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-THEME-

Optimization of solar powered hydrogen production using electrolysis devices

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Dedication

To my lovely parents,

No words or deeds can ever express my thankfulness. It is due to your unremitting encouragement, understanding, and unwavering support by my side that I could achieve this milestone. I hope this success will make you proud and not let down the hopes and aspirations you had reposed in me.

To my dear cousin,

Thank you for the support, your confidence and your wise counsel that guided me through the toughest times. I wish you all success and happiness in your life too.

To all my friends and family, In this short paragraph, I am not able to convey all the appreciation and love that I feel for you. All that I can honestly say is thank you sincerely, thank you to all those people who helped and supported, in any manner, to finalize this thesis.

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I would also like to thank all the individuals who, directly or indirectly, helped bring this project to fruition, either in the form of academic support, technical support, or moral support. I would like to thank my loving family and parents for their support, sacrifices, and encouragement. They helped me in my studies and success. They gave me the belief in myself that made all things possible and worthwhile.

Summary

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Nomenclature

P_{pv}	Electric power output of a PV array (kw)
Y_{pv}	Rated power of the photovoltaic array (kw)
f_{pv}	Derating factor
G_T	Incident solar radiation on the PV array (kw/m^2)
$G_{T,STC}$	Standard incident radiation (kw/m^2)
α_p	Power temperature coefficient (%/C°)
T_c	PV cell temperature (C°)
$T_{c,STC}$	Standard temperature (PV) (C°)
P_{EL}	Energy consumption of an electrolyzer
η_{EL}	Efficiency of the electrolyzer
HHV_{H2}	Higher heating value of hydrogen
m_{H2}	Hydrogen flow rate at the electrolyzer output
$C_{NPC,tot}$	Total net present cost ($)
$C_{ann,tot}$	Total annualized cost ($/year)
N	Number of years
i	Annual real discount rate
E_{served}	Total electrical load served (kwh/year)
L_{H2}	Total annual hydrogen load (kg/year)

Abbreviation

AEL	Alkaline Electrolyzer

ATR   Autothermal Reforming

CCS   Carbon Capture and Storage

CRF   Capital Recovery Factor

DC   Direct Current

FCEVs   Fuel Cell Electric Vehicles

GHI   Global Horizontal Irradiation

HOMER Pro   Hybrid Optimization of Multiple Energy Resources

HRES   Hybrid Renewable Energy Systems

KOH   Potassium Hydroxide

LCC   Life Cycle Cost

LCOE   Levelized Cost of Energy

LCOH   Levelized Cost of Hydrogen

LOHCs   Liquid Organic Hydrogen Carriers

NPC   Net present cost

PV   Photovoltaic

PV-EC   Photovoltaic-Electrolysis

PEM   Proton exchange membrane

SMR   Steam Methane Reforming

SOEC   Solid Oxide Electrolyzer Cells

Optimization of solar powered hydrogen production using electrolysis devices

Abstract

This thesis uses HOMER Pro to simulate and optimize a solar-powered off-grid green hydrogen system. Because of its high solar potential, Ouargla, Algeria, is chosen as the case study. Alkaline, PEM, and SOEC types of electrolyzer were examined. The most economically viable option was the alkaline electrolyzer, which successfully produced 10 kg of hydrogen per day using only renewable energy. The research confirms the technological and economic feasibility of off-grid hydrogen production in regions of plentiful sun and stresses the importance of component cost and efficiency in system design.

Key words: Electrolyzer, simulation, optimization, Hydrogen production.

Optimisation de la production d'hydrogène solaire en utilisant des dispositifs d'électrolyse

Résumé

Cette mémoire utilise HOMER Pro pour simuler et optimiser un système d'hydrogène vert solaire hors réseau. Ouargla, en Algérie, a été choisie comme étude de cas en raison de son potentiel solaire élevé. L'étude a examiné les types d'électrolyseurs alcalins, PEM et SOEC. L'option la plus rentable était l'électrolyseur alcalin, qui produisait avec succès 10 kg d'hydrogène par jour en utilisant uniquement de l'énergie renouvelable. La recherche confirme la faisabilité technologique et économique de la production d'hydrogène hors réseau dans les régions riches en soleil, soulignant l'importance du coût des composants et de l'efficacité dans la conception du système.

Mots-clés : Électrolyseur, simulation, optimisation, production d'hydrogène.

تحسين إنتاج الهيدروجين بالطاقة الشمسية باستخدام أجهزة التحليل الكهربائي

ملخص

تستخدم هذه المذكرة برنامج HOMER Pro لمحاكاة وتحسين نظام الهيدروجين الأخضر الذي يعمل بالطاقة الشمسية خارج الشبكة. ونظرا لإمكاناتها الشمسية العالية، تم اختيار مدينة ورقلة بالجزائر كدراسة حالة. تم فحص أنواع المحللات الكهربائية القلوية، PEM، و .SOECوكان الخيار الأكثر جدوى من الناحية الاقتصادية هو المحلل الكهربائي القلوي، الذي نجح في إنتاج 10 كجم من الهيدروجين يوميًا باستخدام الطاقة المتجددة فقط. ويؤكد البحث الجدوى التكنولوجية والاقتصادية لإنتاج الهيدروجين خارج الشبكة في المناطق ذات الشمس الوفيرة ويشدد على أهمية تكلفة المكونات وكفاءتها في تصميم النظام.

الكلمات المفتاحية: المحلل الكهربائي، المحاكاة، التحسين، إنتاج الهيدروجين.

General Introduction

The global energy market is increasingly focused on capping greenhouse gas emissions and transitioning to green energy systems. Hydrogen, as a clean energy carrier and one that is highly versatile, has been the pillar of this shift, enabling industry, transport, and energy storage decarbonization. [1] However, the environmental benefits of hydrogen depend significantly on the method of its production. While most hydrogen is made today through steam methane reforming (SMR), a fossil-fuel process that emits tons of CO_2, green hydrogen—made from water electrolysis fueled by renewables is a clean option. [2]

Among all renewable energy sources, solar energy stands out due to its omnipresence, scalability, and decreasing cost. Direct sunlight-to-electricity-conversion photovoltaic (PV) technology has made unprecedented progress in the last few decades, with commercial module efficiencies exceeding 20% and laboratory-scale perovskite cell efficiencies exceeding 30%.[3] With water electrolyzer, PV systems enable carbon-emission-free production of green hydrogen, and therefore solar-powered hydrogen production is a key driver of the global energy transition. [4]

Solar-powered hydrogen production is handicapped by some constraints despite potential. The solar power being variable demands efficient energy management policies for the continuous operation of electrolyzers. Moreover, the relatively low overall efficiency of PV-electrolysis systems varying from 8% to 14% is another constraining factor of its application at a large scale [5]. And even humongous capital costs of PV panels and electrolyzers limit economic viability of the systems because now the levelized cost of hydrogen (LCOH) comes to $4-$6/kg, whereas that for hydrogen from fossils is $1-$2/kg. [6]

At the global level, Algeria too has taken tangible steps towards becoming an emerging green hydrogen hub in the future. Algeria's National Hydrogen Strategy, published in 2021, laid down ambitious goals to produce and export green hydrogen on the back of the rich solar resources available in the country and its proximity to the EU market. The strategy includes constructing demonstration schemes, constructing domestic capability, and incorporating hydrogen into the national energy transition plan highlighting the country's commitment to clean energy innovation and global decarbonization.

