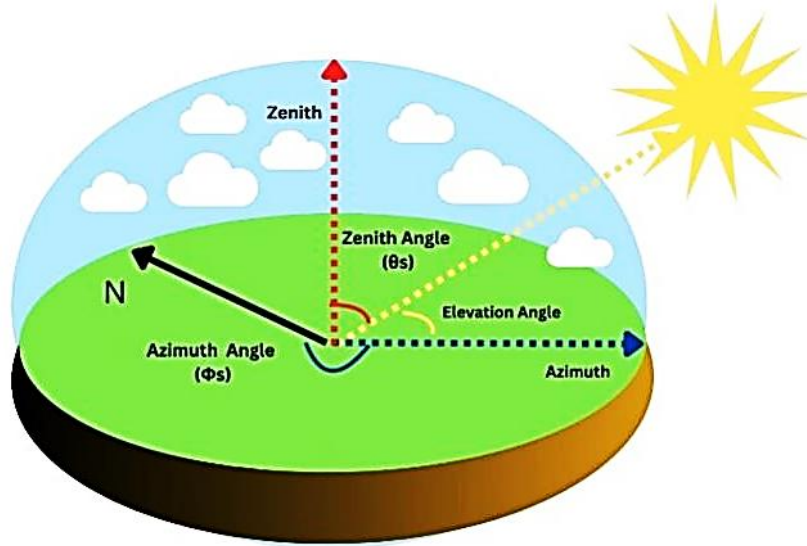


Figure 9: Solar angles geometry (Zenith, azimuth, & elevation) (Eopedia, 2025)

3.2.2.1 Solar zenith angle:

An angle between the sun and the vertical

$$\cos(\theta_s) = \sin(\varphi) \times \sin(\delta) + \cos(\varphi) \times \cos(\delta) \times \cos(h) \quad (19)$$

- ϕ : Latitude
- δ : Solar declination

$$\delta = -23.44 \times \cos\left(\frac{360}{365} \times (N + 10)\right) \quad (20)$$

- N: Day number of the year
- h: Hour angle $h=15(t-12)$

3.2.2.2 Solar elevation angle:

An angle between the sun and the horizon

3.2.2.3 Solar azimuth angle:

The direction of the sun relative to north

$$\sin(\varphi_s) = -\sin(h) \times \frac{\cos(\delta)}{\sin(\theta_s)} \quad (21)$$

There are three main components of solar radiation global horizontal irradiance GHI, direct normal irradiance DNI, and diffuse horizontal irradiance DHI, which play a crucial role in determining the amount of solar energy received at the earth's surface. (Suncom Energy, 2024)

- **Direct normal irradiance DNI**

DNI represents the solar radiation received directly from the sun on a surface that is always perpendicular to the sun's rays. This component is highly dependent on atmospheric conditions such as cloud cover and air pollution.

- **Diffuse horizontal irradiance DHI**

DHI corresponds to the portion of solar radiation that has been scattered by molecules and particles in the atmosphere. Unlike direct radiation, it reaches the earth's surface from all directions.

- **Global horizontal irradiance GHI**

GHI is the total solar radiation received on a horizontal surface. It is the sum of the direct and diffuse components and can be expressed as:

$$GHI = DNI \times \cos(\theta_s) + DHI \quad (22)$$

Where θ_s is the solar zenith angle. GHI is the most commonly used parameter for evaluating the overall solar energy potential of a given location.

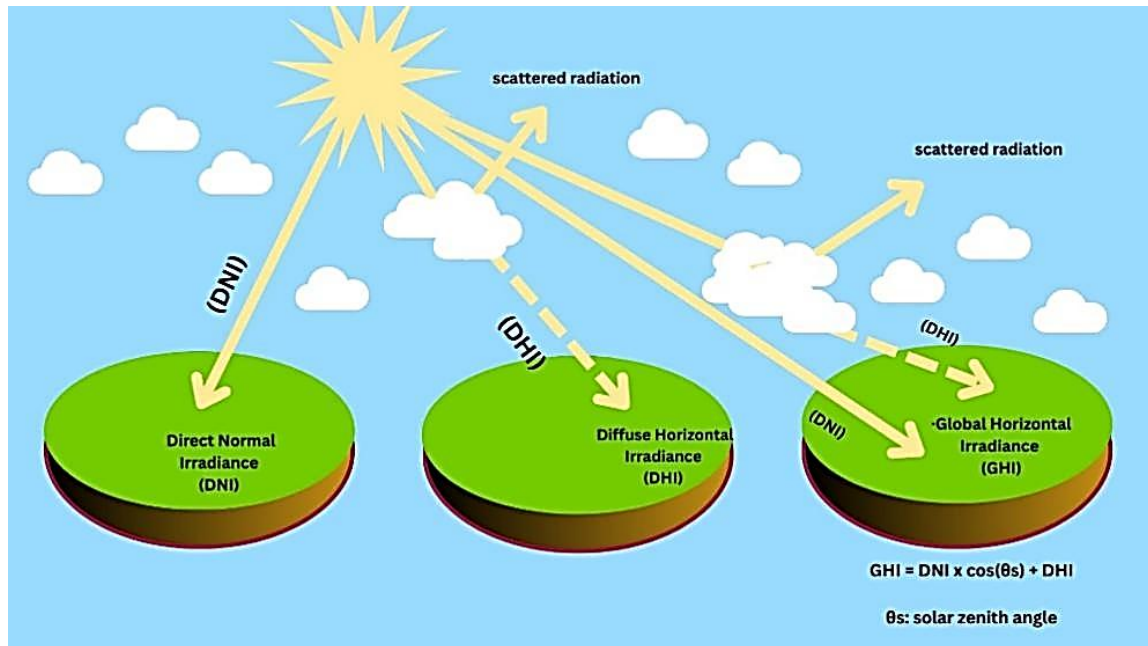


Figure 10: Components of solar irradiance: DNI, DHI, & GHI (Suncom Energy, 2024)

3.2.3 Solar resource in Algeria:

Algeria has a high solar energy potential due to its geographical location within the global Sun Belt region. The country benefits from high solar irradiation levels throughout the year, particularly in the southern desert areas where sky conditions are generally clear and cloud cover is minimal. The assessment of solar resources based on long-term climatological data exceeding 20 years, ensuring reliable and representative results. (World Bank Group, 1994-2018) .

Table 3: Daily & annual solar irradiation statistics in Algeria (World Bank Group, 1994-2018)

		DNI (kWh/m ²)	GHI (kWh/m ²)	DHI (kWh/m ²)
Daily statistics	Average value	5.87	5.92	2.11
	Max value	6.97	6.51	2.52
	Min value	4.41	4.64	1.77
Yearly statistics	Average value	2142.55	2160.8	770.15
	Max value	2544.05	2376.15	919.8
	Min value	1609.65	1693.6	646.05

The statistical analysis of solar radiation components global horizontal irradiance GHI, direct normal irradiance DNI, and diffuse horizontal irradiance DHI shows that Algeria receives significant solar energy. The average daily GHI reaches approximately 5.92 kWh/m², while DNI values remain close, indicating a strong contribution of direct solar radiation. In contrast, DHI values are relatively low, reflecting the predominance of clear sky conditions and limited atmospheric scattering.

On an annual basis, GHI exceeds 2160 kWh/m², confirming the high solar potential of the region. Similarly, DNI values can reach up to 2544 kWh/m², which is particularly favorable for technologies that rely on direct radiation; this encourages thinking about green energy projects such as solar-driven hydrogen production.

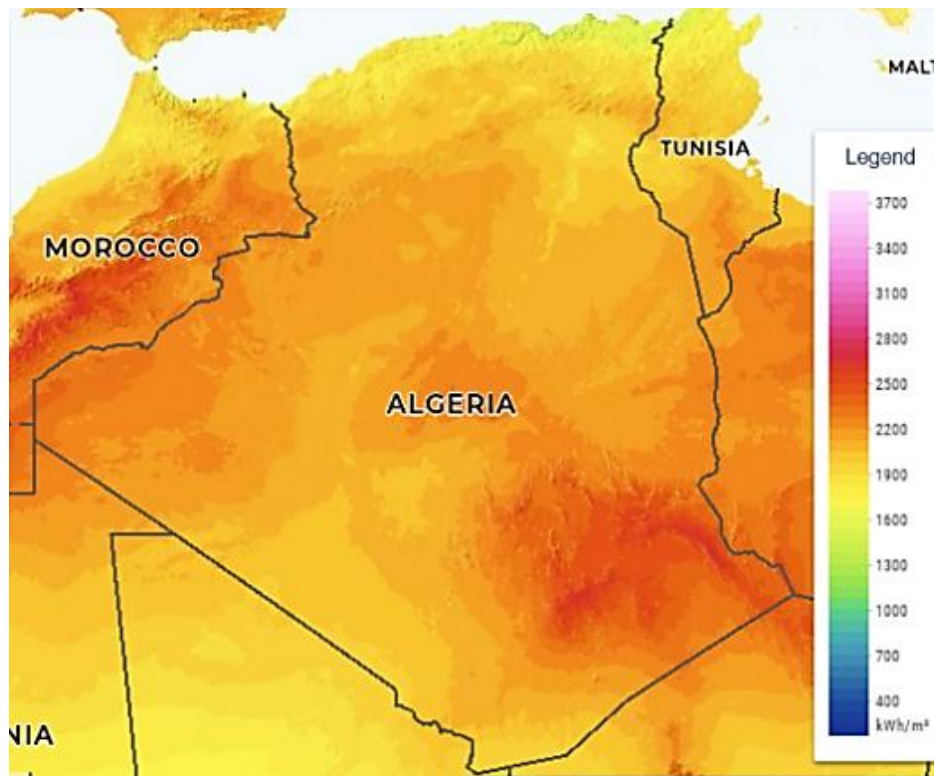


Figure 11: Spatial distribution of direct normal irradiance DNI in Algeria ($\text{kWh}/\text{m}^2/\text{year}$)
(World Bank Group, 2026)

The spatial distribution of solar radiation across Algeria shows significant regional variation. The highest DNI values, exceeding $2500 \text{ kWh}/\text{m}^2/\text{year}$, are observed in the southeastern regions. These values gradually decrease toward the central and western parts of the country but remain above $2000 \text{ kWh}/\text{m}^2/\text{year}$ in most areas. Lower values are recorded along the northern coastal regions, where irradiation can drop to approximately $1300 \text{ kWh}/\text{m}^2/\text{year}$ due to increased atmospheric humidity and cloud presence.

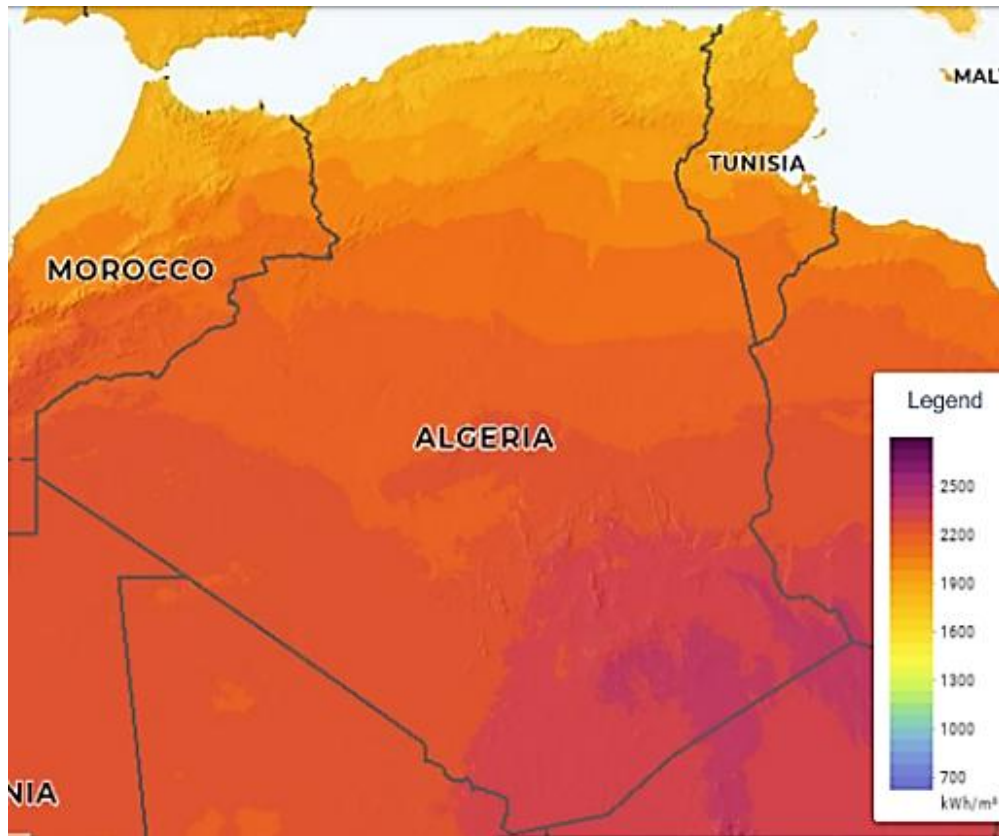


Figure 12: Spatial distribution of global horizontal irradiance GHI in Algeria (kWh/m²/year) (World Bank Group, 2026)

A similar trend is observed for GHI, with maximum values in the southern regions and a gradual decrease toward the north. This distribution highlights the strong potential of Algeria for large-scale solar energy projects.

3.2.4 Solar energy technologies:

Solar energy cannot be directly utilized in its natural form as a continuous energy source. Therefore, it must be converted into usable forms through advanced technologies. The most widely used solar energy technologies are concentrated solar power CSP systems and photovoltaic PV systems.

3.2.4.1 Concentrated solar power CSP:

Concentrated solar power systems generate electricity by converting solar energy into thermal energy. These systems use reflective mirrors to concentrate sunlight onto a receiver, where a heat transfer fluid is heated to high temperatures, typically between 400°C and 1000°C.

The generated heat is then used to produce steam, which drives a turbine connected to an electrical generator, similar to conventional power plants.

One of the key advantages of CSP systems is the possibility of thermal energy storage, often using molten salts, allowing electricity generation even in the absence of sunlight. However, CSP systems are generally more expensive compared to photovoltaic systems. (Silva, Arachchige, U, Kumaragamage, C, & Perera, V, 2024).

3.2.4.2 Solar photovoltaic PV:

Photovoltaic systems convert solar radiation directly into electricity. PV system is composed of modules, which consist of multiple solar cells. The PV cell is the fundamental unit responsible for converting solar radiation into electrical energy. It operates based on semiconductor materials, most commonly crystalline silicon. A single solar cell typically produces a small amount of electrical power, usually in the range of a few watts depending on its size and technology.

To generate practical levels of electricity, multiple cells are electrically connected to form a photovoltaic module. Several modules can then be combined to form an array, which represents the complete power-generating unit in photovoltaic systems. The total electricity output depends on the number of cells and modules used. (Ahmed, et al., 2025).



Figure 13: Solar power plants concentrating solar CSP & Photovoltaic PV

(Tech, ARS Glass, 2022)

3.3 Photovoltaic energy

Photovoltaic energy is based on the direct conversion of sunlight into electricity. This process is carried out by the photovoltaic cell, which converts solar radiation into electrical energy. The electrical performance of the cell is characterized by the relationship between current I and voltage V , typically represented by the I - V curve.

3.3.1 PV cell:

The solar cell is the fundamental unit responsible for energy conversion.

Most solar cells are made of silicon and are based on a p-n junction structure formed by two layers of semiconductor material. The n-type layer is doped with phosphorus and contains an excess of electrons, while the p-type layer is doped with boron and contains holes. At the interface between these layers, an internal electric field is created.

When sunlight, composed of photons, strikes the surface of the solar cell, it transfers its energy to the electrons. If the energy is sufficient, electrons are released from their atomic bonds. Under the effect of the built-in electric field, electrons move toward the n-type layer, while holes move toward the p-type layer. When an external circuit is connected, this movement generates an electric current.

The electricity produced is in the form of direct current DC, and its volume depends on the intensity of solar radiation. (Silva, Arachchige, U, Kumaragamage, C, & Perera, V, 2024)

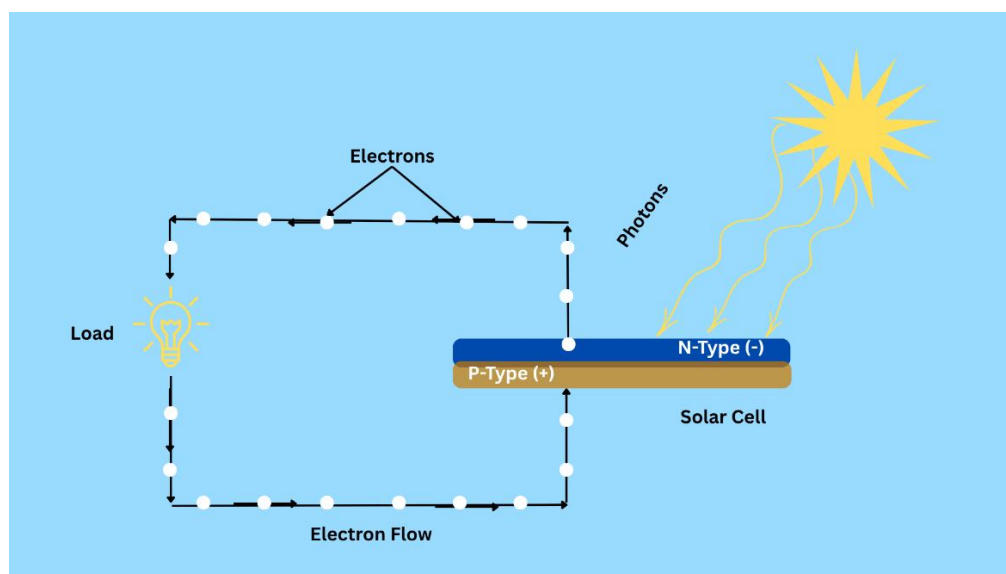


Figure 14: Generation of electricity from a PV cell (Kosol, VanGeet, & Stoltenberg, 2016)

3.3.2 PV cell efficiency:

The efficiency of a photovoltaic PV cell is commonly analyzed using the current–voltage [I–V)] characteristic curve, which represents the relationship between the output current and voltage under given environmental conditions. This curve defines the possible operating points of the cell and determines its electrical power output.