The aim of this thesis is to evaluate the feasibility of green hydrogen production through solar photovoltaic-powered electrolysis (PV-EC) under Algerian conditions with focus on optimizing production efficiency, cost competitiveness, and scalability. Throughout the study, advanced simulation and modeling platforms, such as HOMER Pro, are employed to simulate system operation and conduct a techno-economic assessment, hence complementing the whole vision of sustainable hydrogen systems as per Algeria's and global climate goals.

Chapter one gives general background information on hydrogen as a clean energy carrier, such as production processes, applications, and storage technologies, with particular emphasis on green hydrogen generated through solar-powered electrolysis. Chapter two gives an overview of the HOMER Pro simulation and optimization software, its main features, system modeling, and methodological workflow. Chapter three addresses the design, modeling, and simulation of a hybrid renewable energy system for stand-alone hydrogen production, with Ouargla, Algeria being taken as the case study location. The chapter includes system configuration, input parameters, component specifications, and performance analysis.

Chapter I

Generalities on hydrogen, production methods and applications

I.1 Introduction

The global energy economy is undergoing an unprecedented transition to meet the need for reducing greenhouse gas emissions and mitigating global warming. Carbon dioxide release as fossil fuel-based energy systems poses a significant challenge, thereby necessitating the production of clean and sustainable energy carriers. Hydrogen is being considered as an energy carrier because it has high energy value, is versatile, and zero-emission at the point of use if produced from renewable sources. Green hydrogen, generated by water electrolysis with renewable energy sources such as solar or wind, offers a pathway to decarbonize transportation, industry, and power generation sectors. [7] This chapter seeks to explore hydrogen production, storage, and utilization technologies with special emphasis on solar-powered hydrogen generation systems.

I.2 Hydrogen definition

Hydrogen is the simplest and most abundant element in the universe, consisting of just one proton and one electron. This lightweight, colorless gas is found in great abundance in stars and gas giants and is a fundamental building block in the chemistry of life. As a versatile energy carrier with the highest energy content of any common fuel by weight, hydrogen holds promise in various fields, including renewable energy and space exploration. It's essential in teaching the foundations of chemical reactions, bonding, and energy transformations, providing a gateway to understanding more complex scientific concepts. [8] The main characteristics of hydrogen, including its atomic structure, physical state, and discovery, are summarized in **Figure I.1**.
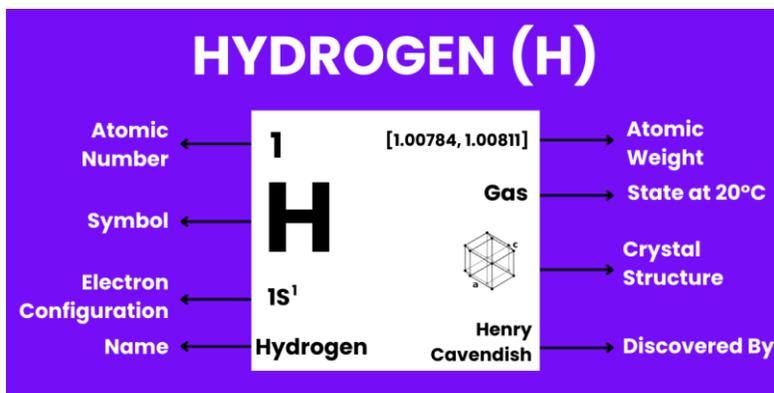
Fig I.1: Hydrogen properties [9]

I.3 Types of hydrogen

Hydrogen is classified into different forms based on the production method and the subsequent environment effect, most broadly differentiated by a color code. The primary types of hydrogen are green, blue, grey, brown, pink, and white hydrogen. [10]

Green hydrogen: is produced by renewable energy-based electrolysis such as solar, wind, or hydropower, which is the most sustainable and eco-friendly type of hydrogen that produces no greenhouse gas emissions. [11]

Blue hydrogen: is manufactured from natural gas through the steam methane reforming process but with CCS to reduce GHG emissions. Blue hydrogen is an intermediate low-carbon option. [11]

Grey hydrogen: which is ubiquitous in the world, is also manufactured from fossil fuels like natural gas but without CCS and is high in carbon emissions. [11]

 Brown (or black): hydrogen is created by coal gasification and is one of the most carbon-intensive production methods. [12]

Pink hydrogen: is produced by nuclear energy-fueled electrolysis, offering the carbon-neutral alternative. [12]

White hydrogen: is geological hydrogen naturally occurring in the ground. This color-coded categorization allows for the differentiation of hydrogen types according to their ecological imprint and informs sustainable hydrogen development strategies. [12]

I.4 Hydrogen production methods

Hydrogen can be produced by a number of methods, traditionally dominated by processes based on fossil fuels. These processes, although commercially established and inexpensive, have a high greenhouse gas emission impact and are thus non-green. **Fig I.2** provides a schematic overview of various hydrogen production methods.
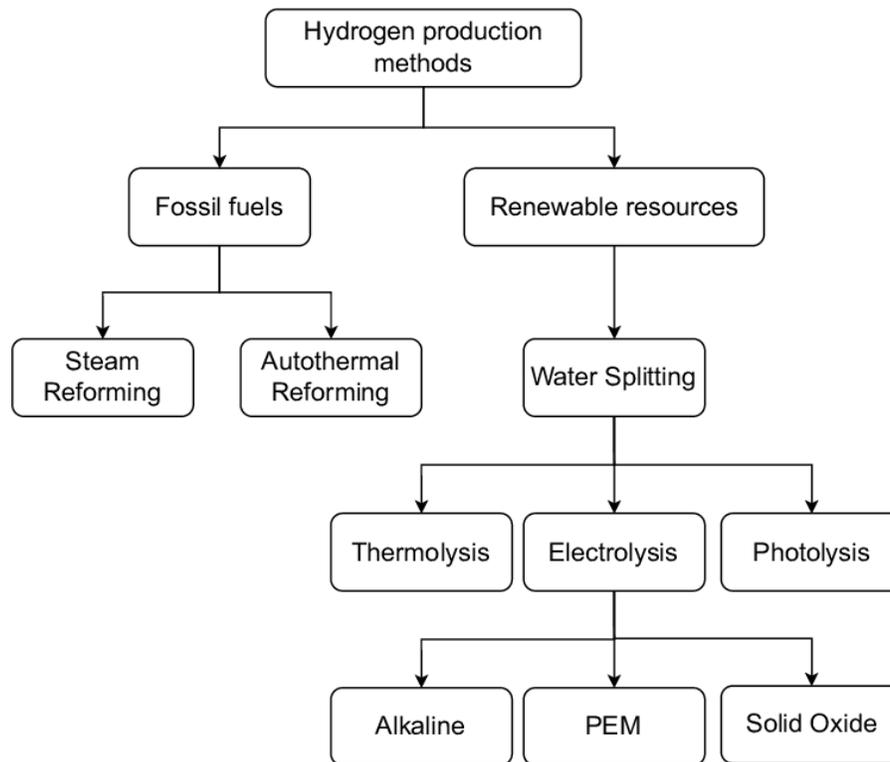
Fig I.2: schematic of hydrogen production methods [13]