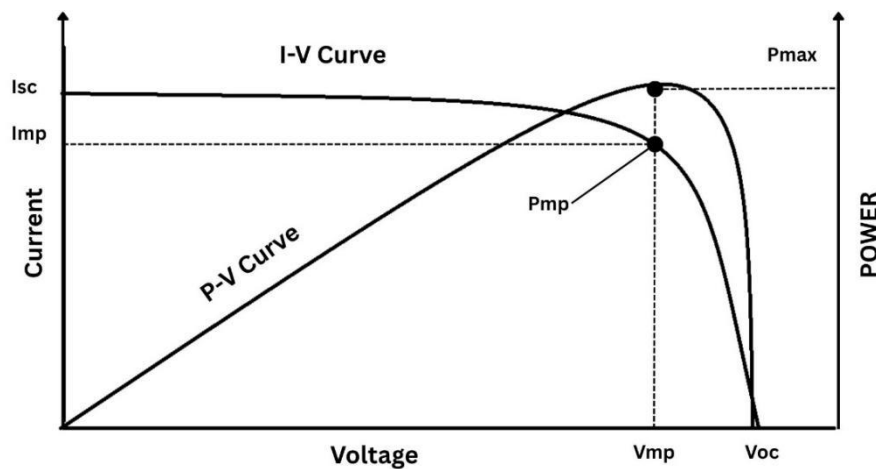


Figure 15: The current–voltage I–V characteristic curve (Tutorials, Alternative Energy, n.d)

A photovoltaic cell behaves as a non-linear device whose operating point depends on the external load connected to it. The intersection between the I–V curve of the cell and the load line determines the actual operating point. Two key parameters define the limits of the curve: the short-circuit current I_{sc} , corresponding to maximum current at zero voltage, and the open-circuit voltage V_{oc} , corresponding to maximum voltage at zero current.

The maximum power point MPPT represents the optimal operating condition at which the product of current and voltage is maximized. Operating away from this point results in reduced power output, highlighting the importance of proper system design and the use of power electronic devices such as maximum power point tracking MPPT.

The quality of the I–V curve is evaluated using the fill factor FF, which is defined as the ratio between the maximum power delivered by the cell and the theoretical maximum power given by the product of V_{oc} and I_{sc} :

$$FF = V_{mp} \times \frac{I_{mp}}{(V_{oc} \times I_{sc})} \quad (23)$$

A higher fill factor indicates a more square-shaped I–V curve, reflecting lower internal losses and better performance. In practice, high-quality silicon solar cells typically exhibit FF values in the range of 0.75 to 0.80, while the ideal value of 1 is not physically attainable.

The overall efficiency of a photovoltaic cell depends on the combined effect of V_{oc} , I_{sc} , and FF, which together determine the maximum electrical power that can be extracted from the incident solar energy. (Tutorials, Alternative Energy, n.d).

The following table presents the classification of photovoltaic technologies according to their efficiency and materials:

Table 4: Solar cell generations & efficiency (Mdallal, et al., 2025)

PV Generation	Materials Used	Efficiency %
1st Generation	Crystalline Silicon	27.6% (Laboratory value)
	- Monocrystalline silicon (Mono-Si) - polycrystalline silicon (Poly-Si)	26.1% (Mono-Si) 23.3% (Poly-Si)
2nd Generation	Thin-film multi-junction	
	- Cadmium Telluride (CdTe) - Copper Indium Gallium Selenide (CIGS) - Amorphous Silicon	23.1% (Cdte) 23.6% (CIGS)

	(a-Si)	14% (a-Si)
3rd Generation	• Dye-sensitized solar cell (DSSC) • Organic solar cells (OSC) • Perovskite Solar Cells	15.2% (DSSC) 19.2% (OSC) 26.7% (Perovskite)
Advanced Generation	Tandem Cells • Perovskite/Si • III-V/Si • Four-junction	34.6% 36.1% 47.6%

Photovoltaic cells are generally classified into three generations according to the evolution of materials and manufacturing technologies. First-generation cells, based on crystalline silicon, dominate the global market due to their high reliability and long-term stability, accounting for nearly 90% of installed capacity. Second- and third-generation technologies aim to reduce material consumption and improve efficiency, although they are still developing in terms of large-scale deployment.

One of the most promising approaches to improving efficiency is the use of tandem solar cells. These cells combine multiple semiconductor layers with different bandgaps to capture a broader range of the solar spectrum. This configuration allows them to surpass the theoretical efficiency limit of single-junction cells, known as the Shockley–Queisser limit approximately 33.7%, by enabling better utilization of both high- and low-energy photons. (Mdallal, et al., 2025).

3.4 Photovoltaic systems

In order to convert solar radiation into usable electrical energy, photovoltaic systems rely on a set of interconnected components that manage energy generation,

conversion, and distribution. The proper design, installation, and control of these components are essential to ensure efficient and reliable operation.

3.4.1 PV system components:

Photovoltaic PV systems consist of several essential components that ensure the efficient conversion of solar energy into usable electrical power, as well as its regulation, storage, and safe operation.

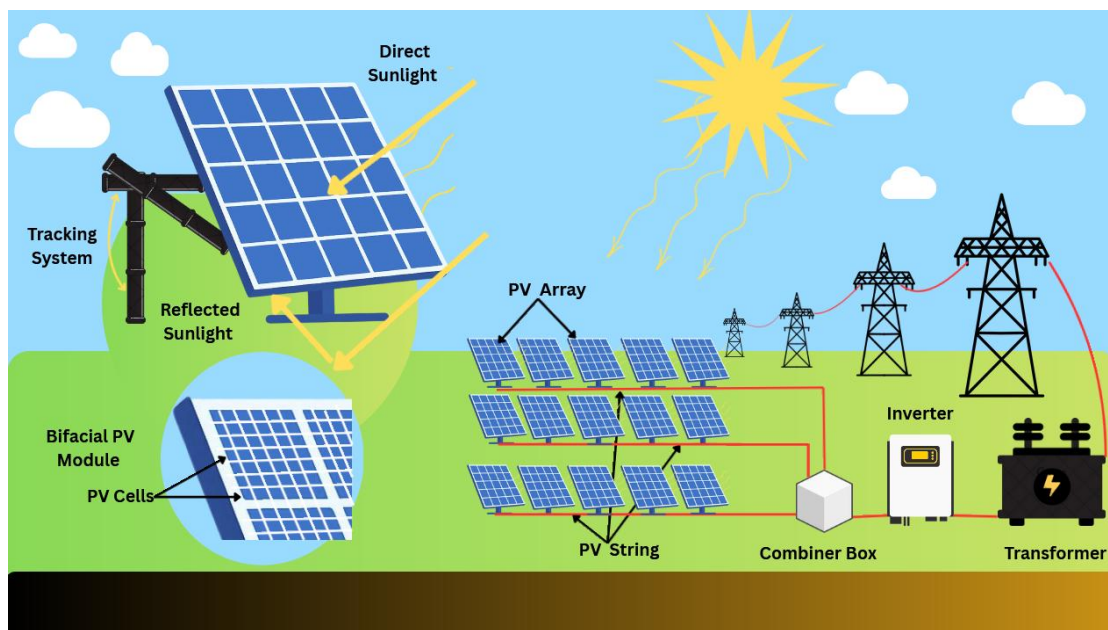


Figure 16: Structure of a photovoltaic system (Kosol, VanGeet, & Stoltenberg, 2016; Anern, n.d)

3.4.1.1 Photovoltaic modules:

Photovoltaic modules are the primary energy conversion units in a PV system. They are composed of multiple solar cells connected in series and encapsulated within a protective structure, typically consisting of tempered glass and an aluminum frame. These modules generate direct current DC electricity when exposed to solar radiation.

Advanced technologies such as bifacial modules can capture solar radiation from both the front and rear sides, increasing energy yield. In addition, solar tracking systems can dynamically adjust panel orientation to maximize incident solar radiation.

Modules can be interconnected to form arrays. Series connections increase voltage, while

parallel connections increase current. Over time, module performance may degrade due to environmental factors such as temperature, humidity, and corrosion. (Franklin, 2018; Mdallal, et al., 2025).

3.4.1.2 Combiner box:

The combiner box serves as a central point where multiple PV strings are electrically combined. It simplifies wiring and improves system organization by merging several parallel connections into a single output.

3.4.1.3 Inverter:

The inverter is a key component that converts the direct current DC produced by PV modules into alternating current AC, which is compatible with most electrical loads and grid systems. Modern inverters often integrate maximum power point tracking MPPT to optimize energy extraction from the PV array under varying environmental conditions. (Franklin, 2018).

3.4.1.4 Energy storage system:

Energy storage systems, typically based on lithium-ion or lead-acid batteries, allow excess energy generated during the day to be stored for later use. These systems enhance reliability and energy autonomy, particularly in standalone applications.

A charge controller is used to regulate the charging and discharging processes, preventing overcharging and deep discharge, thereby extending battery life. (Daze, 2025)

3.4.1.5 Protection & safety devices:

PV systems must include protection devices to ensure safe and reliable operation. These include circuit breakers for overload and short-circuit protection, residual current devices RCD for detecting leakage currents, and surge protection devices to guard against lightning and voltage spikes. Disconnect switches are also essential for maintenance and system isolation. (Daze, 2025).

3.4.2 Installation & control of PV systems:

The installation and control of photovoltaic PV systems are critical for ensuring optimal performance and long-term reliability. Proper system design requires careful evaluation of site conditions, structural constraints, and solar resource availability.

3.4.2.1 Installation & site considerations:

PV systems can be installed on rooftops, ground-mounted structures, or parking areas.

- Roof installations require assessment of structural integrity and load-bearing capacity, as PV systems typically impose additional loads of approximately 15–20 kg/m².
- Ground-mounted systems offer greater flexibility and can be designed as fixed or tracking systems. The required land area depends on the technology used; crystalline silicon systems typically require 18–32 m²/kW, while thin-film technologies require larger area due to lower efficiency.
- The orientation and tilt angle of PV modules significantly affect energy production. In the northern hemisphere, optimal orientation is generally south-facing, with a tilt angle close to the site latitude.
- Shading analysis is also essential, as even partial shading can significantly reduce system output. Ideally, the installation site should achieve solar exposure above 90%

3.4.2.2 Control & optimization:

Efficient operation of PV systems relies on advanced control strategies.

- MPPT is widely used to ensure that the PV system operates at its optimal point on the current–voltage I–V curve, thereby maximizing power output under varying environmental conditions.
- Solar tracking systems can be employed to increase energy production by adjusting panel orientation throughout the day. Single-axis trackers can increase energy yield by approximately 20–25%, while dual-axis systems can

achieve higher gains at increased cost and maintenance requirements.

- Monitoring systems are also essential for performance evaluation. These range from basic inverter displays to advanced systems that measure solar irradiance and module temperature, allowing comparison between expected and actual energy production. (Kosol, VanGeet, & Stoltenberg, 2016).

3.4.2 Performance & efficiency of PV systems:

The performance of a photovoltaic system is commonly evaluated based on its efficiency and energy output under real operating conditions. The efficiency of a PV cell is defined as the ratio between the electrical power generated at the maximum power point P_{mpp} and the incident solar power:

$$\eta = \frac{P_{mpp}}{G \times A} \quad (24)$$

Where G is the incident solar irradiance W/m^2 and A is the surface area of the module.

In practice, PV performance is influenced by several factors, including solar irradiance, temperature, and system losses. Higher temperatures generally reduce the voltage of PV modules, leading to decreased efficiency. Additional losses may occur due to shading, dust accumulation, wiring resistance, and inverter conversion.

To better evaluate system behavior under varying conditions, the concept of relative efficiency can be used to compare performance at different irradiance levels relative to standard test conditions. ($1000 W/m^2$). (SA, PVSyst, n.d).

Overall, the efficiency of a PV system depends not only on the performance of individual components but also on the effectiveness of system design, installation quality, and operational control. Performance indicators such as energy yield and system efficiency are widely used to assess system effectiveness.

3.5 Conclusion

Solar energy represents a highly abundant and sustainable energy source. The efficiency of its utilization depends on the proper design and control of photovoltaic

systems. However, its intermittent nature poses challenges for continuous energy supply.

To address this limitation, energy storage becomes essential, with hydrogen emerging as a promising solution. By using electricity generated from solar systems to power electrolysis, energy can be stored in chemical form and used when needed.

Therefore, the integration of solar energy with hydrogen production offers an effective pathway toward clean, reliable, and long-term energy sustainability

Chapter four: Case study & system modeling

Chapter four: Case study & system modeling

4.1 Introduction

This chapter presents the overall framework of the proposed green hydrogen production system and introduces the study site, system configuration, and research methodology adopted in this work. The study investigates the feasibility of producing green hydrogen using solar energy in Khenchela, a region characterized by high solar irradiation potential, which makes it a promising location for renewable hydrogen production.

The main research problem addressed in this study is whether hydrogen can be produced efficiently and sustainably under the climatic conditions of the region using a standalone photovoltaic-based system. Therefore, the study aims to evaluate the technical, economic, and environmental feasibility of a green hydrogen production system.

The proposed system consists of a grid-independent photovoltaic PV plant directly coupled with a proton exchange membrane PEM electrolyzer, in addition to hydrogen compression and storage units. The system operates using real hourly solar data extracted from the System Advisor Model SAM, while hydrogen production and system performance are simulated using a Python-based model over a 25-year project lifetime.

The adopted methodology is based on the simulation of a PV–electrolyzer system to assess energy production, hydrogen yield, environmental benefits, and economic viability. Key indicators such as hydrogen production, energy losses, carbon emission reduction, net present value NPV, and levelized cost of hydrogen LCOH are used to evaluate the overall feasibility of the proposed system.

4.2 Description of the study area

Khenchela is located in northeastern Algeria between latitudes 34.5 N° and 7.14°E longitude at an elevation of around 1200 m above sea level. Indicators such as hydrogen production, energy losses were evaluated the system. the region characterized by

predominantly rocky and calcareous soils in the mountainous zones, with steppe and grassland areas across the surrounding plateaus. The northern part includes forested areas, giving the region a mainly semi-arid climate. In addition, the regional albedo is estimated to range between 0.20 and 0.25. (Maroua & Mariama ,2022 ;Global Solar Atlas, 2026).

Table 5: Summary of meteorological data & solar irradiance components for Khenchela. (Global Solar Atlas, 2026)

	Maximum	Minimum	Average
Direct Normal Irradiance DNI (KWh/m²)	5.77	5.11	5.40
Global Horizontal Irradiance GHI (KWh/m²)	5.34	4.92	5.21
Diffuse Horizontal Irradiance DHI (KWh/m²)	2.05	1.77	1.90
Air Temperature °C	22.3	12.8	18.2

The table presents the maximum, minimum, and average values of solar irradiation and ambient temperature in the Khenchela region over a 20-year period. The average GHI value of 5.21 kWh/m²/day indicates strong solar potential for photovoltaic power generation. Moreover, the high DNI and relatively low DHI values reflect clear-sky conditions favorable for efficient solar energy exploitation. The average ambient temperature of 18.2 °C also supports stable photovoltaic system performance with limited efficiency losses. (Global Solar Atlas, 2026)).

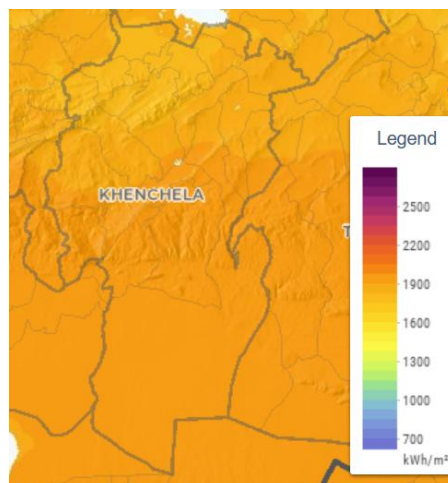


Figure 17: Khenchela global horizontal irradiance (GHI) map

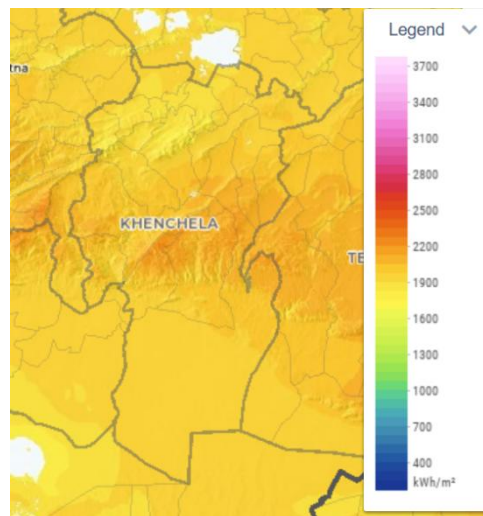


Figure 18: Khenchela direct normal irradiance (DNI) map

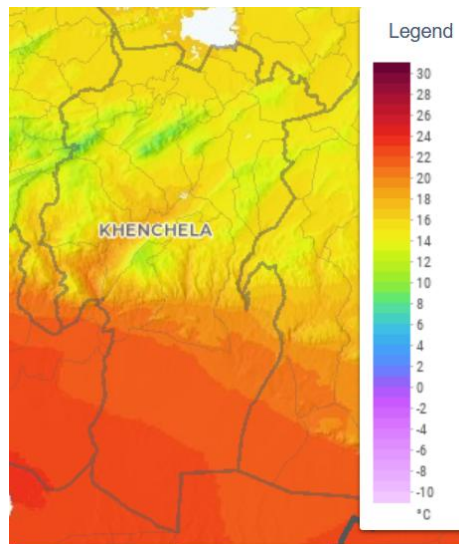


Figure 19: Khenchela air temperature °C map

The DNI map shows annual values ranging from 1900 to 2200 kWh/m², indicating high direct solar potential and predominantly clear-sky conditions favorable for renewable energy projects. The GHI map presents a relatively uniform distribution across the region, confirming the suitability and competitiveness of the selected location for solar energy exploitation. The temperature map indicates moderate annual average temperatures, ranging from 14–18 °C in the north and 20–26 °C in the south, which remain within acceptable operating conditions for photovoltaic systems and support stable performance. (Global Solar Atlas, 2026)).

These data is used for geographical characterization and not for simulation inputs.