I.4.1 Conventional Hydrogen Production

The most common process is Steam Methane Reforming (SMR), a process by which natural gas comes into contact with high-temperature steam to produce hydrogen and carbon dioxide. The process accounts for approximately 70% of world hydrogen production. Other fossil fuel-based processes include: [14]

- **Autothermal Reforming (ATR):** This is a combination of partial oxidation and steam reforming in a reactor with enhanced thermal efficiency.
- **Partial Oxidation (POX):** Hydrocarbon oxidation with a low oxygen supply to produce hydrogen and CO.
- **Coal Gasification:** Converts coal into syngas (a H_2-CO mixture), followed by water-gas shift reactions to increase the hydrogen yield.

They are high-carbon-emitting processes and fall under the classification of gray hydrogen production. If carbon capture and storage (CCS) is added, then it is blue hydrogen, which reduces but not eliminates emissions.

I.4.2 Green Hydrogen Production

Production of hydrogen from biomass: There are two different ways to produce hydrogen from biomass: thermochemical conversion, which is exemplified by processes like pyrolysis or gasification, and biological processes, which include methods like biophotolysis of water using dark fermentation, microalgae, and a two-step procedure that combines photo and dark fermentation. [15]

Water electrolysis uses electricity from renewable energy sources like wind, solar, or geothermal and hydraulic power. [16] In this work, hydrogen was produced via electrolysis driven by renewable energy sources. Additionally, as seen in Figure I.3 below:

Fig I.3: Green hydrogen production [17]

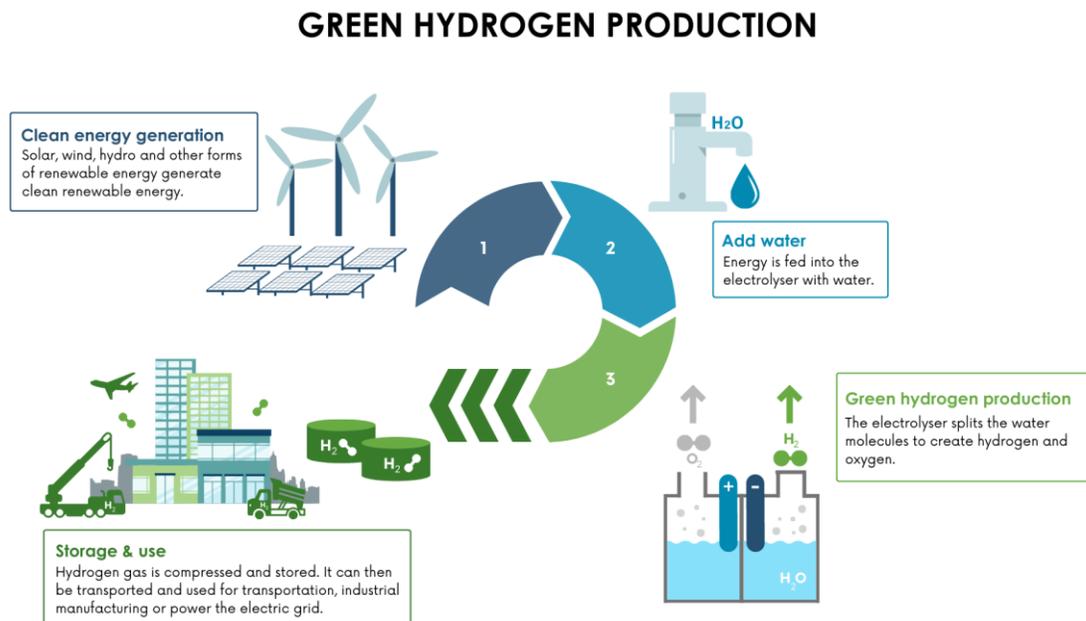## I.5 Water electrolysis

Water electrolysis is one such electrochemical water splitting technique for green hydrogen production with the help of electricity, which is emission-free technology. The basic reaction of water electrolysis is as follows in Eq. (1) [18]

$$2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g) \qquad\qquad (1)$$
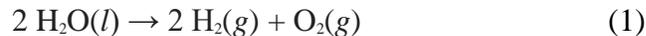
This is carried out within a device known as an electrolyzer, which is usually composed of an electrolyte situated between two electrodes (an anode and a cathode). When water molecules are exposed to direct current (DC), they oxidize at the anode to produce oxygen gas and protons, and they are reduced at the cathode to form hydrogen gas. The kind of electrolyte utilized dictates its nature based on the technology. [19]

Alkaline water electrolysis, solid oxide water electrolysis, proton exchange membrane water electrolysis, are the most crucial methods for producing green hydrogen. Each of these technologies has advantages, disadvantages, and potential applications in the production of hydrogen.

I.5.1 Alkaline Electrolyzer (AEL)

The oldest and most used electrolysis method for producing hydrogen is alkaline electrolyzer (AEL). They employ non-precious metal electrodes like nickel or stainless steel and function on a liquid alkaline electrolyte, usually potassium hydroxide (KOH) or sodium hydroxide (NaOH). A diaphragm keeps the hydrogen and oxygen gasses from mingling as the electrochemical reaction takes place between two electrodes, as illustrated in Fig I.4. It works at relatively low temperatures (60–80°C). The advantages are low initial cost and long operational life. However, AEL systems have: [20]