4.3 System description

This section presents the overall configuration of the proposed green hydrogen production system, which is based on the direct coupling of a utility-scale photovoltaic PV power plant with a Proton Exchange Membrane PEM electrolyzer. The system converts solar irradiance into hydrogen through water electrolysis via a fully renewable pathway. Crucially, no battery storage and no grid connection are incorporated; consequently, all system components, the electrolyzer and the compression unit, operate exclusively on instantaneous solar-generated electricity. During nighttime hours or periods of insufficient solar irradiance, PV generation drops to zero and both the electrolyzer and the compressor cease operation entirely.

4.3.1 Photovoltaic PV system:

The photovoltaic system constitutes the sole primary energy source of the proposed configuration. A utility-scale PV plant with a nominal installed capacity of 20,005.186 kW is considered in this study. The generated electrical energy is supplied to the electrolyzer through a power conditioning unit that ensures stable and efficient operation under variable solar irradiance conditions.

The PV system performance depends mainly on solar irradiance, ambient temperature, tracking configuration, and system losses. A mono-crystalline silicon bifacial PV technology was selected on account of its high conversion efficiency and demonstrated suitability for large-scale ground-mounted applications.

Annual PV degradation at a rate of 0.7%/year is embedded directly in the SAM-generated hourly output time series, so that the exported dataset of 219,000 hourly records (25 years $\times$ 8,760 h/year) inherently reflects the progressive decline in energy yield over the project lifetime.

To maximize energy extraction from the PV array, a maximum power point tracking MPPT mechanism is assumed. The power conditioning unit is modeled with an overall DC-to-AC conversion efficiency of 97.53%, consistent with the SAM simulation configuration. In addition, total DC and AC losses were considered in the simulation to account for wiring, mismatch, availability, and operational losses.

Since the electrolyzer stack operates on direct current DC, the inverter is conceptually treated as a DC–DC power conditioning and MPPT unit with comparable efficiency and cost characteristics.

The technical specifications of the photovoltaic modules and the power conditioning unit were obtained from the SAM software database.

The main technical characteristics of the PV system are summarized as follows:

- PV technology: Mono-crystalline silicon (Mono-c-Si)
- Module efficiency: 20.16%
- Module peak power: 664.845 W
- Installed capacity: 20,005.186 kW
- Nominal Operating Cell Temperature (NOCT): 45.4°C
- Degradation rate: 0.7%/year
- Tracking system: Single-axis tracking
- Tracker rotation limit: 45°
- Ground coverage ratio (GCR): 0.3
- Bifacial mode: Enabled
- Annual albedo: 0.234
- Total estimated area: 30.09 hectares

The system was designed without battery storage and without grid support in order to evaluate the standalone performance of the PV-powered hydrogen production system under intermittent solar conditions.

For the economic data, real costs were considered in this study in order to evaluate the potential competitiveness of green hydrogen production. (National Renewable Energy Laboratory (NREL), 2024).

- CAPEX: 31,172,083.88\$
- Fixed O&M: 440114.4\$

In this study, the excess photovoltaic electricity remaining after supplying the electrolyzer and compression system is considered curtailed energy and is excluded from the economic analysis.

4.3.2 Electrolyser system:

The hydrogen production unit is based on a Proton Exchange Membrane PEM electrolyzer powered directly by the photovoltaic system. PEM technology was selected due to its high efficiency, rapid dynamic response, and suitability for renewable energy applications characterized by intermittent operation.

The electrolyzer converts electrical energy and purified water into hydrogen through the electrolysis process. In this study, the electrolyzer operates without grid support or battery storage, meaning that its operation depends entirely on the availability of solar energy generated by the PV system.

A nominal electrolyzer capacity of 10,000 kW lower than the PV plant capacity of 20,005 kW was intentionally sized in order to reduce investment costs while improving the utilization of the generated solar energy under partial-load conditions and to limit curtailment losses.

The main technical and economic assumptions adopted for the electrolyzer system are summarized below:

- Electrolyzer technology: Proton Exchange Membrane (PEM)
- Nominal electrolyzer capacity: 10,000 kW
- Specific energy consumption (SEC): 55.3 kWh/kg H₂
- Operating pressure: 30 bar
- Stack lifetime: 50,000 h
- Operating temperature: 80°C

The operation of the electrolyzer follows the intermittency of solar energy production. Therefore, hydrogen production varies according to the hourly availability of solar power.

During periods of insufficient solar irradiance, including nighttime hours, the electrolyzer receives zero power input and hydrogen production ceases.

In this study, hydrogen is considered the main useful product, while oxygen generated during electrolysis is treated as a secondary by-product and is not included in the economic analysis

The electrolyzer is assumed to be replaced with a next-generation unit based on future technological projections, to evaluate the impact of technological progress on the LCOH. Recent international scenarios for PEM electrolyzers suggest notable efficiency gains and significant reductions in capital costs are expected between 2030 and 2050.

Table 6: The current and expected economic and technical assumptions. (Alex Badgett, et al., 2024) (IRENA, 2020)

Parameter	Current Scenario (2026)	Future Scenario (2030–2036)
CAPEX	1,300–1,700 USD/kW	200–500 USD/kW
SEC	50–83 kWh/kg H ₂	<45 kWh/kg H ₂
Stack life time	50,000 –80,000 h	100,000–120,000 h
Operating pressure	30 bar	>70 bar

4.3.3 Compressor & storage system:

The compressor and storage system is responsible for conditioning and storing the hydrogen produced by the electrolyzer. After the electrolysis process, hydrogen is delivered at a moderate pressure and must be compressed before storage in high-pressure tanks for later utilization, transportation, or commercialization.

In the proposed configuration, the compression system is powered directly by the photovoltaic system in order to maintain a fully renewable hydrogen production pathway. In addition, the compression system is powered exclusively by surplus PV electricity defined as PV generation exceeding the electrolyzer rated capacity of 10,000 kW. The compressor therefore operates only during hours in which solar irradiance is sufficient to

simultaneously saturate the electrolyzer and provide additional power for compression. During nighttime or low-irradiance periods, no compression takes place.

An intermediate buffer tank is conceptually assumed between the electrolyzer outlet and the compressor inlet to allow operational decoupling between hydrogen production and compression. Hydrogen produced by the electrolyzer accumulates in this buffer and is compressed whenever surplus PV power is available.

Compressor energy consumption was modeled using a constant specific compression energy demand of 1.2 kWh/kg H₂. the model does not explicitly account for variations in electrolyzer outlet pressure or compression stages. The hydrogen is subsequently compressed to a storage pressure of 350 bar using a high-efficiency compression system. The compressor efficiency is assumed to be approximately 92%.

The compressed hydrogen is stored in pressurized tanks designed for medium-pressure hydrogen applications. In this study, hydrogen storage is considered as an intermediate stage intended to stabilize production fluctuations and facilitate system operation.

The model does not explicitly simulate dynamic hydrogen storage behavior, buffer tank inventory evolution, or compressor dispatch control. Instead, compressor energy consumption is represented using a constant specific compression energy demand applied to the hourly hydrogen production rate.

The buffer tank is represented conceptually to justify operational flexibility between hydrogen production and compression; however, transient storage dynamics are outside the scope of the present study.

The main technical and economic assumptions adopted for the compressor and storage system are summarized as follows:

- Storage pressure: 350 bar
- Compressor efficiency: 92%
- Compressor electricity consumption (SEC_{comp}): 1.2 kWh/kg H₂
- Compressor lifetime: 90,000 h

Economic parameters:

- CAPEX (compressor) = 800000\$
- CAPEX (storage) = 825000\$

- CAPEX (compressor + storage)system=1625000 \$
- O&M(compressor+storage)system=4%CAPEX(compressor+storage)system \$

For the current compressor and storage systems, the capital cost is estimated at approximately 1.625 M\$. These components are expected to experience lower future capital costs. Compressor replacement within the system's operational lifetime is also considered, assuming progressive reductions in equipment costs and improvements in compression efficiency due to technological advancements expected by 2030. (Serag, Adil Echchelh, & Biagio Morrone, 2024).

4.3.4 System coupling & operation strategy:

The proposed system is configured as a direct coupled photovoltaic-to-hydrogen PV-H₂ system, where the PV plant supplies electricity directly to the electrolyzer and the compression unit, without connection to the electrical grid and without any form of electrical energy storage.

This direct coupling approach ensures a simplified system architecture and reduces conversion losses associated with multiple energy transformation stages. However, it introduces operational variability due to the intermittent nature of solar energy.

The coupling strategy defines how energy flows between the different components of the system, namely the PV generator, the power conditioning unit, the electrolyzer, and the hydrogen compression and storage system.

The energy flow logic is organized as follows:

- The PV system generates AC electricity depending on solar irradiance and ambient conditions. This output is passed through a power conditioning unit before being allocated to system loads.
- The electrolyzer receives power up to its rated capacity of 10,000 kW. If available PV generation is below this threshold, the electrolyzer operates at partial load; if PV generation exceeds this threshold, the electrolyzer is saturated and the surplus is directed to the compressor.

- The compressor operates exclusively on surplus PV power above 10,000 kW and compresses hydrogen that has accumulated in the intermediate buffer tank. No compression occurs in the absence of surplus solar generation.
- The produced hydrogen is subsequently compressed and stored in high-pressure tanks for later use or commercialization.
- Any PV electricity not consumed by either the electrolyzer or the compressor is classified as curtailment and is excluded from the economic analysis.

The overall energy flow can be summarized as follows:

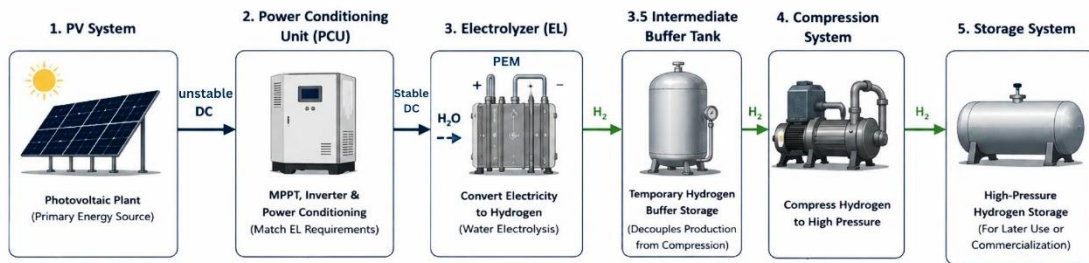


Figure 20:PV-Hydrogen direct coupled system architecture

Since the system is designed without electrical grid connection or battery storage, a mismatch may occur between PV generation and electrolyzer capacity.

When PV power exceeds the electrolyzer capacity, the excess PV electricity remaining after satisfying electrolyzer and compression demand is considered curtailed energy, this phenomenon is inherent to direct-coupled systems and represents a trade-off between system simplicity and energy utilization efficiency.

Although the storage system does not eliminate production intermittency, it provides temporal decoupling between production and demand, making the system more suitable for practical applications.

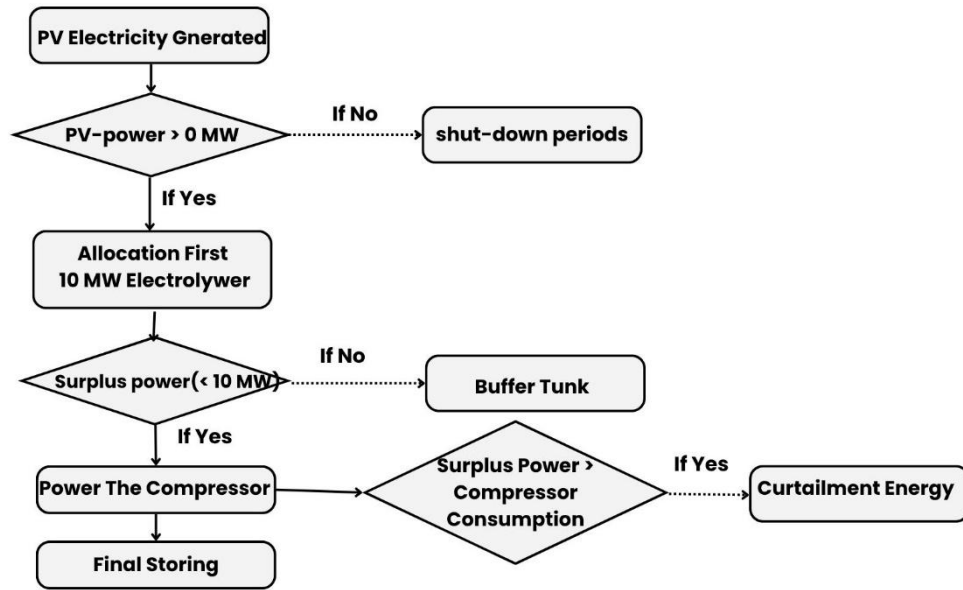


Figure 21: Operation Strategy & Energy Flow

4.4 Methodology

This study develops a comprehensive techno-economic and environmental model for a grid-independent green hydrogen production system based on photovoltaic PV energy and PEM electrolysis. The system is designed for the case study of Khenchela, Algeria, and integrates hourly solar production data to simulate hydrogen production, energy flows, degradation effects, component replacement, and financial performance over a 25-year project lifetime.

The modeling framework is implemented in SAM and Python and is structured into: data preprocessing, energy system simulation, environmental assessment, and economic evaluation

This section presents the methodology adopted in this study, including the simulation approach, the software tools used, and the main assumptions considered for the techno-economic assessment of the proposed green hydrogen system.

4.4.1 Simulation approach:

The methodology is based on a sequential hourly simulation approach that couples photovoltaic power generation with hydrogen production modeling.

First, hourly PV electricity generation is obtained from SAM and used as the primary energy input to the hydrogen system. This electricity is then allocated to the electrolyzer first, which converts electrical energy into hydrogen according to its SEC. The compressor is then supplied with any surplus PV power remaining above the electrolyzer saturation point; any further surplus is treated as curtailment.

Hydrogen production is computed at each hourly timestep while enforcing system constraints, including the rated electrolyzer capacity of 10,000 kW and instantaneous energy availability. Because no battery storage is present, the model does not carry over unused electrical energy between timesteps. The simulation further incorporates time-dependent operational behavior, including independent cumulative operating hour tracking for the electrolyzer and compressor, stack efficiency improvement following electrolyzer replacement, and component lifetime thresholds that trigger replacement events.

4.4.2 Software tools:

The photovoltaic energy production data used in this study were obtained using the System Advisor Model SAM, developed by the National Renewable Energy Laboratory NREL in collaboration with Sandia National Laboratories, with funding from the U.S. Department of Energy. SAM is widely used for simulating the technical and economic performance of renewable energy systems based on site-specific meteorological and technical inputs. (National Renewable Energy Laboratory, NREL, 2025).

In this work, SAM was used to generate hourly PV electricity output for the selected location Khenchela. The resulting data were exported and further processed using Python to develop a customized hydrogen production model, compression, component replacement, and system economics.

The results were exported to Excel files to facilitate further analysis and reporting.

4.4.3 Calculation methodology:

The simulation was conducted in two sequential stages, as described below.

4.4.3.1 Simulation framework:

- **Stage one: Photovoltaic system modeling SAM**

In the first stage, the System Advisor Model SAM was used to simulate the photovoltaic PV system. Geographic coordinates of the study area were defined and meteorological data were imported. The project lifetime, system losses, and degradation rate were specified.

The PV system was designed using single-axis tracking with mono-crystalline silicon bifacial modules and a power conditioning unit operating at 97.53% efficiency. and MPPT.

The simulation produced 219,000 hourly AC power output records covering the full 25-year lifetime, which were exported for use as the primary input to the hydrogen system model.

- **Stage two: Hydrogen system simulation Python model**

The hourly PV output obtained from SAM was processed using a Python-based simulation model to represent the hydrogen production system. Further details on the simulation code are provided in the appendix, where relevant code snippets are included.

The hourly PV output is allocated to the electrolyzer up to its rated capacity of 10,000 kW. Any PV generation exceeding this limit is directed to the compressor; any remaining surplus constitutes curtailment. Because the system contains no electrical storage, unused PV energy cannot be carried forward to subsequent timesteps.

The PV electricity is first supplied to the electrolyzer, which converts electrical energy into hydrogen based on its SEC, Hydrogen production at each hour is calculated as:

$$H_2 = \frac{E_{el}}{SEC} \quad (25)$$

Where E_{el} is the electrical energy supplied to the electrolyzer (kWh) and SEC is the specific energy consumption (kWh/kg H_2).

The compressor energy demand is calculated as:

$$E_{comp} = H_2 \times SEC_{comp} \quad (26)$$

Where $SEC_{comp} = 1.2$ kWh/kg H_2 . The compressor operates only when PV surplus above the electrolyzer saturation threshold is available and when hydrogen has accumulated in the buffer tank.

The electrolyzer capacity factor quantifies the fraction of maximum theoretical annual energy input that is actually delivered to the electrolyzer. It is defined as:

$$CF_{el} = \frac{E_{el} \text{ avg}}{(8760 \times P_{el} \text{ rated})} \quad (27)$$

Where $E_{el} \text{ avg}$ is the average annual electrical energy consumed by the electrolyzer (kWh/year), computed over the 25-year simulation period; $P_{el} \text{ rated} = 10,000 \text{ kW}$ is the rated electrolyzer capacity; and 8,760 is the number of hours per year. A capacity factor well below unity is expected, reflecting both the intermittent solar resource and the absence of any electrical storage that could extend electrolyzer operation beyond daylight hours.

The overall system efficiency, referred to as the Solar-to-Hydrogen STH efficiency, characterizes the fraction of total solar-generated AC electricity delivered by the PV plant that is ultimately recovered as chemical energy stored in the produced hydrogen, evaluated on a LHV basis:

$$\eta_{\text{system}} = \frac{(H_2 \text{ avg} \times \text{LHV}_{H_2})}{EPV_{\text{avg}}} \times 100\% \quad (28)$$

where $H_2 \text{ avg}$ is the average annual hydrogen production (kg/year), $\text{LHV}_{H_2} = 33.33 \text{ kWh/kg}$ is the lower heating value of hydrogen, and EPV_{avg} is the average annual AC electrical energy generated by the PV system kWh/year; both quantities are computed as 25-year means over the full simulation period.

This indicator integrates into a single end-to-end metric all losses occurring along the conversion chain: power conditioning losses, electrolyzer conversion losses, and the curtailment losses inherent to the direct-coupling architecture. It is therefore the most representative measure of overall system performance for a standalone PV-to-hydrogen configuration. Since a fraction of the PV output is curtailed η_{system} is inherently lower than the electrolyzer conversion efficiency alone.

The system energy balance is defined as:

$$\text{Curtailment} = EPV - E_{el} - E_{\text{comp}} \quad (29)$$

The model ensures that system constraints are respected, including electrolyzer capacity limits and hourly energy availability.

The model incorporates dynamic operational behavior by tracking cumulative operating hours of the electrolyzer and compressor.

When the lifetime threshold of a component is reached, replacement is triggered. After replacement, the electrolyzer performance is updated, with a reduction in specific energy

consumption from 55.3 to 45 kWh/kg H₂.

Replacement costs are included in the economic analysis and are assigned to the corresponding year of operation.

4.4.3.2 Economic Modeling:

The project lifetime is assumed 25 years. All economic calculations are performed in real terms, excluding inflation effects.

The real discount rate:

Is derived using the Fisher equation as follows:

- $r_{nominal}$: Nominal discount rate = 10% (Penev, et al., 2024)
- i : Inflation rate = 4.82% (Trading Economics(2026 ,
- r_{real} : Real discount rate $\approx 5\%$

$$r_{real} = \frac{1 + r_{nominal}}{1 + i} - 1 \quad (30)$$

- **Levelized Cost of Hydrogen (LCOH)**

The LCOH is computed using a discounted cash flow approach that accounts for all costs incurred over the project lifetime:

$$LCOH_2 = \frac{\sum \frac{Costs_t}{\left(1 + r_{real}\right)^t}}{\sum \frac{H_{2t}}{\left(1 + r_{real}\right)^t}} \quad (31)$$

Where $Costs_t$ includes CAPEX at $t = 0$, annual OPEX, and replacement costs assigned to the year in which each component reaches its lifetime threshold; and H_{2t} is the annual hydrogen production in year t (kg/year).

- **Total Initial CAPEX:**

The total initial capital expenditure, assigned at year zero, is:

$$\begin{aligned} \text{CAPEX}_{\text{total}} &= \text{CAPEX}_{\text{pv}} + \text{CAPEX}_{\text{el}} + \text{CAPEX}_{\text{comp}} \\ &= 46,167,083.88 \text{ USD} \end{aligned} \quad (32)$$

Comprising 31,172,083.88 USD for the PV system, 13,370,000 USD for the electrolyzer, and 1,625,000 USD for the compressor and storage system.

- **Annual OPEX**

The total annual operating expenditure is:

$$\begin{aligned} \text{OPEX}_{\text{total}} &= \text{OPEX}_{\text{pv}} + \text{OPEX}_{\text{el}} + \text{OPEX}_{\text{comp}} \\ &= 1,173,614.40 \text{ USD/year} \end{aligned} \quad (33)$$

- **Financial Performance Indicators**

Three hydrogen selling price scenarios are evaluated: 4, 6, and 8 USD/kg.

The discounted cash flow DCF approach was used to evaluate the economic performance of the system by converting future costs and revenues into present values using a real discount rate of 5%.

The discounted cash flow for year t was calculated as:

$$\text{DCF}_t = \frac{\text{CF}_t}{(1+r)^t} \quad (34)$$

The following indicators are computed for each scenario:

- **Net Present Value (NPV):**

Where CF_t is the net cash flow at year t and r is the real discount rate

$$\text{NPV} = \sum_{t=0}^n \frac{\text{CF}_t}{(1+r)^t} \quad (35)$$

- **Internal Rate of Return (IRR):**

IRR is the discount rate that makes the NPV equal to zero.

$$0 = \sum_{t=0}^n \frac{\text{CF}_t}{(1+\text{IRR})^t} \quad (36)$$

- **Payback Period:**

The payback period is defined as the year at which the cumulative discounted cash flow becomes positive.

$$\sum \text{CF}_t \geq 0$$

4.4.33 Sensitivity Analysis:

A deterministic one-at-a-time sensitivity analysis is performed to evaluate the influence of key input parameters on the LCOH. Each parameter is independently varied within a predefined range while all others are held at their base values. The parameters examined and their variation ranges are presented in the following Table

Table 7: Parameters & variation ranges for the sensitivity analysis

Parameter	Variation Range	Basis
PV CAPEX	±20% of base value	Capital cost scaling
Electrolyzer CAPEX	±20% of base value	Capital cost scaling
Discount Rate	±20% of base value	Financial assumption
SEC	±15% of base value	Electrolyzer efficiency
Capacity Factor	±15% of base value	H ₂ yield scaling

Results are presented as a tornado chart in which each bar represents the absolute LCOH influence magnitude (difference between the high and low scenarios) for a given parameter, with parameters ranked in descending order of influence.

4.4.3.4 Environmental assessment:

The environmental impact is evaluated in terms of avoided CO₂ emissions, under the assumption that the PV electricity consumed by the system displaces electricity that would otherwise be generated from the Algerian national grid. An emission factor of EF = 0.500 kg CO₂/kWh is adopted. (International Energy Agency, 2025).

The total CO₂ avoided at each hourly time step is computed as:

$$CO_2\text{avoided} = (E_{el} + E_{comp}) \times EF \quad (37)$$

Both the electrolyzer and compressor electricity demands are included, since both are supplied exclusively from the PV system.

4.4.3.5 Temporal Aggregation:

All simulation outputs are computed on an hourly basis and subsequently aggregated into the following temporal resolutions:

- **Annual totals:** energy flows, hydrogen production, and avoided CO₂ are summed for each of the 25 project years to support economic evaluation and long-term trend analysis.
- **Representative year:** the year whose annual hydrogen production is closest to the 25-year mean is selected as the representative year for monthly and seasonal profiling.
- **Monthly and seasonal profiles:** derived from the representative year to characterize intra-annual variability in solar resource, hydrogen production, and system performance.

4.4.3.6 System Assumptions:

The following assumptions underpin the simulation model:

- The system is a standalone, grid-independent PV-to-hydrogen configuration; neither battery storage nor grid connection is incorporated.
- The electrolyzer and compressor operate solely on instantaneous PV generation; both units receive zero power input during nighttime hours and periods of insufficient solar irradiance.
- The electrolyzer is limited to its rated capacity of 10,000 kW. PV power exceeding this limit is first directed to the compressor; any further surplus is curtailed.
- A degradation mechanism was not explicitly modeled for the electrolyzer and compressor. Instead, a technology replacement scenario was considered, where the original electrolyzer stack is replaced by a next-generation unit with improved efficiency.
- The compressor operates exclusively on surplus PV power above the electrolyzer saturation threshold.

- Compressor energy consumption is modeled using a constant specific energy demand of 1.2 kWh/kg H₂; variations in electrolyzer outlet pressure, multi-stage compression, and transient thermodynamic effects are not explicitly modeled.
- An intermediate buffer tank is conceptually assumed between the electrolyzer and the compressor to allow operational decoupling; dynamic hydrogen inventory modeling is outside the scope of the present study.
- Hydrogen is temporarily stored in an intermediate buffer tank before final compression and storage.
- Curtailment is defined as the unused PV electricity after satisfying both electrolyzer and compressor demand.
- Economic assumptions reflect Algerian financial conditions, including the local inflation rate used to derive the real discount rate.

4.5 Conclusion

This chapter presented the proposed photovoltaic-based green hydrogen production system, including the study site characteristics, system configuration, modeling assumptions, and overall research methodology. The analysis is based on the climatic conditions of Khenchela, using SAM-generated photovoltaic data integrated with a Python-based techno-economic and environmental simulation model.

A defining characteristic of the proposed system is its fully standalone, grid-independent architecture: neither battery storage nor grid connection is incorporated, so all operational activity of the electrolyzer and compression unit is governed entirely by instantaneous solar availability. During nighttime hours and periods of low irradiance, all hydrogen-related processes cease, which is an inherent consequence of the direct PV-to-hydrogen coupling strategy adopted in this study.

The present model adopts a simplified steady-state representation of hydrogen compression and storage and does not simulate transient thermodynamic effects or detailed compressor dispatch strategies.

The adopted methodology combines energy performance analysis, hydrogen production assessment, environmental evaluation, and discounted cash flow analysis to investigate the feasibility of the proposed system over its operational lifetime. The next chapter presents and discusses the simulation results, focusing on the technical, economic, and environmental performance of the system under the selected operating conditions.

Chapter five: Results analysis

Chapter five: Results analysis

5.1 Introduction

This chapter presents a comprehensive analysis of the simulation results obtained for the proposed standalone photovoltaic-to-hydrogen system over a 25-year operational period. Building upon the modelling framework, system configuration, and assumptions established in the previous chapter, the following sections focus on interpreting the resulting performance indicators in terms of technical, economic, and environmental outcomes.

The analysis is structured into three main dimensions: technical performance, economic viability, and environmental impact, in order to provide an integrated assessment of the system behavior under the defined design and operational assumptions.

The technical section examines the performance of the PV plant, the operation of the PEM electrolyzer, the contribution of auxiliary components such as the compressor, as well as system-wide energy losses and curtailment phenomena. It also evaluates the overall energy conversion efficiency of the system and the interaction between its main subsystems.

The economic section investigates the cost structure of the system, including Capex and Opex, the LCOH, and key financial indicators under different hydrogen selling price scenarios. In addition, a sensitivity analysis is conducted to identify the most influential parameters affecting system economics.

The environmental assessment quantifies the avoided carbon emissions associated with substituting grid electricity with renewable energy-based hydrogen production, and analyzes their temporal distribution over the project lifetime.

Overall, this chapter aims to provide a consistent and systematic interpretation of the simulation outputs, highlighting the interdependence between technical performance, economic outcomes, and environmental benefits within the proposed system configuration

5.2 Technical analysis

The technical assessment covers the full 25-year operational period of the system, and encompasses PV energy generation, hydrogen production, electrolyzer operation, compression, curtailment, and overall system conversion efficiency. The following Table summarises the principal technical indicators derived from the hourly simulation.

Table 8: System Technical results

Technical Results	Value
PV System	
Total PV Energy Produced	914,384,766 (kWh)
PV Energy Produced in year 1	37,939,292 (KWh)
Energy Yield in year 1	1896.47 (KWh/KW)
DC Capacity Factor	20.9%
PV Performance Ratio in year 1	80%
Electrolyzer & Hydrogen Production	
Total Electrolyzer Energy Consumed	762,940,830 (kWh)
Electrolyzer Capacity Factor	34.84 %
Total Electrolyzer Operating Hours	105,640 (h)
Average Operating Hours per Year	4,225.6 (h/yr)
Electrolyzer Replacement Year	Year 12
Electrolyzer Efficiency η (before replacement)	60.27 % (LHV)
Electrolyzer Efficiency η (after replacement)	74.07 % (LHV)
Total H ₂ Production	15,434,869 (kg)
Annual Average H ₂ Production	617,395 (kg/yr)

Average H ₂ Flow Rate during Operation	146.1 (kg/h)
Compression & System Balance	
Total Compressor Energy	18,470,679 (kWh)
Total Curtailment	132,973,257 (kWh)
Curtailment as Fraction of Total PV	14.5%
Overall System Efficiency η_{system}	~56.3%

5.2.1 Photovoltaic system performance:

The photovoltaic PV system represents the primary energy source of the overall plant, delivering electricity to the downstream hydrogen production system over a project lifetime of 25 years. The total AC electricity generated over this period amounts to 914,384,766 kWh, corresponding to an average annual production of approximately 36.6 GWh/year. This long-term value reflects the combined effect of high solar resource availability and gradual performance degradation over time.

During the first year of operation, before the impact of cumulative degradation, the PV system produced 37,939,292 kWh, which serves as the reference performance level of the plant under optimal operating conditions. This corresponds to a specific yield of 1,896.47 kWh/kW, indicating the annual energy output per installed kilowatt of PV capacity. This value confirms a strong solar resource potential at the site and an effective system design.

The system also achieved a DC capacity factor of 20.9%, which represents the ratio between the actual energy produced and the theoretical maximum energy that would be generated if the PV plant operated at full rated capacity continuously throughout the year. This value is considered high and consistent with well-performing utility-scale PV plants located in semi-arid regions such as North Africa, where solar irradiation levels are strong but still subject to diurnal cycles and seasonal variability. (Bendaas, et al., 2026).

In addition, the performance ratio PR of 80% reflects the overall quality of the PV system from a technical standpoint, excluding the effects of solar resource availability. It accounts for losses related to temperature, inverter efficiency, wiring, mismatch between modules, and other system-level inefficiencies. A PR of 80% indicates a well-optimized and

efficiently operated PV installation within the expected range for modern utility-scale systems. (International Electrotechnical Commission IEC , 2017).

Over the project lifetime, the PV output gradually decreases due to an assumed annual degradation rate of 0.7%, which is consistent with the natural aging of PV modules under long-term exposure to environmental conditions such as temperature variations and irradiance stress. This progressive decline reduces the amount of electricity available for downstream processes, particularly hydrogen production via electrolysis.

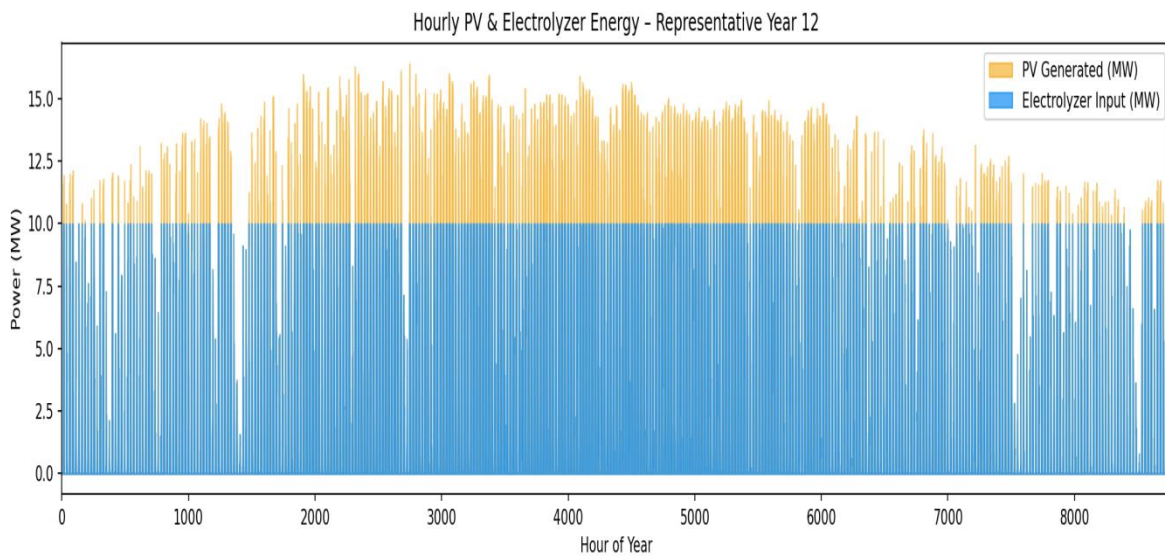


Figure 22: Hourly PV power & electrolyzer consumption during representative year

The Figure presents the hourly photovoltaic PV power generation and electrolyzer power input profiles for a representative year of the project lifetime. The orange bars represent the electrical power generated by the PV system, while the blue bars correspond to the power supplied to the PEM electrolyzer for hydrogen production. A prominent feature of the figure is the complete absence of generation during nighttime hours, evidenced by the recurring zero-power intervals throughout the 8,760-hour period. This behavior confirms the standalone and battery-free configuration of the system, where electrolyzer operation is entirely dependent on instantaneous solar power availability.

The PV output exhibits substantial hourly and seasonal variability, ranging from nearly zero during nighttime periods to peak values approaching 16 MW under high solar irradiance conditions. Although the installed PV capacity is 20 MW, the maximum observed power remains below this value due to system losses, power conversion inefficiencies, operating conditions, and the cumulative effect of PV module degradation.

Consequently, the energy available to the electrolyzer varies continuously throughout the year.

The electrolyzer operates under partial-load conditions during periods of low solar irradiance and reaches its rated capacity of 10 MW only when sufficient PV power is available. Because the PV array is intentionally oversized relative to the electrolyzer (20 MW versus 10 MW).

$$\text{Sizing Ratio} = \frac{\text{PV Capacity}}{\text{PEM Electrolyzer Capacity}} = \frac{20 \text{ MW}}{10 \text{ MW}} = 2 \quad (38)$$

The electrolyzer frequently operates at its maximum allowable power during periods of high solar production, particularly between approximately hours 2,000 and 6,000, corresponding to the spring and summer seasons. During these periods, additional PV generation beyond the electrolyzer capacity cannot be processed for hydrogen production. The resulting surplus energy is either directed to the compressor when operational conditions permit or otherwise curtailed.

This seasonal behavior highlights two distinct operating regimes. During spring and summer, the electrolyzer becomes capacity-constrained, meaning that hydrogen production is limited by the electrolyzer rated power rather than by solar resource availability. In contrast, during winter months approximately hours 0–1,000 and 7,000–8,760, PV generation rarely reaches the 10 MW threshold, causing the electrolyzer to operate predominantly at partial load. Under these conditions, the system becomes resource-constrained, with hydrogen production limited by the available solar energy rather than by electrolyzer capacity.

Overall, the figure demonstrates that the selected PV-to-electrolyzer sizing strategy successfully maximizes hydrogen production by ensuring frequent operation of the electrolyzer at rated capacity during high-irradiance periods. However, this design choice also results in significant surplus renewable energy and associated curtailment during peak production hours, reflecting the trade-off between maximizing electrolyzer utilization and minimizing excess solar generation. The observed operating pattern is consistent with the calculated electrolyzer capacity factor of 34.84%, which reflects the combined influence of seasonal solar variability and the absence of electrical energy storage.