- Lower current density, i.e., larger system sizes.
- Slower dynamic response, and hence are less appropriate to use with variable renewable energy sources.
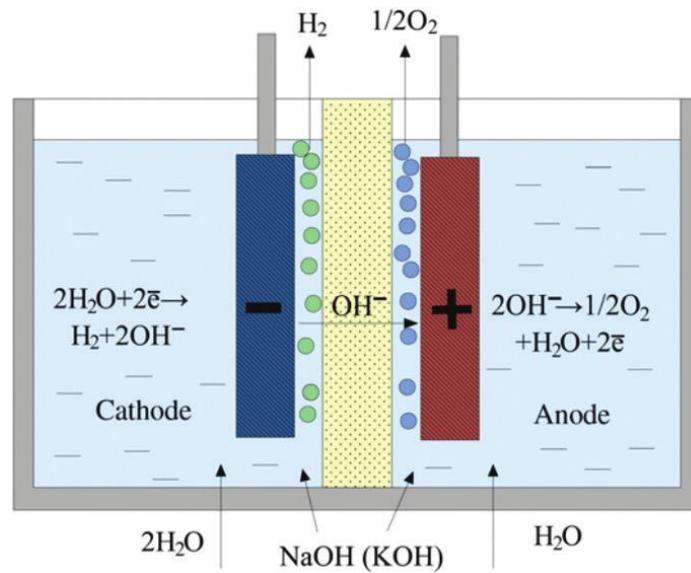
Fig I.4: Schematic diagram of the alkaline electrolysis cell [21]

I.5.2 Proton Exchange Membrane (PEM) Electrolyzer

In contrast to other forms, PEM electrolyzer technology depends on low temperatures. A polymer electrolyte membrane, sometimes referred to as a proton exchange membrane, functions as an ionic conductor at its center. This calls for an acidic electrolyte solution, and for effective reactions, costly precious metal catalysts, such as platinum, must be used on the electrodes. Usually composed of Nafion, this membrane is firm and thin. Protons H+ are transferred from the anode to the cathode via the membrane. The anode and cathode are also separated by it. The anode and cathode processes are unaffected by this separation, which permits free movement of hydrogen and oxygen ions. [20] the chemical equations are presented in Figure (I.5)

The purpose of this method is to decrease the downsides of alkaline electrolysis. Although this technology has multiple advantages (such as being small and effective, which makes it appropriate for small-scale applications), it is costly and yet in the early stages of research.
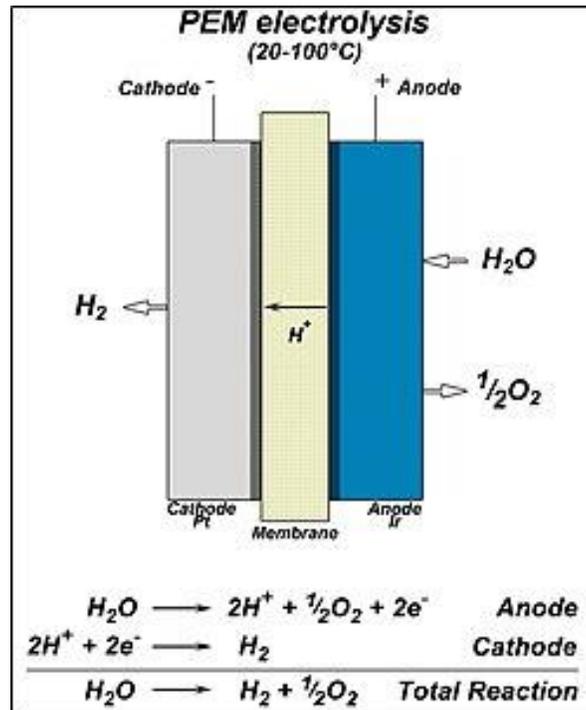
Fig I.5: Diagram of PEM electrolysis reactions [22]

I.5.3 Solid Oxide Electrolyzer Cells (SOEC)

The most effective type of electrolyzer is Solid Oxide Electrolyzer Cells (SOEC), which function at high temperatures (usually 600–850°C). As depicted in Fig I.6, they transfer ions of oxygen from the cathode towards the anode using a solid ceramic oxide as an electrolyte. Compared to AEL or PEM technologies, SOECs can achieve electrical efficiencies of up to 85% since they use both electricity and heat, usually from cogeneration systems or industrial waste heat. Faster reaction kinetics and less electrical energy are needed to split water thanks to the high-temperature operation, especially when some of the energy is supplied as heat. Because of this, SOECs are especially appealing for large-scale hydrogen production in industries with access to high-temperature heat. However, SOEC technology's current commercial viability is limited by issues with material durability at high temperatures, system complexity, and high capital expenditures, which keep it at the pilot or demonstration stage.[20]

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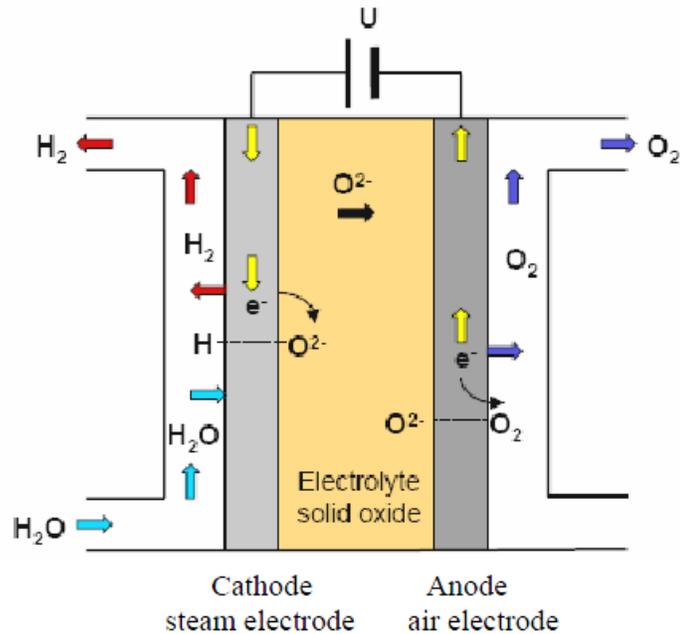
Fig I.6: Diagram of solid oxide electrolyzer cell [23]

I.6 Applications of Hydrogen

Hydrogen, thanks to its unique chemical properties and high energy density, is an extremely versatile element with a wide variety of applications across a large number of industries. Its importance is also increasing consistently as the world shifts towards sustainable energy pathways and cleaner industrial processes. From a commodity chemical feedstock to a promising energy carrier, hydrogen's importance is still on the rise as R&D efforts improve its practical uses and the efficiency of its production and utilization. [24]

I.6.1 Transport Sector

Hydrogen is used in the transportation industry primarily as a green fuel for Fuel Cell Electric Vehicles (FCEVs). As illustrated in Fig I.7 hydrogen is carried in FCEVs in high-pressure tanks and fed into a fuel cell, where it reacts with oxygen in the atmosphere in an electrochemical process to generate electricity. Electricity powers an electric motor, enabling the vehicle to move with zero tailpipe emissions the sole emission being water vapor. This makes hydrogen particularly beneficial towards alleviating urban pollution and assisting decarbonization.