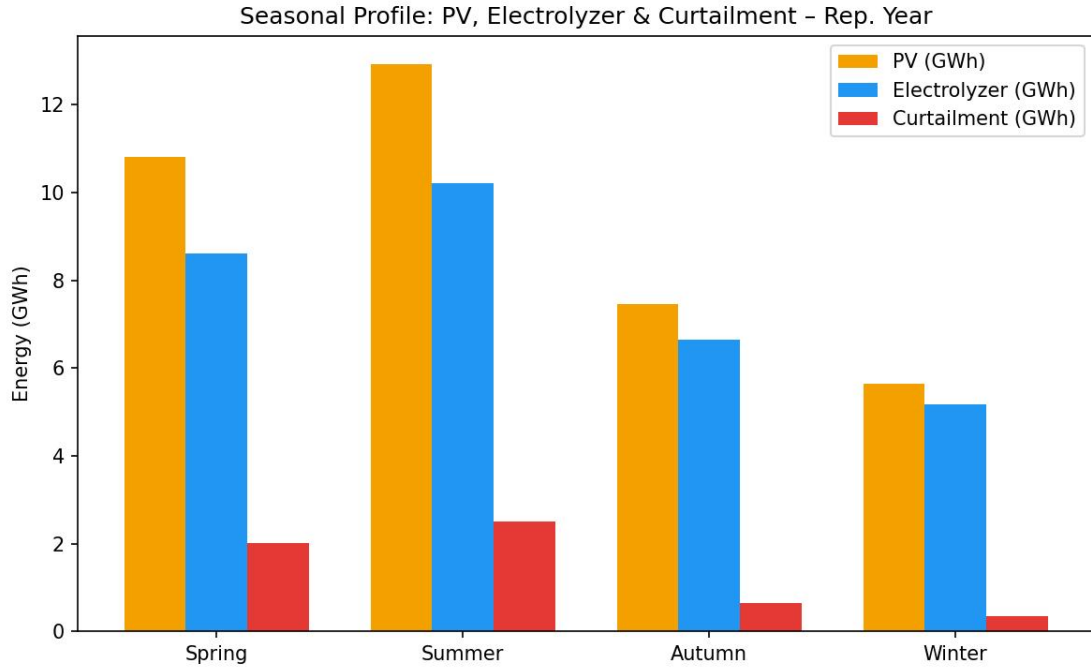


Figure 23: Seasonal energy distribution: Solar PV production, electrolyzer consumption & curtailment

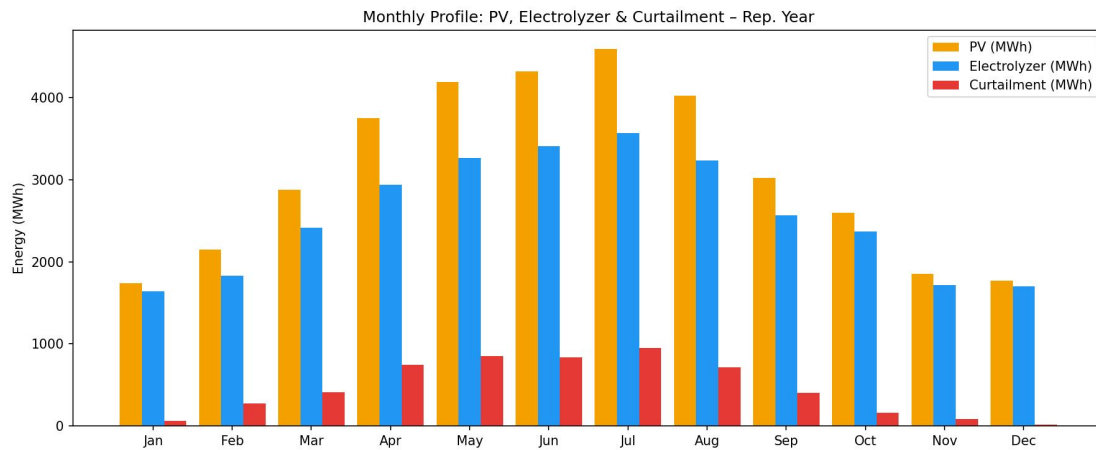


Figure 24: Monthly energy distribution: Solar PV production, electrolyzer consumption & curtailment

The two Figures present the seasonal and monthly distributions of photovoltaic electricity generation, electrolyzer electricity consumption, and curtailed energy for the integrated PV–PEM hydrogen production system. Together, these figures provide complementary perspectives on the annual energy balance, highlighting the influence of solar resource variability on system operation. The orange bars represent the electricity generated by the photovoltaic plant, the blue bars correspond to the electricity consumed by the PEM electrolyzer, and the red bars indicate curtailed energy resulting from the

mismatch between renewable generation and the processing capacity of the hydrogen production system.

A clear seasonal trend can be observed in photovoltaic electricity generation, which follows the annual variation in solar irradiance and daylight duration. Electricity production gradually increases from winter to summer, reaching approximately 13 GWh during the summer season, compared with only about 5.6 GWh in winter. This seasonal contrast is further confirmed by the monthly profile, where PV generation rises from a minimum of approximately 1.75 GWh in January to a maximum of about 4.6 GWh in July. Such behaviour is characteristic of semi-arid and Mediterranean climates, where longer daylight hours and higher solar irradiation levels significantly enhance summer energy production.

Electrolyzer electricity consumption follows the same general seasonal pattern as PV generation because hydrogen production is directly powered by solar electricity. During low-irradiance months, particularly November through January, the difference between PV generation and electrolyzer consumption becomes very small, indicating that nearly all available solar electricity is utilized by the electrolyzer. This near coincidence between the PV generation and electrolyzer consumption bars reflects efficient utilization of the available renewable energy during winter conditions.

However, the relationship changes significantly during spring and summer. As PV production increases, the electrolyzer frequently reaches its rated power limit of 10 MW, while the photovoltaic array continues to generate additional electricity. Since the installed PV capacity 20 MW is intentionally oversized relative to the electrolyzer capacity, excess electricity cannot always be converted into hydrogen. Consequently, the gap between PV generation and electrolyzer consumption widens substantially during high-irradiance periods, resulting in increased energy curtailment.

Curtailment exhibits the strongest seasonal variability among all energy flows. Summer records the highest curtailed energy, reaching approximately 2.5 GWh, compared with only about 0.3 GWh during winter. Spring also shows significant curtailment, close to 2.0 GWh, while autumn presents intermediate values around 0.6 GWh. The monthly distribution reveals the same pattern, with curtailed energy peaking at nearly 950 MWh in July and becoming almost negligible between November and January. This behaviour

confirms that curtailment is primarily driven by periods when PV generation exceeds both the electrolyzer operating limit and the instantaneous compression demand.

yielding a cumulative curtailed energy of approximately 1.33×10^8 kWh. This represents about 14.5% of the total photovoltaic electricity production, indicating that a significant fraction of the installed renewable generation capacity remains unused during peak solar periods.

Overall, the seasonal and monthly analyses reveal a fundamental characteristic of the selected PV–electrolyzer sizing strategy. The oversized photovoltaic array successfully maximizes hydrogen production and ensures high electrolyzer utilization during periods of moderate solar resource availability. Nevertheless, this design also generates substantial excess electricity during high-irradiance periods, particularly between April and August, making this interval the most critical operational period for both hydrogen production and curtailment losses. The results therefore highlight the trade-off between maximizing renewable energy capture and minimizing unused surplus generation in standalone solar-hydrogen systems.

5.2.2 Electrolyzer operation & hydrogen production:

Over the 25-year project lifetime, the PEM electrolyzer consumed a total of 762,940,830 kWh, corresponding to approximately 83.4% of the total photovoltaic electricity generated. This high energy utilization ratio indicates effective integration between the 20 MW photovoltaic plant and the 10 MW electrolyzer, enabling the conversion of most of the available renewable electricity into hydrogen. The remaining fraction was mainly associated with periods when PV production exceeded the processing capacity of the hydrogen production chain, resulting in curtailment

The electrolyzer achieved a CF of 34.84%, corresponding to approximately 3,052 equivalent full-load operating hours per year. Although this value may appear moderate when compared with continuously operated industrial electrolyzers, it is consistent with the operating characteristics of standalone PV-powered hydrogen systems. In such configurations, electrolyzer operation is entirely dependent on solar resource availability and is therefore constrained by nighttime shutdowns and seasonal irradiance variations rather than by insufficient utilization of the installed electrolyzer capacity. The fact that the electrolyzer absorbed approximately 83.4% of the total PV electricity generated, while

curtailment remained limited to 14.5%, further confirms that the observed capacity factor is primarily a consequence of renewable intermittency rather than poor system sizing or underutilization. (International Renewable Energy Agency, IRENA, 2020)

The adopted configuration, consisting of a 20 MW photovoltaic field coupled to a 10 MW PEM electrolyzer, enhances hydrogen production by increasing the frequency at which the electrolyzer operates at or near its rated power during periods of moderate and high solar irradiance. As a result, the system produced a total of 15,434,869 kg of hydrogen over the project lifetime, corresponding to an average annual production of 617,395 kg/year and an average hydrogen production rate of 146.1 kg/h during operation. Furthermore, the scheduled electrolyzer stack replacement in Year 12 increased the conversion efficiency from 60.27% to 74.07% LHV basis, contributing to improved hydrogen production performance during the second half of the project lifetime.

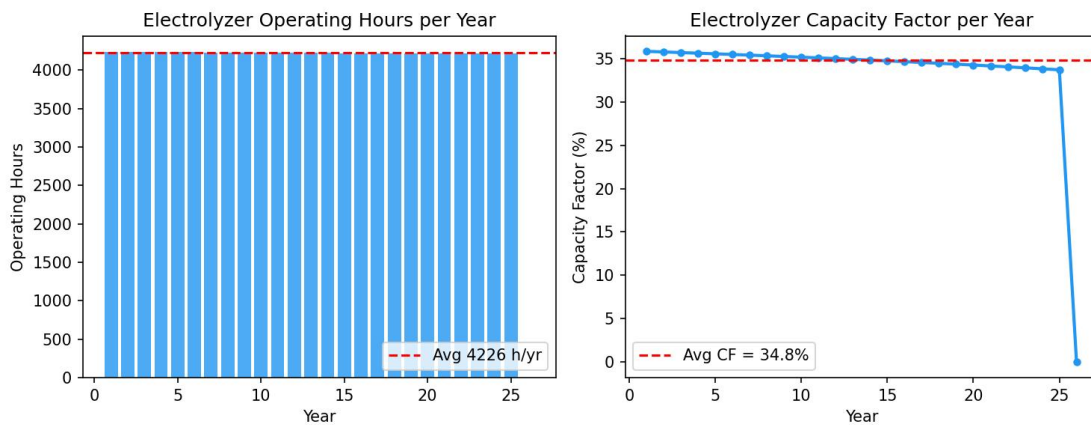


Figure 25: Left: annual electrolyzer operating hours with 25-year average of 4,226 h/yr
Right: annual capacity factor with 25-year average of 34.8%

The Figure presents the annual evolution of electrolyzer operating hours and capacity factor over the 25-year project lifetime. The left panel shows that the electrolyzer operates for approximately 4,200 h/year throughout the study period, with a 25-year average of 4,226 h/year. This relatively stable operating duration reflects the consistency of the solar resource and demonstrates that the selected PV–electrolyzer configuration is capable of sustaining regular hydrogen production over the long term.

A slight downward trend is nevertheless observed, with annual operating hours decreasing from approximately 4,230 h/year in the early years to around 4,150 h/year toward the end of the project. This gradual reduction is primarily attributed to the cumulative effect of PV

module degradation (0.7%/year), which progressively decreases the amount of electricity available to the electrolyzer.

A similar trend is observed for the electrolyzer capacity factor, which decreases from approximately 36% in the first years of operation to about 34% in the final years, yielding a lifetime average of 34.84%. Although this value may appear moderate when compared with continuously operated industrial electrolyzers, it is consistent with the operating characteristics of standalone PV-powered hydrogen systems. Since the electrolyzer operates exclusively when solar power is available, its utilization is inherently constrained by the day–night cycle and seasonal variations in solar irradiance. Consequently, the observed capacity factor reflects renewable energy intermittency rather than inadequate utilization of the installed electrolyzer capacity.

The limited decline in both operating hours and capacity factor over the project lifetime indicates that the impact of PV degradation on electrolyzer operation remains moderate. This result suggests that the adopted PV oversizing strategy successfully compensates for part of the long-term reduction in photovoltaic output, thereby maintaining relatively stable electrolyzer utilization despite the gradual aging of the PV array.

The apparent drop to zero at Year 26 shown in Right panel is a graphical artefact associated with the simulation boundary and has no physical significance.

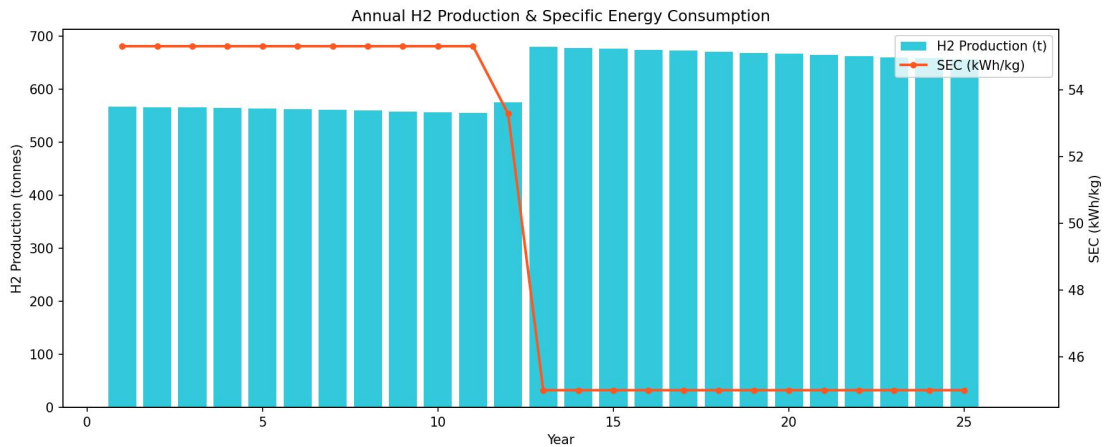


Figure 26: Annual hydrogen production & specific energy consumption over the 25-year project lifetime.

The Figure illustrates the annual hydrogen production and the SEC of the PEM electrolyzer over the 25-year project lifetime. The cyan bars represent yearly hydrogen production, while the orange line shows the electrolyzer specific energy consumption

expressed in kWh/kg H₂. The figure reveals two clearly distinct operational phases separated by the electrolyzer stack replacement event occurring at Year 12–13.

During the first operational phase (Years 1–11), hydrogen production exhibits a slight but continuous decline from approximately 567 t/year to 556 t/year, corresponding to a reduction of about 2%. This decrease is primarily driven by the gradual degradation of the photovoltaic system, which reduces the total electrical energy available for hydrogen production over time. Throughout this period, the electrolyzer operates with a constant specific energy consumption of 55.3 kWh/kg H₂, corresponding to an electrochemical efficiency of approximately 60%. The flat profile of the SEC confirms stable electrochemical performance prior to replacement, while the observed decline in hydrogen production is therefore entirely attributable to the reduction in available PV energy rather than changes in electrolyzer behavior.

The year 12 value represents a transitional operating condition, where the electrolyzer stack replacement begins to affect system performance, yielding approximately 575 t of hydrogen as the new unit is introduced during the year.

Following the replacement event (Years 13–25), a clear step-change is observed in system performance. Hydrogen production increases significantly to approximately 680 t/year, representing an improvement of around 19–21% compared to the pre-replacement average (~561 t/year). This increase is directly linked to the reduction in SEC from 55.3 to 45 kWh/kg H₂, which corresponds to an improvement in electrolyzer efficiency from approximately 60% to 74%. As a result, the same amount of available electrical energy is converted into a higher quantity of hydrogen.

Despite this improvement, hydrogen production in the second phase again exhibits a gradual decreasing trend, declining from approximately 680 t/year to around 624 t/year toward the end of the project. This behavior is still governed by long-term PV degradation, which progressively reduces the electrical input available to the electrolyzer over time.

Overall, the results demonstrate that hydrogen production is influenced by two competing effects: one the gradual decline in PV electricity generation due to module degradation, and two the significant performance improvement introduced by the electrolyzer stack replacement. The second effect partially offsets the first, leading to a higher post-replacement production level despite continuing PV degradation.

The relationship between electrical energy input and hydrogen output is governed by the inverse dependence on SEC, expressed as:

$$H_2 \propto \frac{\text{Electricity}}{\text{SEC}} \quad (39)$$

This highlights that reductions in SEC play a decisive role in increasing hydrogen yield and improving system productivity in PV-powered electrolysis systems.

5.2.3 Compressor energy contribution:

The compressor is modeled as a secondary auxiliary load that operates only when photovoltaic generation exceeds the electrolyzer rated capacity 10 MW, creating surplus electricity that can be used for hydrogen compression. Hydrogen produced by the electrolyzer is temporarily accumulated in an intermediate buffer representation, allowing compression to occur whenever both surplus PV power and hydrogen inventory are available. Over the 25-year project lifetime, the compression system consumed a total of 18.47 GWh, representing approximately 2.0% of total PV electricity generation, confirming that compression constitutes a minor auxiliary energy demand within the overall system.

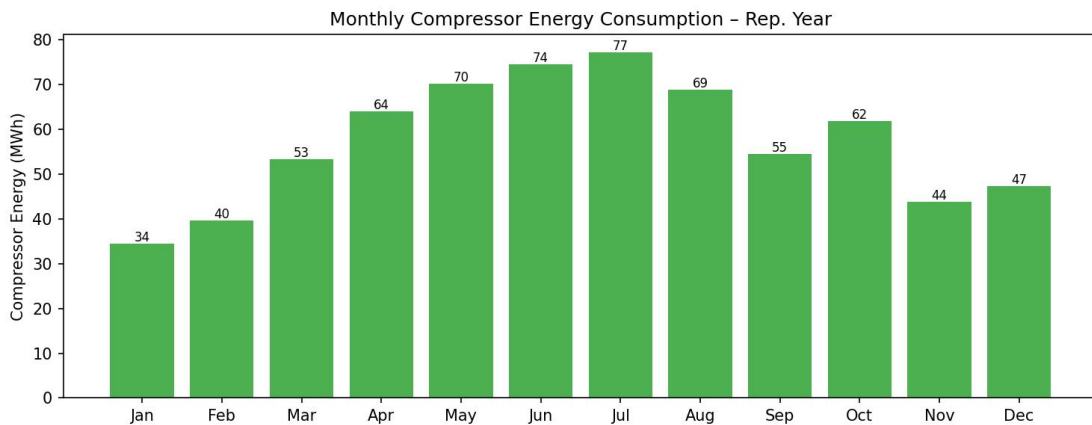


Figure 27: Monthly compressor energy consumption over a representative year

The Figure illustrates the monthly compressor energy consumption for the representative year. The profile exhibits a clear seasonal dependence, increasing from approximately 34 MWh in January to a maximum of 77 MWh in July. This trend closely follows the seasonal variation of solar irradiation and the curtailment pattern observed in the previous figure, since higher summer PV production generates both greater hydrogen

output and larger amounts of surplus electricity available for compression. Conversely, reduced winter irradiance limits both hydrogen production and compressor activity.