Hydrogen vehicles are the sole ones, as opposed to battery-electric vehicles, in which it is possible to re-fuel within a matter of minutes and experience increased driving ranges, and therefore best suit heavy-duty applications like buses, trucks, locomotives, and even shipping and aviation sectors. In addition to being used to power fuel cells directly, hydrogen can also be converted into synthetic fuels like e-methanol or ammonia and fueled into internal combustion engines or ship engines with comparatively modest modifications. The versatility, energy density, and clean nature of hydrogen hold tremendous potential for replacing fossil fuels in a wide variety of transport modes. [25]
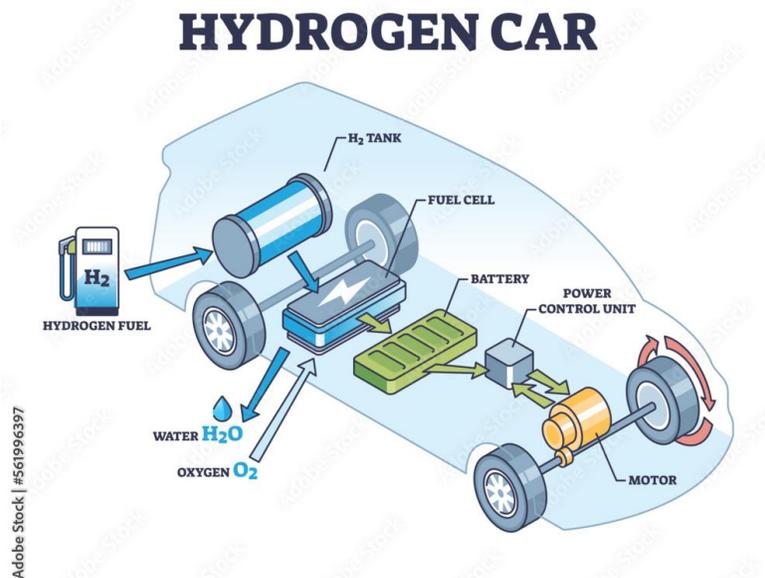
Fig I.7: Schematic Diagram of a Hydrogen Fuel Cell Car [27]

I.6.2 Industrial Uses

Hydrogen has for decades been employed to execute various industrial applications. Fig I.8 illustrates some significant applications include: [26]

- Synthesis of ammonia by Haber–Bosch process.
- Methanol production, a key chemical and synthetic fuel feedstock.
- Petroleum refining, where hydrogen is used in hydrocracking and desulfurization.

- Steel manufacturing, as a potential future coal replacement in direct reduction processes (green steel).
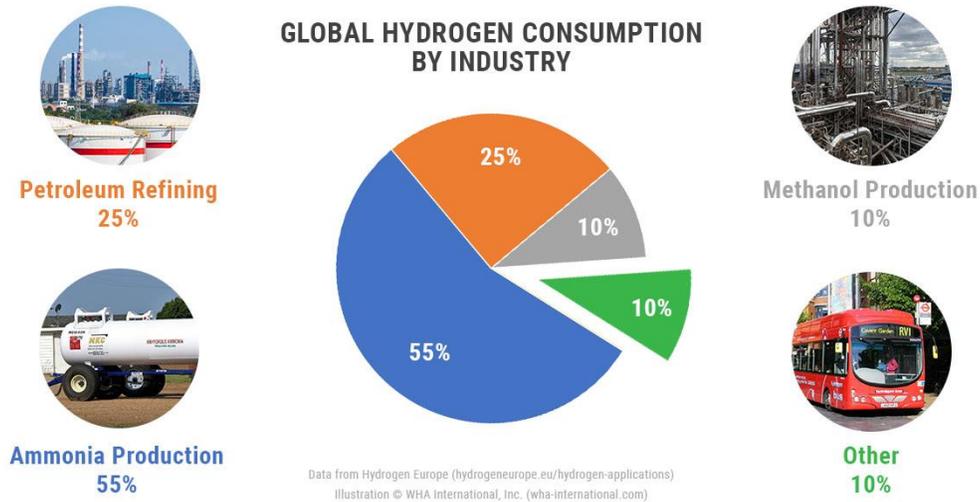
Fig I.8: Top Industrial Uses of Hydrogen [28]

I.6.3 Electricity Generation

Hydrogen is increasingly being utilized as a clean and universal energy carrier for power generation, particularly in high renewable penetration energy systems. Some of the key methods involve the utilization of fuel cells, which convert hydrogen and oxygen into electricity through an electrochemical reaction, with water and heat being the only byproducts. **Fig I.9** illustrates this zero-emission process which makes hydrogen fuel cells appropriate for distributed power, such as residential backup power, remote or off-grid power, and portable applications. Hydrogen can also be utilized in internal combustion engines and gas turbines that have been modified, offering a low-carbon alternative to conventional fossil fuels in industrial processes or large power plants. [29]
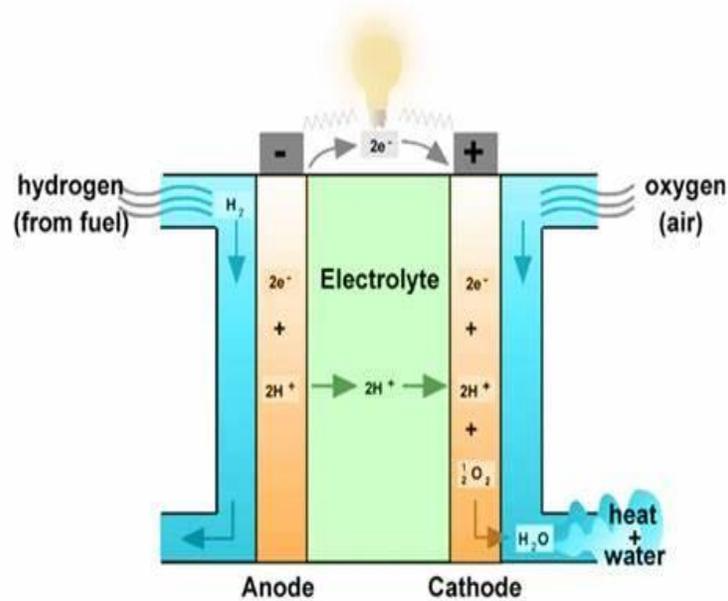
Fig I.9: Schematic of a PEM fuel cell operation [30]

I.6.4 Grid Balancing and Energy Storage

A further important application of hydrogen in electricity generation is its application in grid balancing and energy storage. Excess power produced from variable renewables, i.e., wind or solar, can be used to power electrolysis devices that yield hydrogen. Hydrogen can be stored for long periods and then be converted back to electricity when there is low production from renewable energies, a process known as power-to-gas-to-power. This approach makes the grid more flexible, enables seasonal energy storage, and helps ensure a stable electricity supply. Although challenges such as cost and conversion losses remain, hydrogen can be expected to play a significant role in the decarbonization and stabilization of future power grids as technology continues to evolve and infrastructure expands.

I.7 Hydrogen Storage Methods

The unique properties of hydrogen, such as its low volumetric energy density under room conditions, pose severe challenges to the storage of hydrogen, requiring new solutions for high

storage densities, safety, and economy. Efficient and reliable storage technologies are essential for most applications like fuel cell vehicles, stationary power generation, and grid-scale energy storage for grid balancing. The development of future hydrogen storage technologies is one of the most significant research and development to advance beyond existing constraints and make hydrogen a clean source of energy. [31]

Below are the different methods of hydrogen storage:

I.7.1 Physical Storage Methods

Hydrogen can be stored physically in gaseous or liquid form:

- **Compressed Gas Storage:** Hydrogen gas is highly compressed to pressures usually between 350 and 700 bar (5,000–10,000 psi) in order to increase its volumetric energy density. The compressed gas is safely stored in sophisticated composite pressure vessels. It is the most common practice used in fuel cell vehicles and stationary storage but requires robust containment systems and protective mechanisms.

- **Liquid Hydrogen Storage:** Hydrogen is cooled to cryogenic temperatures (−252.8°C at atmospheric pressure) to liquefy it, increasing energy density above compressed gas. Liquefaction is energy intensive, however, and has to be stored in insulated tanks to minimize boil-off losses. Liquid hydrogen storage can be suitable for large-scale or long-duration storage but is technically and economically demanding.

I.7.2 Material-Based Storage Methods

Material-based storage of hydrogen is storage in or on material using absorption or adsorption processes:

- **Metal Hydrides:** Certain metals and alloys are capable of taking up hydrogen atoms in their lattice structure, and hydrogen can be stored densely under moderate temperature and pressure. Metal hydrides offer high volumetric density and safety advantages but can include heat management during hydrogen uptake and discharge.

- **Chemical Hydrogen Storage**: Hydrogen is kept in the form of chemical compounds such as ammonia or liquid organic hydrogen carriers (LOHCs). They are simpler to store and transport compared to hydrogen and release hydrogen through catalytic reactions when needed.

- **Adsorption on Nanostructured Materials**: Hydrogen is adsorbed onto the surface of carbon nanotubes and metal-organic framework (MOF) and other porous materials. These strategies are being researched to improve storage capacity and kinetics but are suffering with stability and cost issues.
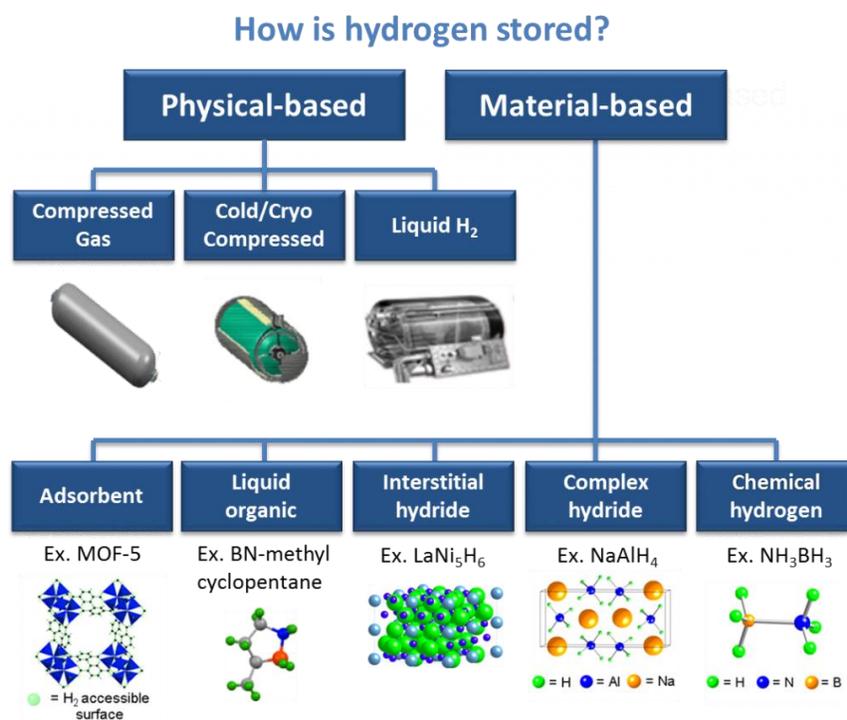
Fig I.10: Classification of Hydrogen Storage Methods [32]

➢ **Advantages and Challenges**

Hydrogen storage enjoys the advantages of high gravimetric energy density (about three times that of gasoline on a weight basis), the capacity to store for long periods with negligible energy loss, and flexibility from small to large scale. It also supports grid stability by serving as an energy reservoir between supply and demand.

Issues related to hydrogen storage are:

- **Low volumetric energy density:** Compressed or liquefied hydrogen has a lower volume-based energy density compared to conventional fuels, necessitating large or pressure tanks for storage.

- **Energy losses:** Round-trip efficiency for hydrogen storage (to hydrogen and back to power) is usually 40–50%, as opposed to efficiencies of battery storage ranging from 70–90%.

- **High capital costs:** Cryogenic tanks, compressors, and fuel cells are costly technology, impacting economies.

- **Safety concerns:** Hydrogen flammability and diffusibility require utmost care in handling and storage.

I.8 Conclusion

This chapter provided an overall overview of the hydrogen energy landscape, identifying the prevalent production technologies, potential applications, and storage options. It established the premise that among various production technologies, solar-electrolysis offers the most sustainable path for the production of hydrogen, but it is currently limited by issues of cost and efficiency. Finally, effective storage solutions are critical to the realization of hydrogen as a clean energy carrier.

The intuition developed here provides the basis for technical modeling and system optimization in the following chapters, particularly stand-alone solar-hydrogen system design and evaluation for real-world use.

Chapter II

GENERALITIES ON HOMER PRO AND KEY EQUATIONS

II.1 Introduction to HOMER Pro

The transition towards clean and decentralized power systems has created the demand for advanced modeling software that can optimize and model high-end hybrid configurations. HOMER Pro (Hybrid Optimization of Multiple Energy Resources) is a premium software tool used to design and techno-economic evaluation of hybrid renewable energy systems (HRES) such as systems incorporating solar, wind, diesel, storage, and hydrogen components. [33]

Initially designed by the U.S. National Renewable Energy Laboratory (NREL) and now maintained current by HOMER Energy by UL, HOMER Pro enables researchers, engineers, and energy planners to model standalone or grid-supporting microgrids under various economic, technical, and environmental constraints. Its primary purpose is to identify the optimum system configuration that supplies energy demand reliably and economically throughout the system life.