Although the overall behavior is governed by the annual solar cycle, minor month-to-month fluctuations can be observed during the autumn and winter periods. For instance, compressor energy consumption increases from approximately 55 MWh in September to 62 MWh in October before declining again in November, while a slight increase is also observed between November 44 MWh and December 47 MWh. These local variations are attributed to changes in the hourly distribution of surplus photovoltaic energy available for compression rather than to any modification of the general seasonal pattern.

Despite this seasonal variability, the absolute magnitude of compressor energy consumption remains relatively small throughout the year. Even during July, when compressor demand reaches its maximum value, it represents less than 2.2% of the electrolyzer electricity consumption for the same month. This confirms that hydrogen compression constitutes a minor auxiliary load with only a limited influence on the overall system energy balance compared with the electrolyzer.

5.2.4 Curtailment & energy loss analysis:

The simulation results indicate a total curtailed energy of approximately 132.97 GWh over the 25-year project lifetime, representing about 14.5% of the total photovoltaic electricity generation. Curtailment corresponds to the fraction of renewable electricity that remains unutilized after satisfying both electrolyzer and compressor energy requirements.

This behavior is primarily attributed to the adopted system configuration, which couples a 20 MW photovoltaic plant with a 10 MW PEM electrolyzer in the absence of electrical storage. During periods of high solar irradiation, photovoltaic output frequently exceeds the electrolyzer rated capacity. Although part of this surplus electricity can be utilized for hydrogen compression, the remaining excess energy cannot be converted, stored, or shifted to later periods and is therefore curtailed.

The results highlight the inherent trade-off associated with PV oversizing in standalone PV–PEM hydrogen systems. On one hand, oversizing the photovoltaic field increases hydrogen production and improves electrolyzer utilization during moderate irradiance conditions by extending operating periods and providing sufficient power more frequently. On the other hand, it inevitably increases surplus generation during peak solar hours,

leading to higher curtailment levels.

As previously observed in Figures Seasonal energy distribution and Monthly energy distribution, curtailment is strongly concentrated during the high-irradiance months, particularly between April and August, when photovoltaic generation most frequently exceeds the combined energy absorption capability of the electrolyzer and compression system. Although curtailment represents an energy utilization penalty, it remains a direct consequence of the selected design strategy, which prioritizes a simple standalone configuration without battery storage or grid support.

5.2.5 The overall system efficiency:

The overall Solar-to-Hydrogen STH system efficiency represents the ratio between the chemical energy content of the produced hydrogen LHV basis and the total AC electrical energy generated by the PV plant over the 25-year simulation period. The resulting value of approximately **56.3%** indicates that more than half of the available solar electricity is effectively converted into hydrogen energy.

This performance reflects the combined effect of system operation under intermittent solar conditions and the fixed capacity constraint of the 10 MW electrolyzer, which limits the fraction of PV energy that can be directly processed at any given time. As a result, part of the generated solar electricity is not converted into hydrogen due to curtailment and auxiliary consumption within the system, particularly compression energy demand.

Overall, the obtained efficiency represents the net energetic performance of the integrated PV–electrolyzer–compression system and highlights that hydrogen production is the dominant useful energy pathway within the overall conversion chain.

To summarize the technical part the results indicate that the proposed PV–PEM hydrogen production system operates in a coherent and stable manner over the 25-year simulation period under the adopted modeling assumptions. The system successfully converts a significant fraction of the available solar resource into hydrogen, with performance governed primarily by PV intermittency and electrolyzer capacity constraints.

The observed curtailment levels and compressor energy demand remain limited relative to total PV generation, confirming that auxiliary processes do not significantly alter the

overall energy balance. Operational indicators such as capacity factor, hydrogen yield, and long-term production stability reflect a consistent system behavior driven by the direct coupling between PV generation and electrolyzer operation.

However, these conclusions are inherently conditioned by the modeling framework, which excludes explicit storage sizing constraints and simplified certain dynamic operational aspects. Therefore, the findings should be interpreted as representative of the modeled configuration rather than a fully optimized industrial-scale design.

From a technical standpoint, the system demonstrates consistent functional operation within its defined boundaries, providing a reliable basis for further design refinement and techno-economic evaluation.

5.3 Economic analysis

The economic performance of the system was evaluated using a real DCF framework over the 25-year project lifetime, with a real discount rate of 5% derived from the Fisher equation. The following table summarizes the principal economic indicators. The equivalent economic values in Algerian dinar DZD are presented in Appendix A

Table 9: System economic results

Economic Results	Value
Capital and Operating Costs	
Total Initial CAPEX	46,167,083.88 USD
PV System	31,172,083.88 USD (67.5%)
PEM Electrolyzer	13,370,000.00 USD (28.9%)
Compressor + Storage	1,625,000.00 USD (3.5%)
Total Annual OPEX	1,173,614.40 USD/yr
PV Fixed O&M	440,114.40 USD/yr (37.5%)
PEM Electrolyzer O&M (5% of CAPEX)	668,500.00 USD/yr (56.9%)
Compressor + Storage O&M (4% of CAPEX)	65,000.00 USD/yr (5.5%)
Electrolyzer Replacement Cost	4,500,000.00 USD (Year 12)

Compressor Replacement	Not triggered
Levelized Cost of Hydrogen (LCOH)	
LCOH (discounted CF)	7.6816 USD/kg
CAPEX Component	5.4381 USD/kg (70.8%)
OPEX Component	1.9484 USD/kg (25.4%)
Replacement Component	0.2952 USD/kg (3.8%)
Financial Performance by Selling Price	
NPV (at \$4/kg)	−31,255,323 USD
NPV (at \$6/kg)	−14,276,130 USD
NPV (at \$8/kg)	+2,703,062 USD
IRR (at \$4/kg)	−3.26%
IRR (at \$6/kg)	1.82%
IRR (at \$8/kg)	5.54%
Payback Period (at \$4/kg)	Not recovered
Payback Period (at \$6/kg)	21 Years
Payback Period (at \$8/kg)	15 Years

5.3.1 Capital & operating cost structure:

The total initial capital expenditure amounted to 46,167,083.88 USD, with the photovoltaic system representing the dominant share at 67.5%, followed by the electrolyzer at 28.9%, and the compressor–storage system at only 3.5%. This distribution reflects the capital-intensive nature of PV-based hydrogen systems, where the large installed solar capacity constitutes the primary cost driver even in configurations where the electrolyzer is significantly oversized relative to conventional designs.

The annual operating expenditure reaches 1,173,614.40 USD/year and is largely driven by electrolyzer maintenance, which alone accounts for 56.9% of total OPEX. This highlights the maintenance-intensive character of PEM technology, where stack operation and

periodic servicing represent a significant recurring cost component compared to balance-of-plant systems. Over the project lifetime, the cumulative undiscounted OPEX becomes substantial, indicating that long-term operational costs play a non-negligible role in overall project economics despite the high upfront investment.

A single major replacement event occurs at Year 12 for the electrolyzer stack, amounting to 4,500,000 USD, confirming the expected mid-life refurbishment requirement of PEM systems. In contrast, the compressor system does not reach its lifetime operating threshold within the project duration, consistent with its relatively low energy share and intermittent operation. Overall, the cost structure indicates that while CAPEX is dominated by PV infrastructure, long-term economics are increasingly influenced by electrolyzer operation and maintenance rather than auxiliary subsystems

5.3.2 Levelized cost of hydrogen LCOH:

The obtained levelized cost of hydrogen LCOH is 7.68 USD/kg, reflecting the combined effect of high upfront investment costs and limited system utilization. This value is primarily driven by the capital-intensive nature of the configuration, where the photovoltaic system represents the dominant share of total CAPEX, followed by the electrolyzer system.

A key contributor to the elevated LCOH is the relatively low utilization of the electrolyzer, with a capacity factor of approximately 35%, which limits the annual hydrogen output despite the significant installed capacity. This underutilization is a direct consequence of the intermittent nature of solar resources in a standalone configuration, combined with the fixed sizing ratio between the PV plant and the electrolyzer.

In addition, the absence of electrical storage or grid export capability leads to significant curtailment of excess photovoltaic generation, which further reduces the effective conversion of available solar energy into hydrogen. This results in a higher cost per unit of hydrogen produced, as fixed capital and operating costs are distributed over a reduced production volume.

When compared to conventional grey hydrogen production costs 0.5–1.7 USD/kg, the obtained value indicates that the system remains economically non-competitive under current assumptions. However, this outcome is consistent with standalone PV-to-hydrogen

systems operating without storage integration and under relatively low capacity factors. (International Energy Agency, IEA, 2021)

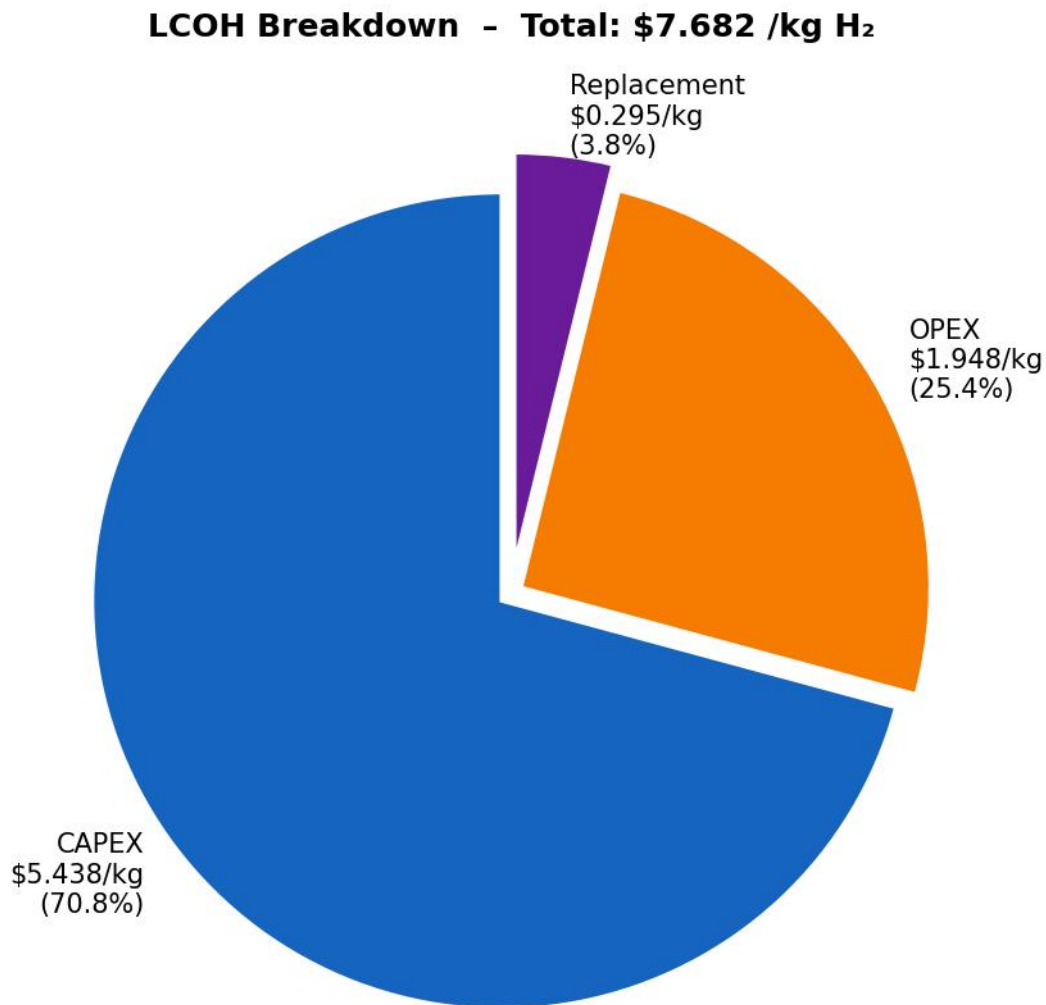


Figure 28: LCOH breakdown by cost component

The LCOH decomposition presented in the figure highlights the dominant contribution of capital investment to the overall hydrogen production cost. A proportional chart, decomposing the LCOH into its three cost components: CAPEX (blue: \$5.44/kg), OPEX (orange: \$1.95/kg), and Replacement (purple: \$0.30/kg), providing a clear visualization of the contribution of each cost category to the total hydrogen production cost of 7.682 \$/kg H₂.

The capital expenditure CAPEX component constitutes the largest share of the LCOH, accounting for 70.8% (5.44 \$/kg) of the total cost. This dominant contribution reflects the

capital-intensive nature of stand-alone photovoltaic-hydrogen systems, where all infrastructure costs including the photovoltaic plant 31.2 M\$, electrolyzer 13.4 M\$, and hydrogen compression and storage system 1.6 M\$ must be recovered exclusively through hydrogen production revenues. Unlike conventional energy systems, no fuel expenses are incurred during operation; therefore, the cost of energy supply is effectively embedded within the initial investment required to capture solar energy and convert it into hydrogen.

The large contribution of CAPEX is further amplified by the partial utilization of installed assets. Because the electrolyzer capacity limits the conversion of available photovoltaic electricity, a portion of the generated solar energy is curtailed rather than converted into hydrogen. As a result, the substantial upfront investment is distributed over a reduced hydrogen output, increasing the capital cost contribution per kilogram of hydrogen produced.

The OPEX component accounts for 25.4% (1.95 \$/kg) of the total LCOH. Although the system does not incur fuel costs, operating expenses remain significant due to the maintenance requirements of the electrolyzer and other system components. In the present study, annual operation and maintenance costs are assumed to be proportional to the installed equipment costs, with electrolyzer maintenance representing the largest share of these expenditures. This result indicates that improvements in electrolyzer reliability and reductions in maintenance requirements could provide substantial economic benefits over the project lifetime.

The replacement cost contributes 3.8% (0.30 \$/kg) to the total LCOH and corresponds to a single electrolyzer stack replacement scheduled in year 12 at an estimated cost of 4.5 M\$. Although this contribution remains relatively modest under the current assumptions, it highlights the influence of electrolyzer stack lifetime on long-term project economics. Any reduction in stack durability requiring additional replacements during the project lifetime would increase the overall hydrogen production cost.

Overall, the cost distribution demonstrates that the economics of the proposed system are entirely dominated by fixed and semi-fixed expenditures. Since no variable operating costs were assumed in the economic model and solar energy is available without fuel expenses, the LCOH is determined exclusively by capital recovery, operation and maintenance costs, and electrolyzer stack replacement expenditures. Consequently, the most effective strategies for reducing hydrogen production costs involve lowering equipment costs,

extending component lifetimes, improving asset utilization, and increasing hydrogen output from the existing infrastructure.

Overall, the obtained LCOH of 7.68 \$/kg confirms that hydrogen production cost is mainly governed by capital recovery and electrolyzer-related operational expenses. The difference between this value and lower cost benchmarks for green hydrogen is therefore primarily linked to the high capital intensity of PV–electrolyzer systems and their relatively low capacity utilization under intermittent renewable conditions.

5.3.3 Financial performance analysis:

The financial viability of the system is examined using NPV, IRR, and payback period indicators to capture the sensitivity of project economics to hydrogen selling price

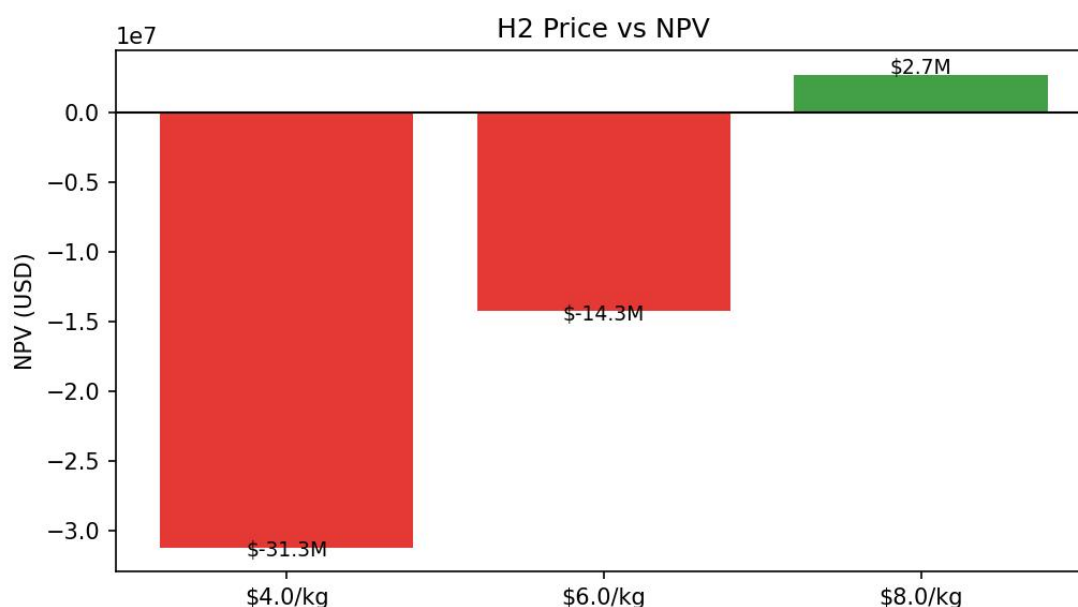


Figure 29: Net present value (USD) for each of the three hydrogen selling price scenarios

The figure presents the Net Present Value for 3 selling price 4,6 and 8. Red bars indicate negative NPV (loss); green bar indicates positive NPV (profit).

The Net Present Value results indicate a strong dependence of project profitability on the hydrogen selling price. At lower price levels 4 and 6 USD/kg, the project remains financially unviable, as revenues are insufficient to offset the high capital and operating expenditures over the project lifetime. A transition toward positive NPV is observed only at 8 USD/kg, indicating that the system operates near its economic break-even threshold.