What distinguishes HOMER Pro from other modeling programs is that it is able to simulate hourly a whole year and even perform sensitivity and optimization analyses. This allows users to explore trade-offs between many different system configurations and component sizes with consideration for variability in resource availability, load profiles, and cost parameters.

HOMER Pro has been applied extensively in off-grid renewable energy system analysis, microgrid feasibility studies, and more recently, in green hydrogen system production, where it helps evaluate the interconnection of electrolyzers and hydrogen storage with intermittent renewable power sources

II.2 HOMER Pro Key Features

HOMER Pro is a robust energy system design and optimization software package that includes:

System Modeling: HOMER Pro has the ability to model intricate energy systems with various components like photovoltaic (PV) arrays, wind turbines, diesel generators, batteries, converters, hydrogen electrolyzers, and loads. The software supports both AC and DC bus configurations, making it feasible for users to model hybrid systems with a mix of power electronics and varied topologies. The operation of every component is simulated hourly for a full

year (8,760 hours), taking into account technical parameters such as efficiencies, operational limitations, degradation, and dispatch strategy.

Economic Analysis: One of the key strengths of HOMER is that it can conduct detailed life cycle cost analysis. It calculates key economic metrics such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), internal rate of return (IRR), and payback period. These metrics consider various cost factors including capital investment, replacement cost, operation and maintenance (O&M) cost, fuel cost, and economic assumptions such as inflation and discount rates. This enables users to assess the economic feasibility and long-term sustainability of energy system configurations.

Sensitivity Analysis: HOMER Pro provides a robust basis for sensitivity analysis, allowing users to analyze the effect of uncertainties on system performance and economic outcomes. Parameters such as solar irradiance, fuel prices, component efficiencies, hydrogen demand, and load variations can be systematically varied to identify critical variables influencing optimum system design. This capability is particularly useful for renewable energy projects, where externalities have the tendency to change and continue to be uncertain in the long run. [34]

II.3 System Component Modeling

HOMER Pro has a free-form, modular way of modeling all the major components of hybrid power systems. All components, whether for generation, storage, conversion, or utilization, are described by a set of technical and economic parameters. These include rated capacity, efficiency, operating limits, cost relationships, and lifespan. The software simulates dynamic component interactions under changing conditions such as solar irradiance, ambient temperature, and load demand to enable accurate determination of performance throughout the entire project period. [35]

II.3.1 Photovoltaic (PV) Modules

Photovoltaic modules are a fundamental component of solar-based hybrid systems. As shown in Fig II.1 HOMER Pro PV systems are modeled based on their rated capacity (kW), derate factor (to account for losses such as dust, wiring, and shadow), and cost parameters such as capital, replacement, and maintenance costs. The software uses hourly solar radiation data (either Global

Horizontal Irradiance or Direct Normal Irradiance) and calculates the actual energy yield by the PV array for the year. [36]

HOMER also comprises:

Temperature Effects: Since PV efficiency reduces with rising cell temperatures, HOMER applies temperature derating based on manufacturer-specified temperature coefficients and air ambient temperatures.

Tilt and Orientation Corrections: The tilt and azimuth orientation of the PV panels may be specified by the user, affecting annual solar collection. The parameters can also be optimized by HOMER for maximum output.

Weather-Induced Fluctuation: Cloud cover and irradiance variability are both included in the model in order to replicate the variability of solar power, allowing for accurate sizing of storage and backup systems.

Fig II.1: Configuration and Cost Parameters for Photovoltaic Systems in HOMER

II.3.2 Wind Turbines

If included, wind turbines can be simulated as part of hybrid renewable power systems to augment solar generation in locations where wind resources are of economic significance in HOMER Pro. Hourly wind speeds and each turbine's power curve are used by the program to compute electricity output for each time step in the simulation year. Local wind profiles can be inputted for specific sites, or default datasets can be utilized to characterize local wind conditions.[37] Primary modeling features are:

Wind Speed Distribution and Power Curve Use:

The electrical output of the wind turbine is obtained through matching hourly wind speeds to the power curve supplied by its manufacturer with specific electrical output at specific wind speeds. The curve is critical in evaluating turbine performance, especially for those turbines that only produce optimal performance under particular speed intervals.

Hub Height Adjustments:

HOMER applies a logarithmic wind profile equation to wind speed correct at the turbine hub height, based on surface roughness and reference height. This allows accurate simulation of wind speed variation at installed height.

Environmental Adjustments:

Air density, affecting wind turbine performance, is automatically adjusted for altitude and ambient temperature at the site. As air density decreases with altitude or higher temperatures, these are necessary in providing accurate power estimates.

Turbine Operating Conditions:

HOMER allows specification of main turbine operating limits, including:

- Cut-in speed: Speed of the wind that power is produced.

- Rated speed: Speed of the wind that the turbine delivers maximum (rated) power.

- Cut-out speed: The maximum safe wind speed at which the turbine will cut off to avoid mechanical damage.

II.3.3 Electrolyzer

In HOMER Pro, electrolyzers are modeled as hydrogen-generating units that convert electrical energy to chemical energy by water molecule splitting into oxygen and hydrogen via electrolysis. While HOMER uses a simplified model for the representation of electrolyzer dynamics, it can also give meaningful analysis of their impact on system performance and economics. Fig II.2 illustrates the various settings available for electrolyzer systems.

The electrolyzer efficiency can be input either as fixed percentage or via an efficiency look-up table that is a function of input power. Fixed efficiency is the default assumption of HOMER, that is, the same amount of electricity will always produce the same volume of hydrogen. This is a simplification useful for rough system design but does not permit variations in performance with temperature, pressure, or dynamic loading. [38]

In a majority of off-grid applications, the electrolyzer consumes excess electricity—electricity not immediately needed by electric loads or other devices. However, when hydrogen is needed to meet a hydrogen load or to power a hydrogen generator, the electrolyzer runs, consuming renewable or stored electricity that is on hand.

Key electrolyzer parameters the user can define are:

- Rated power consumption (kW): Maximum electrical input capability.

- Hydrogen production rate (kg/hour): Rated capability for output based on input and efficiency.

- Efficiency (%): Typically 55% to 85% based on technology (AEL, PEM, or SOEC).

- Minimum and maximum load ratios (%): Operational limits that define flexibility toward varying power input.

Fig II.2: Configuration and Optimization Parameters for Electrolyzer Systems in HOMER

II.3.4 Hydrogen Storage and Fuel Cells

Hydrogen storage is simulated in HOMER Pro using pressurized tanks, which act as buffers to balance hydrogen production and demand. This is crucial in stand-alone systems where the operation of the electrolyzer and hydrogen demand do not overlap in time. The storage tank parameters are:

- Storage capacity (kg): The total hydrogen that can be stored.
- Charge/discharge constraints: Defines the rates and times at which hydrogen can be stored or retrieved.
- Compression energy and leakage losses: If specified, HOMER takes into account the energy required to compress and store hydrogen and minor leakage over time.