This behavior is consistent with the calculated LCOH 7.68 USD/kg, suggesting that profitability is achieved only when the selling price exceeds the effective production cost. The results therefore highlight that system economics are governed by both production cost structure and utilization constraints, where the relatively low capacity factor and curtailment losses reduce the effective use of installed assets and amplify the sensitivity of profitability to market price variations

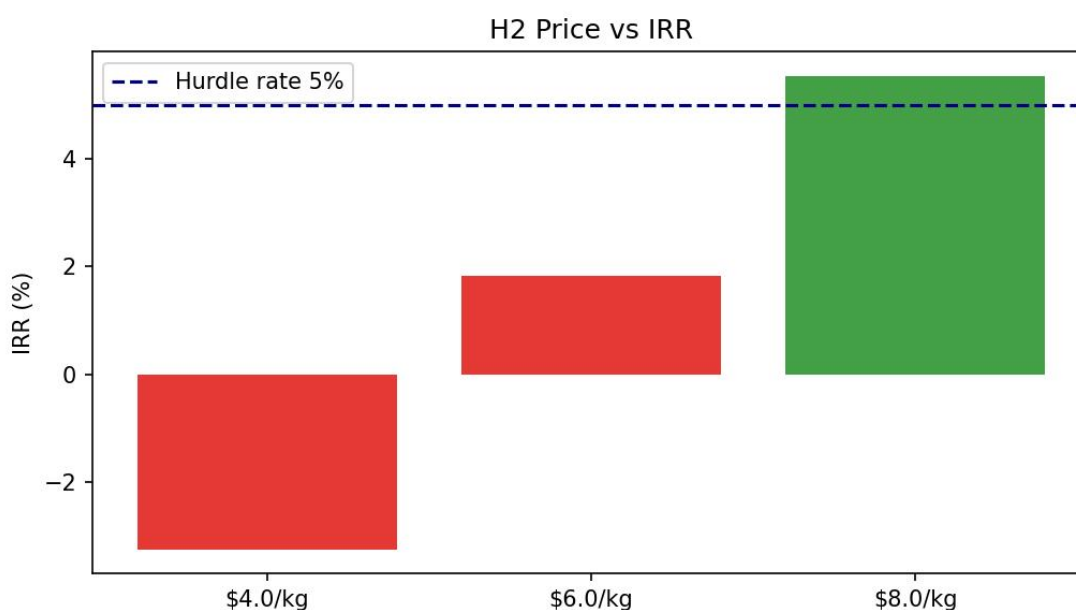


Figure 30: Internal rate of return (%) for each selling price scenario

The figure shows the IRR (%) for each selling price scenario, with the 5% real hurdle rate dashed blue line shown for reference.

The IRR results further confirm the limited financial robustness of the project. At hydrogen selling prices of 4 and 6 USD/kg, the IRR remains below the assumed discount rate, indicating that the project does not meet the minimum investment return requirements under these conditions. Even though positive cash flows are generated at higher prices, the return remains insufficient to ensure strong investment attractiveness.

Only at 8 USD/kg does the IRR slightly exceed the discount rate, indicating marginal financial feasibility. However, the narrow margin between the IRR and the required return suggests that project profitability is highly sensitive to variations in key economic parameters, including capital cost, operating expenses, and hydrogen selling price.

For the payback period analysis, the results emphasize the long-term capital recovery characteristic of standalone green hydrogen systems. At 4 USD/kg, the project fails to recover its initial investment within the 25-year lifetime, confirming its economic infeasibility under low-price scenarios. At 6 USD/kg, capital recovery is achieved only after a very long operational period, reflecting high investment risk and limited early-stage liquidity.

At 8 USD/kg, the payback period decreases significantly, indicating improved financial performance; however, recovery still occurs only after a substantial portion of the project lifetime. This confirms that even under favorable conditions, the project remains capital-intensive and highly dependent on sustained high hydrogen market prices to achieve acceptable economic performance.

Overall, the results indicate conditional financial feasibility governed primarily by hydrogen selling price and capital intensity. System performance remains economically constrained under current assumptions, with viability achieved only under high-price scenarios. Limited asset utilization under intermittent renewable supply further reinforces economic sensitivity.

To further investigate the sensitivity of project economics to key input parameters, a tornado analysis is presented to quantify the relative influence of the most critical technical and financial variables on overall project viability.

5.3.4 Sensitivity analysis:

A deterministic one-at-a-time sensitivity analysis was conducted to identify the parameters exerting the greatest influence on the LCOH. Each parameter was independently varied by $\pm 20\%$ (CAPEX components, discount rate) or $\pm 15\%$ (SEC, CF) around its base value, while all other parameters were held constant. The absolute LCOH impact defined as the difference between the high and low LCOH scenarios for each parameter is presented in following figure.

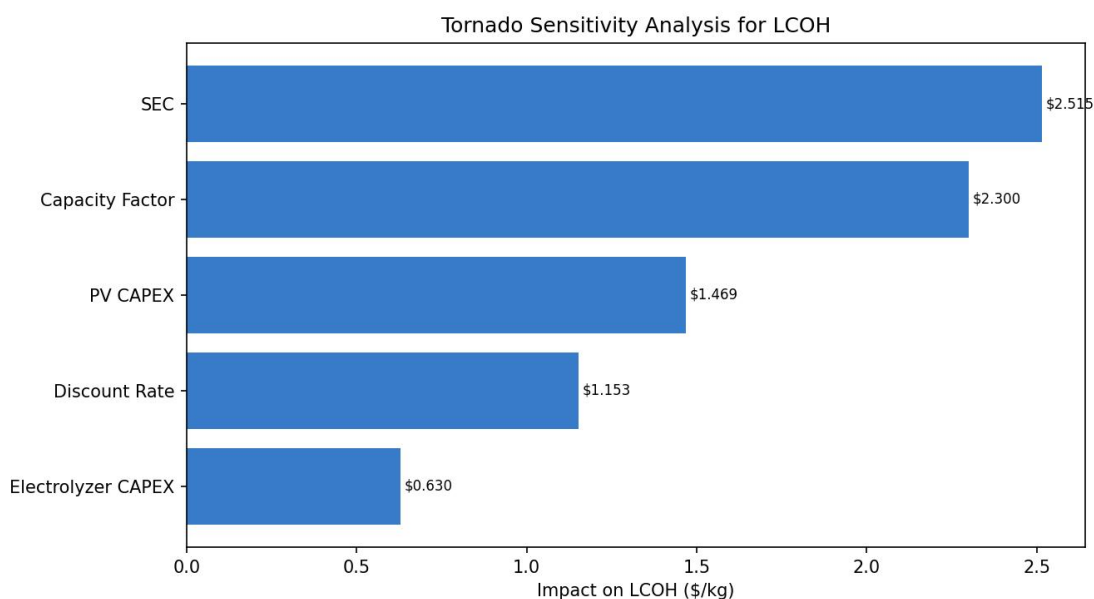


Figure 31: Tornado chart of LCOH sensitivity

The Figure presents the results of the deterministic one-at-a-time sensitivity analysis as a tornado chart, in which each bar represents the absolute impact on the LCOH expressed in USD/kg resulting from a independent variation of each input parameter within its predefined range, while all other parameters are held constant at their base values. Parameters are ranked in descending order of influence, with the most sensitive parameter at the top and the least sensitive at the bottom.

- **SEC \$2.515/kg (Most influential)**

The specific energy consumption of the electrolyzer is the single parameter exerting the greatest influence on the LCOH, with an impact range of \$2.515/kg. This result is physically and economically intuitive: SEC directly governs the mass of hydrogen produced per unit of electrical energy consumed, and therefore acts through the denominator of the LCOH formula. A reduction in SEC corresponding to a more efficient electrolyzer increases hydrogen output from the same electrical input, spreading the fixed capital and operating costs over a larger hydrogen mass and reducing the LCOH. Conversely, an increase in SEC reduces hydrogen yield and raises the LCOH proportionally. This finding reinforces the central importance of electrolyzer technology performance in determining the economics of PV-to-hydrogen systems, and explains why the stack replacement in Year 12 which reduced SEC from 55.3 to 45.0 kWh/kg has a measurable positive effect on system economics beyond its purely technical contribution.

This further confirms that renewable energy projects are not limited only by project costs, but also by system efficiency and the conversion of electrical energy into a final product: green hydrogen.

- **Capacity factor CF \$2.300/kg (Second)**

The electrolyzer CF ranks a close second, with an impact of \$2.300/kg, nearly equal to that of SEC. Both parameters operate through the same economic mechanism: the capacity factor governs the total number of effective operating hours per year, and therefore the total hydrogen produced over the project lifetime. A higher capacity factor achievable through better solar resource utilisation, partial-load optimisation, or a more favourable site increases the denominator of the LCOH and reduces the cost per kilogram. The proximity of this bar to that of SEC is significant: it indicates that improvements in solar resource exploitation are as economically valuable as improvements in electrolyzer efficiency. In the context of this study, the CF of 34.84% is largely determined by the Khenchela solar resource and the direct-coupling architecture; increasing it would require either a higher-irradiance site or the introduction of electrical storage, connecting to the electricity grid or system hybridization, all of which carry their own cost implications.

- **PV CAPEX \$1.469/kg (Third)**

The capital cost of the PV system ranks third, with an impact of \$1.469/kg. Although PV CAPEX constitutes the largest single cost component 67.5% of total CAPEX, its influence on the LCOH is moderate relative to the two operational parameters above. This is because capital costs are discounted over 25 years, diluting their per-kilogram impact compared to parameters that directly affect annual hydrogen output. Nevertheless, the \$1.469/kg sensitivity confirms that reductions in PV module and balance-of-system costs a trend that has been consistent over the past decade would meaningfully improve the economics of this system. A 20% reduction in PV CAPEX alone would reduce the LCOH by approximately \$0.73/kg, bringing it closer to the \$6/kg threshold.

- **Discount rate \$1.153/kg (Fourth)**

The real discount rate ranks fourth with an impact of \$1.153/kg, reflecting the sensitivity of a capital-intensive project to financing conditions. A lower discount rate reduces the present value of future costs and, crucially for this system, reduces the annualised burden of the large upfront CAPEX. This finding has a direct policy implication: concessional financing mechanisms such as green bonds, development bank loans, or

public guarantees that reduce the effective cost of capital could meaningfully lower the LCOH even without any change in system technology or configuration. The relatively modest ranking of the discount rate compared to SEC and capacity factor suggests, however, that financing improvements alone are insufficient to achieve competitiveness; they must be accompanied by technical performance improvements.

- **Electrolyzer CAPEX \$0.630/kg (Least influential)**

The electrolyzer capital cost exerts the least influence on the LCOH, with an impact of only \$0.630/kg less than one quarter of the SEC impact despite representing 28.9% of total initial investment. This apparently counterintuitive result is explained by two compounding factors: first, like all capital costs, the electrolyzer CAPEX is discounted over 25 years, reducing its per-kilogram weight; second, the electrolyzer O&M cost (5% of CAPEX per year) is already captured separately in the OPEX component of the LCOH. The modest sensitivity to electrolyzer CAPEX should not be interpreted as an argument against pursuing electrolyzer cost reductions such reductions also lower the replacement cost and annual O&M but rather as evidence that, under the adopted assumptions, the economic case for this system is more sensitive to operational performance than to equipment procurement costs.

The tornado chart illustrates that the LCOH of this system is more sensitive to operational performance parameters SEC and CF, combined impact \$4.815/kg than to capital cost parameters PV CAPEX + Electrolyzer CAPEX + Discount Rate, combined impact \$3.252/kg. This finding has direct implications for the design and policy priorities of future PV-to-hydrogen projects in Algeria:

- The highest-return improvement pathway is the adoption of next-generation electrolyzers with lower SEC already partially captured in the post-replacement scenario of this study.
- The second priority is maximising the capacity factor through site selection, system sizing optimisation, or, connecting to the electricity grid or system hybridization where economically justified, partial electrical storage.
- Reductions in PV CAPEX and financing costs, while beneficial, yield a lower marginal return on the LCOH than equivalent improvements in operational efficiency.

Finally, it is noted that the direction of each sensitivity is consistent with physical expectations: reductions in SEC and increases in capacity factor both decrease the LCOH, while increases in any of the three cost parameters raise it. The symmetry of these relationships within the $\pm 15\text{--}20\%$ variation ranges confirms that the LCOH responds approximately linearly to each parameter within the tested bounds, which validates the use of a deterministic one-at-a-time approach for this analysis.

Overall, the economic assessment indicates that the proposed PV–PEM green hydrogen system operates within a cost structure that is primarily driven by high capital intensity and limited asset utilization under intermittent solar conditions. The Levelized Cost of Hydrogen remains above conventional hydrogen benchmarks, reflecting the combined effect of significant upfront investment, moderate electrolyzer utilization, and the presence of curtailment losses inherent to the direct-coupled configuration.

Financial indicators further show that project viability is highly sensitive to hydrogen selling price, with acceptable returns achieved only under high-price scenarios. This confirms that, under the current assumptions, economic performance is constrained more by structural and market conditions than by isolated component costs.

Sensitivity analysis supports this interpretation by identifying electrolyzer efficiency and capacity factor as the dominant drivers of hydrogen cost, exceeding the influence of individual capital cost components. This highlights that improvements in system utilization and conversion efficiency would have a stronger economic impact than marginal reductions in equipment costs.

In summary, the system demonstrates coherent internal economic behavior, but its competitiveness remains dependent on favorable market conditions and technological improvements that enhance effective energy utilization.

5.4 Environmental analysis

The environmental assessment quantifies the CO₂ emissions avoided by the proposed system over its 25-year operational lifetime, under the assumption that the electricity consumed by the electrolyzer and compressor displaces equivalent generation

from the Algerian national grid, which carries an emission factor of 0.500 kg CO₂/kWh. The following Table summarises the principal environmental indicators.

Table 10: System environmental results

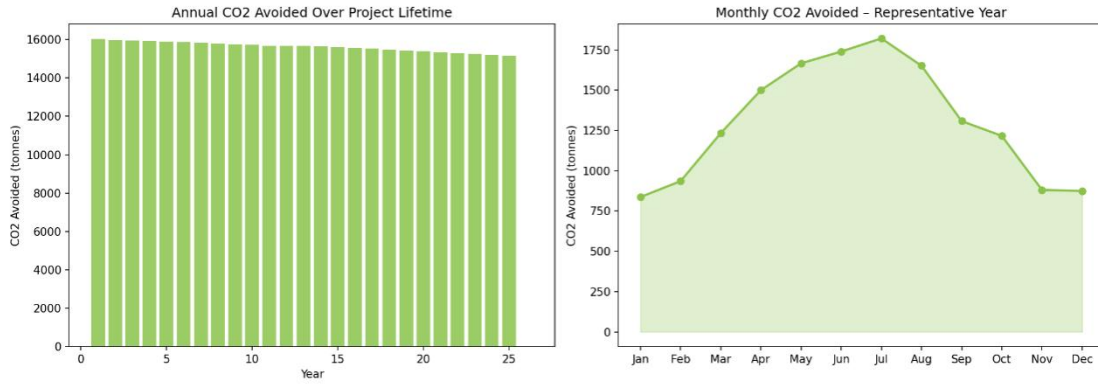
Environmental results	Value
Emission Factor (Algerian grid)	0.500 (kg CO ₂ /kWh)
Total CO ₂ Avoided	390,705,755(kg CO ₂)
Annual CO ₂ Avoided	15,628,230 kg (CO ₂ /yr)
Daily CO ₂ Avoided	42,817 (kg CO ₂ /day)
CO ₂ Avoided per kg H ₂ Produced	~25.3(kg CO ₂ /kg H ₂)

5.4.1 Cumulative CO₂ emissions avoided:

The avoided emissions over the 25-year horizon amount to 390.7 kt CO₂, with an average annual reduction of 15.63 kt CO₂/yr. This reduction is structurally driven by the complete substitution of grid electricity with photovoltaic generation across both the electrolysis and compression stages, meaning that emissions savings are not an independent system output but a direct function of total electrical demand and grid carbon intensity.

When expressed on a hydrogen output basis, the avoided emission intensity reaches 25.3 kg CO₂/kg H₂. This relatively high value reflects the carbon intensity of the displaced Algerian electricity mix applied over a high electricity consumption process chain.

From a system perspective, the environmental performance is therefore governed by two dominant factors: the total electricity requirement of the integrated PV electrolyzer–electrolyzer and the total electricity requirement of the integrated PV of the integrated PV avoidance scales linearly with both hydrogen production volume and auxiliary energy consumption, reinforcing the coupling between energy efficiency and environmental benefit in standalone renewable hydrogen systems

Figure 32: Annual & monthly CO₂ avoided

The Figure presents both the long-term and intra-annual variability of avoided CO₂ emissions. The annual profile (left panel) shows a gradual decline from approximately 16,000 t/yr in the first year to around 15,000 t/yr by Year 25, corresponding to a total reduction of approximately 6.3% over the project lifetime. This trend is directly consistent with the assumed PV degradation rate of 0.7%/year, indicating that the environmental performance of the system is primarily governed by the long-term decline in photovoltaic output.

The absence of any compensatory effect from the electrolyzer stack replacement confirms that avoided emissions are insensitive to conversion efficiency improvements at the device level, and instead scale with the total electrical energy supplied to the system. In this configuration, CO₂ avoidance is therefore controlled by net PV generation rather than by internal electrochemical performance.

The monthly distribution (right panel) exhibits a strong seasonal pattern, with values ranging from approximately 837 t CO₂ in January to 1,821 t CO₂ in July, yielding a seasonal amplitude ratio of 2.18:1. This profile closely follows the solar irradiance pattern of the site, confirming a near-linear dependence between photovoltaic production and avoided emissions in the absence of storage or grid interaction.

Seasonally, the highest contribution is observed during summer 34.1%, followed by spring 28.8%, autumn 22.3%, and winter 17.3%. This seasonal concentration reflects the climatic characteristics of the Khenchela region, where solar availability is maximized during warm months. From a broader system perspective, the seasonal concentration of avoided emissions reflects the underlying solar resource profile of the site, given that the model considers only internal generation and consumption pathways.

In general, the environmental assessment indicates that the PV–PEM hydrogen system delivers a consistent reduction in life-cycle greenhouse gas emissions over the 25-year operational period. Total avoided emissions are directly driven by the substitution of grid electricity with photovoltaic generation across both electrolysis and compression processes, resulting in a cumulative CO₂ reduction of approximately 390.7 kt.

At a system level, the environmental performance is strongly governed by the temporal profile of solar resource availability. This is reflected in both the gradual decline in annual avoided emissions due to PV degradation and the pronounced seasonal variability aligned with solar irradiance patterns. Consequently, the environmental benefit is not uniform over time but follows the intrinsic variability of renewable energy input.

On a specific basis, the system achieves a CO₂ avoidance intensity of 25.3 kg CO₂ per kg of hydrogen produced, confirming that environmental performance is closely linked to the overall energy consumption of the system rather than a single subsystem. In this configuration, both electrolyzer operation and compression demand contribute to the total electricity footprint, which defines the magnitude of emissions displacement.

Overall, the system demonstrates a clear capacity to reduce indirect carbon emissions through renewable energy substitution, with performance primarily constrained by the variability and long-term degradation of photovoltaic generation.

5.5 Conclusion

This chapter presented a comprehensive techno-economic and environmental characterization of the proposed standalone PV-to-hydrogen system in Khenchela, Algeria, over a 25-year operational horizon, based on simulation-derived results and aggregated performance indicators.

From a technical perspective, the simulation results confirm that the proposed system is technically operable under the solar conditions of northeastern Algeria. The PV plant demonstrated strong performance, with a first-year specific yield of 1,896 kWh/kW and a performance ratio of 80%, consistent with best practices for utility-scale installations in semi-arid climates. The electrolyzer achieved a capacity factor of 34.84% and absorbed 83.4% of total PV generation, producing a cumulative 15,434,869 kg of green hydrogen

over 25 years. The scheduled stack replacement in Year 12 yielded a 21% improvement in annual hydrogen output by reducing the specific energy consumption from 55.3 to 45.0 kWh/kg, demonstrating the long-term value of incorporating next-generation electrolyzer technology. The overall Solar-to-Hydrogen system efficiency of approximately 56.3% confirms that hydrogen production is the dominant energy conversion pathway, with curtailment losses of 14.5% representing an inherent but manageable consequence of the direct-coupling architecture in the absence of electrical storage. The system was assessed as technically feasible in the operational sense, with no critical barriers identified that would preclude deployment at the Khenchela site.

From an economic standpoint, the LCOH of \$7.68/kg reflects the capital-intensive nature of current PV-electrolysis systems, with CAPEX constituting 70.8% of the total LCOH. Project profitability was demonstrated only at a selling price of \$8/kg, yielding a narrow positive NPV of \$2.7M and a payback period of 15 years, while the \$6/kg scenario produced an IRR of 1.82% insufficient to attract private investment without policy support. The sensitivity analysis identified the electrolyzer specific energy consumption and the system capacity factor as the two parameters exerting the greatest influence on the LCOH, collectively accounting for over \$4.8/kg of parametric impact. This finding underscores that operational performance improvements driven by advances in electrolyzer efficiency and better solar resource utilization offer a greater economic return than equivalent reductions in capital costs alone. The gap between the computed LCOH and commercially competitive hydrogen targets of \$2–4/kg reflects the early-stage status of the technology and the conservative financial assumptions adopted, including the absence of any grid revenue, by-product credit, or concessional financing.

From an environmental perspective, the system avoids approximately 390.7 kt of CO₂ over its lifetime, corresponding to an average of 15,628 t/yrs., with a clear seasonal concentration aligned with solar resource availability. The gradual decline in annual avoided emissions reflects the impact of long-term PV degradation, reinforcing the dependence of environmental performance on photovoltaic output.

Overall, the results suggest that while the system is technically coherent and environmentally beneficial, its economic performance remains strongly dependent on hydrogen market conditions and system-level design choices that affect overall energy utilisation and conversion efficiency

Conclusion

This work investigated the feasibility of green hydrogen production from solar photovoltaic energy in Khenchela, Algeria, through an integrated 3E framework encompassing energy, economic, and environmental dimensions. The study focused on a standalone PV-to-hydrogen configuration combining a utility-scale photovoltaic plant, a PEM electrolyzer, and a hydrogen compression and storage system operating without battery storage or grid support.

From the technical perspective, the results demonstrate that the solar resource available in the Khenchela region is capable of supporting reliable green hydrogen production over the long term. The proposed configuration successfully converts a significant share of the generated photovoltaic electricity into hydrogen while maintaining stable operation throughout the simulation period. The study confirms that solar-powered hydrogen production is technically achievable under the climatic conditions of northeastern Algeria and can constitute a viable pathway for renewable energy valorization.

From the economic perspective, the analysis highlights that the competitiveness of green hydrogen remains strongly dependent on technology costs, electrolyzer performance, and market conditions. Although the calculated hydrogen production cost remains above current competitiveness targets, the results indicate that ongoing technological progress, economies of scale, and supportive policy mechanisms could substantially improve project viability in the coming years. The sensitivity analysis further emphasizes the critical role of electrolyzer efficiency and system utilization in reducing production costs.

From the environmental perspective, the proposed system achieves substantial carbon emission reductions by replacing fossil-based energy pathways with renewable hydrogen production. This outcome confirms the potential contribution of green hydrogen to both national and global decarbonization objectives.

An important finding of this work is that these results were obtained under deliberately conservative operating assumptions. The system was modeled without electrical storage, without grid connection, and with the electrolyzer and compressor operating exclusively on instantaneous photovoltaic generation. Despite these constraints, the system demonstrated promising technical performance and a competitive hydrogen production cost relative to many values currently reported in the literature for similar standalone renewable hydrogen

projects. This suggests that further optimization, additional operational flexibility, or future technological improvements could yield even more outcomes that are favorable.

Overall, the study confirms that green hydrogen production in Khenchela represents a technically feasible and environmentally beneficial opportunity, while its long-term economic competitiveness will depend on continued reductions in renewable energy and electrolysis costs, improvements in system efficiency, and the development of supportive market and policy frameworks. Given Algeria's abundant solar resources and its strategic position between African renewable energy resources and European energy demand, green hydrogen may become an important component of the country's future energy and industrial development strategy.

Future research may investigate hybrid renewable configurations, advanced storage solutions, dynamic hydrogen inventory management, alternative operating strategies, and comparative assessments across different Algerian regions in order to identify the most favorable conditions for large-scale green hydrogen deployment.

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Appendixes

Appendix A: Economic data conversion to Algerian Dinar (DZD)

To improve readability and ensure transparency of economic results for both international and local contexts, the exchange rate used in this study is 1 USD = 133.23 DZD, based on the official daily exchange rate published by the Bank of Algeria.

Table A.1. Economic Performance of the System (USD and DZD)
Exchange rate: 1 USD = 133.23 DZD (Bank of Algeria, 2026)

Economic Results	Value (USD)	Value (DZD)
Capital and Operating Costs		
Total Initial CAPEX	46,167,083.88	6,151,386,372
PV System	31,172,083.88	4,153,111,433
PEM Electrolyzer	13,370,000.00	1,781,924,100
Compressor + Storage	1,625,000.00	216,350,625
Total Annual OPEX	1,173,614.40	156,331,003
PV Fixed O&M	440,114.40	58,616,220
PEM Electrolyzer O&M (5% of CAPEX)	668,500.00	89,050,005

Compressor + Storage O&M (4% of CAPEX)	65,000.00	8,660,000
Electrolyzer Replacement Cost	4,500,000.00 (Year 12)	599,535,000
Compressor Replacement	Not triggered	—
Levelized Cost of Hydrogen (LCOH)		
LCOH (discounted DCF)	7.6816 USD/kg	1,023.6 DZD/kg
CAPEX Component	5.4381 USD/kg	724.2 DZD/kg
OPEX Component	1.9484 USD/kg	259.6 DZD/kg
Replacement Component	0.2952 USD/kg	39.3 DZD/kg
Financial Performance by Selling Price		
NPV (at \$4/kg, at 532.92 DZD/kg)	−31,255,323	−4,164,365,694
NPV (at \$6/kg, at 799.38 DZD/kg)	−14,276,130	−1,902,184,088
NPV (at \$8/kg, at 1065.84 DZD/kg)	+2,703,062	+360,198,925

Appendix B: Python implementation of the green hydrogen 3E model

The following appendix presents the core computational modules of the simulation model developed for the techno-economic assessment of the green hydrogen system.

B.1 Library imports

```
1 import pandas as pd
2 import numpy as np
3 import matplotlib.pyplot as plt
4 import warnings, os
5 warnings.filterwarnings("ignore")
```

B.2 Financial functions (NPV & IRR)

```
6 def _npv(rate, cashflows):
7     """Net present value: cashflows[0] is year-0 (negative CAPEX)."""
8     return sum(cf / (1 + rate) ** t for t, cf in enumerate(cashflows))
9
10 def _irr(cashflows, guess=0.10, tol=1e-8, max_iter=1000):
11     """Newton-Raphson IRR solver."""
12     r = guess
13     for _ in range(max_iter):
14         f = _npv(r, cashflows)
15         df = sum(-t * cf / (1 + r) ** (t + 1)
16                 for t, cf in enumerate(cashflows))
17         if df == 0:
18             return float("nan")
19         r_new = r - f / df
20         if abs(r_new - r) < tol:
21             return r_new
22         r = r_new
23     return float("nan")
```

B.3 Technical parameters

```
24 # --- PV System -----
25 PV_CAPACITY_KW = 20_005.186 # kW
26 PV_EFFICIENCY_PCT = 20.16 # %
```

```

27 PV_NOCT          = 45.4          # °C
28 PV_TEMP_COEFF    = -0.34         # %/°C
29 PV_DEGRADATION    = 0.007        # /year (embedded in SAM output)
30 PV_INVERTER_EFF   = 97.53        # %
31 PV_DC_AC_RATIO    = 1.0
32
33 # --- Electrolyzer -----
34 EL_CAPACITY_KW     = 10_000        # kW rated power
35 SEC_INITIAL        = 55.3         # kWh/kg H2 (before stack replacement)
36 SEC_AFTER          = 45.0         # kWh/kg H2 (after stack replacement)
37 EL_PRESSURE_BAR    = 30           # bar
38 EL_LIFETIME_H      = 50_000       # operating hours before replacement
39 EL_TEMP_C          = 80           # °C
40
41 # --- Compressor & Storage -----
42 COMP_EFFICIENCY    = 0.92
43 COMP_SEC           = 1.2           # kWh / kg H2
44 STORAGE_PRESSURE   = 350          # bar
45 COMP_LIFETIME_H    = 90_000       # operating hours
46
47 # --- Environment -----
48 EF                 = 0.500        # kg CO2 / kWh (Algeria grid)

```

B.4 Economic parameters

```

49 # --- CAPEX (USD) -----
50 PV_CAPEX          = 31_172_083.88
51 EL_CAPEX          = 13_370_000.00
52 COMP_CAPEX        = 800_000.00
53 STORAGE_CAPEX     = 825_000.00
54 CS_CAPEX          = COMP_CAPEX + STORAGE_CAPEX # 1,625,000
55 EL_REPL_CAPEX     = 4_500_000.00
56 CS_REPL_CAPEX     = 500_000.00
57 TOTAL_INIT_CAPEX  = PV_CAPEX + EL_CAPEX + CS_CAPEX
58
59 # --- OPEX (USD/year) -----

```

```

60 OPEX_PV          = 440_114.40

61 OPEX_EL          = 0.05 * EL_CAPEX          # 5% of EL CAPEX / yr

62 OPEX_CS          = 0.04 * CS_CAPEX          # 4% of CS CAPEX / yr

63 TOTAL_ANNUAL_OPEX = OPEX_PV + OPEX_EL + OPEX_CS

64

65 # --- Financial assumptions -----

66 PROJECT_LIFETIME = 25

67 DISCOUNT_REAL   = 0.05          # 5% real discount rate

68 INFLATION         = 0.0482        # 4.82%

69 H2_PRICES         = [4.0, 6.0, 8.0] # $/kg - selling price scenarios

```

B.5 Hourly simulation loop (25 Years)

```

70 # --- initialise state variables -----

71 el_hours_cum = 0 ; comp_hours_cum = 0

72 el_replaced  = False ; comp_replaced = False

73 current_sec  = SEC_INITIAL ; buffer_h2 = 0.0

74

75 for i in range(n_hours):

76     yr          = int(hidx_arr[i]) // 8760 + 1

77     pv          = float(ac_arr[i])

78

79     # Electrolyzer: saturates at rated capacity

80     el          = min(pv, EL_CAPACITY_KW)

81

82     # Operating hours tracking

83     if el > 0:

84         el_hours_cum += 1

85

86     # Electrolyzer stack replacement check

87     if el_hours_cum >= EL_LIFETIME_H and not el_replaced:

88         el_replaced = True

89         current_sec = SEC_AFTER # efficiency improves

90         el_rep_year = yr

91

92     # Hydrogen production [kg/h]

```

```

93     h2          = (el / current_sec) if el > 0 else 0.0
94     buffer_h2   += h2                # accumulates in buffer tank
95
96     # Compressor: runs ONLY on surplus PV above electrolyzer saturation
97     surplus      = max(0.0, pv - EL_CAPACITY_KW)
98     if surplus > 0 and buffer_h2 > 0:
99         h2_compressed = min(surplus / COMP_SEC, buffer_h2)
100         comp_energy[i] = h2_compressed * COMP_SEC
101         buffer_h2     -= h2_compressed
102         comp_hours_cum += 1
103
104     # Curtailment: PV not used by electrolyzer or compressor
105     curtailment[i] = max(0.0, pv - el - comp_energy[i])

```

B.6 Performance indicators

```

106 LHV          = 33.33                # kWh/kg (Lower Heating Value)
107
108 # Electrolyzer conversion efficiency (LHV basis)
109 eff_before    = LHV / SEC_INITIAL    # ≈ 60.3%
110 eff_after     = LHV / SEC_AFTER     # ≈ 74.1%
111
112 # Electrolyzer capacity factor
113 total_op_hours = int((df["el_energy"] > 0).sum())
114 avg_op_hours_yr = total_op_hours / PROJECT_LIFETIME
115 rep_el_energy   = total_el / PROJECT_LIFETIME
116 CF_el          = rep_el_energy / (8760 * EL_CAPACITY_KW)
117
118 # Average hydrogen flow rate during operation
119 avg_h2_yr      = total_h2 / PROJECT_LIFETIME
120 H2_flow        = avg_h2_yr / avg_op_hours_yr # kg/h
121
122 # Solar-to-Hydrogen system efficiency (STH)
123 avg_pv_yr      = total_pv / PROJECT_LIFETIME
124 avg_h2_energy_yr = (total_h2 / PROJECT_LIFETIME) * LHV
125 eta_system     = avg_h2_energy_yr / avg_pv_yr # ≈ 56.3%

```

B.7 LCOH & economic model (DCF)

```
126 # --- Replacement cost schedule -----
127 replacement_costs = np.zeros(PROJECT_LIFETIME)
128 if el_replaced:
129     replacement_costs[el_rep_year - 1] += EL_REPL_CAPEX
130
131 # --- LCOH (discounted cash flow) -----
132 disc_costs = float(TOTAL_INIT_CAPEX)
133 disc_h2 = 0.0
134 for t in range(PROJECT_LIFETIME):
135     yr_label = t + 1
136     yr_h2 = yearly.loc[yr_label, "h2_kg"]
137     yr_cost = TOTAL_ANNUAL_OPEX + replacement_costs[t]
138     disc_costs += yr_cost / (1 + DISCOUNT_REAL) ** (t + 1)
139     disc_h2 += yr_h2 / (1 + DISCOUNT_REAL) ** (t + 1)
140
141 LCOH = disc_costs / disc_h2
142
143 # --- LCOH component breakdown -----
144 lcoh_capex_component = TOTAL_INIT_CAPEX / disc_h2
145 lcoh_opex_component = sum(TOTAL_ANNUAL_OPEX / (1+DISCOUNT_REAL)**(t+1)
146                             for t in range(PROJECT_LIFETIME)) / disc_h2
147 lcoh_repl_component = sum(replacement_costs[t] / (1+DISCOUNT_REAL)**(t+1)
148                             for t in range(PROJECT_LIFETIME)) / disc_h2
149
150 # --- Multi-price: NPV, IRR, Payback -----
151 for price in H2_PRICES:
152     cfs = [-TOTAL_INIT_CAPEX]
153     for t in range(PROJECT_LIFETIME):
154         rev = yearly.loc[t+1, "h2_kg"] * price
155         cfs.append(rev - TOTAL_ANNUAL_OPEX - replacement_costs[t])
156     npv_val = _npv(DISCOUNT_REAL, cfs)
157     irr_pct = _irr(cfs) * 100
```

```

158     cum        = np.cumsum(cfs)

159     payback     = next((i for i, v in enumerate(cum) if v >= 0), "Not Recovered")

```

B.8 Sensitivity analysis (Tornado)

```

160 def compute_lcoh(pv_c, el_c, dr, h2_total_override=None):
161     """Recompute LCOH for one-at-a-time sensitivity."""
162     tc = pv_c + el_c + CS_CAPEX
163     dc = float(tc) ; dh = 0.0
164     for t in range(PROJECT_LIFETIME):
165         yr_h2 = (h2_total_override / PROJECT_LIFETIME
166                 if h2_total_override
167                 else yearly.loc[t+1, "h2_kg"])
168         dc += (TOTAL_ANNUAL_OPEX + replacement_costs[t]) / (1+dr)**(t+1)
169         dh += yr_h2 / (1+dr)**(t+1)
170     return dc / dh
171
172 SENSITIVITY = {
173     "PV CAPEX"          : ([0.8, 1.2], "pv_capex"),
174     "Electrolyzer CAPEX": ([0.8, 1.2], "el_capex"),
175     "Discount Rate"     : ([0.8, 1.2], "discount"),
176     "SEC"               : ([0.85, 1.15], "sec"),
177     "Capacity Factor"   : ([0.85, 1.15], "cf"),
178 }
179
180 for param, (factors, kind) in SENSITIVITY.items():
181     for label, factor in zip(["Low", "High"], factors):
182         pv_c = PV_CAPEX * (factor if kind=="pv_capex" else 1)
183         el_c = EL_CAPEX * (factor if kind=="el_capex" else 1)
184         dr   = DISCOUNT_REAL * (factor if kind=="discount" else 1)
185         h2o   = None
186         if kind == "sec":
187             h2o = total_el / (SEC_INITIAL * factor)
188         if kind == "cf":
189             h2o = total_h2 * factor
190         lcoh_val = compute_lcoh(pv_c, el_c, dr, h2o)

```