Fuel cells, on the other hand, are simulated as conversion devices that generate electricity from stored hydrogen. They play a key role in systems where hydrogen is used to support electrical loads during periods of low renewable generation. The key parameters for fuel cell modeling include:

- Electrical efficiency (%): Typically 55–85%, technology-dependent.

- Startup and shutdown behavior: Some fuel cells experience warm-up times and cannot operate instantaneously.

- Hydrogen consumption rate (kg/kWh): Specifies how much hydrogen is needed to meet a given electric load.

II.3.5 Batteries

HOMER Pro also supports different battery technologies like lead-acid, lithium-ion, and flow batteries. As illustrated in Fig II.3, batteries are a necessary element for power supply stabilization, particularly if the renewable input source is intermittent, i.e., solar or wind. They also allow for the optimization of electrolyzer operation by storing excess electricity for use during low generation periods. [39]

Battery behavior is modeled in the software through detailed simulation of:

- State of Charge (SOC): Keeps track of the amount of usable energy in the battery at each hour.

- Round-trip efficiency (%): The ratio of energy recovered from the battery to energy used for charging, typically 80–95%.

- Depth of Discharge (DoD): Defines the percentage of the total capacity of the battery that may safely be used without causing harm.

- Cycle life and degradation: HOMER takes into account battery degradation over time by reducing effective storage capacity per charge-discarge cycle.

Fig II.3: Configuration and Performance Parameters for a Battery in HOMER

Behavior of batteries plays a critical role in power supply stabilization and optimization of the electrolyzer when renewable input is intermittent.

II.3.6 Loads

HOMER Pro allows the definition of load profiles that mirror actual energy use. Loads may be classified as AC loads, DC loads, or hydrogen-specific loads, and may vary hourly, daily, or seasonally to represent actual usage. [40]

Some of the key modeling aspects for loads include:

- Sectoral demand: Users can model residential, commercial, or industrial electricity consumption, each having different consumption patterns.
- Hybrid hydrogen demand: HOMER has the capability to simulate hydrogen consumption for refueling stations, ammonia production, or power generation via fuel cells.

II.3.7 Power Converters

n hybrid systems that combine AC and DC components, power converters are instrumental in making generation sources, storage, and loads interoperable with one another. HOMER Pro simulates bidirectional converters that perform both inversion (DC to AC) and rectification (AC to DC) as needed. [41]

The following converter parameters are considered:

- Conversion efficiency (%): Typically ranges from 90–98% depending on technology and quality.
- Rated capacity (kW): Defines the maximum power that can be converted in both directions.
- Directionality of operation: HOMER automatically determines the direction of power flow based on source and load characteristics.

II.4 Workflow in HOMER Pro

The HOMER Pro modeling process has a structured workflow that guides the user from system definition to simulation and ultimately results interpretation. The workflow helps ensure that hybrid renewable energy systems are thoroughly analyzed by considering technical design, economic factors, and system constraints in an organized way. The major steps include data input, system configuration, simulation, optimization, and results analysis. [42]

II.4.1 Data Input

Data gathering and input of all necessary input data is the first process:

Resource data: Hourly time-series data for solar radiation, wind speed, temperature, and other site-specific environmental data are inputted.

Load profiles: Hourly electric load profiles are specified, which can include critical, deferrable, or seasonal loads.

Component specifications: Technical and financial characteristics (capital cost, replacement cost, efficiency, lifetime, etc.) are specified for each system component—such as PV panels, wind turbines, batteries, electrolyzers, and hydrogen storage tanks.

This ensures that the simulation properly reflects real-world system properties and environmental conditions.

II.4.2 System Configuration

The user further defines the hybrid energy system architecture by selecting what components to include and how they are intercoupled (AC, DC, or hybrid bus configurations). HOMER Pro supports a wide range of components, including:

- Renewable generators (solar PV, wind turbines)
- Storage systems (batteries, hydrogen tanks)
- Electrolyzers and fuel cells
- Inverters and converters
- Grid and generators (in case they exist)

II.4.3 Simulation

Once the system configuration has been defined, HOMER Pro performs an hourly simulation over a full one-year time horizon (8,760 hours). The program calculates the energy flows, component interactions, and system behavior at each time step from the input data and operating constraints.

Key outputs of the simulation procedure are:

- Energy Balance Calculations: Scheduling generation and load hourly.
- Battery and Hydrogen Storage Behavior: Charging, discharge, and state-of-charge monitoring.
- Component Performance: Real-time activity of electrolyzers, converters, and fuel cells.
- Resource Curtailment or Unmet Load: Calculation of curtailed renewable energy or unmet demand.

- This phase provides a technical description in detail of system operation and forms the basis for economic and optimization studies.

II.4.4 Optimization

During the optimization process, HOMER Pro iterates over thousands of possible system configurations to find the optimum one to meet pre-set objectives. The software performs combinatorial optimization by varying component sizes (e.g., PV from 10 kW to 200 kW in increments) and configurations within the defined search space.

The most common optimization objective is the NPC reduction, but measures such as LCOE or percentage load not met may also be focused on. HOMER compares each configuration based on technical feasibility, cost-effectiveness, and constraint fulfillment (e.g., lowest hydrogen production, proportion of renewables, battery life).

In addition to that, users are able to perform multi-variable sensitivity analysis to determine the effects of changes in assumptions fundamental to the system design and economic viability based on changes in fuel price, component cost, hydrogen demand, or discount rate. That lends credibility to modeling because it shows to what extent the result is sensitive to outside uncertainty.

II.4.5 Results interpretation

After simulation and optimization, HOMER Pro provides an interactive and comprehensive results dashboard to facilitate analysis and comparison of system design. The process of result interpretation includes:

- Optimal System Configuration: Selection of cost-effective system design, which varies from component sizes, hydrogen yield, and operating parameters of the system.

- Economic Metrics: Selection of key economic metrics like NPC, LCOE, Capital Recovery Factor (CRF), and payback period.

- Technical Performance Reports: Plots and tabulations of power output, battery state-of-charge, hydrogen production rates, and fuel cell operation.
- Time-Series Data: Hourly plots showing component performance, energy flow, renewable penetration, and grid interaction (where relevant).
- Sensitivity Plots: Graphical representation of variation in system performance and cost with variation in input assumptions.

II.5 Mathematical Modeling and Equation Presentation

II.5.1 PV System

PV panels are integral parts of most RES, efficiently transforming incident solar conversion of radiation into electrical energy through the photovoltaic effect [43]. The electric power output of a PV array can be stringently calculated through the following mathematical formula [25]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \left(1 + \alpha_P \left(T_C - T_{C,STC} \right) \right) \quad (1)$$

Where the Y_{PV} is the rated power of the photovoltaic (PV) array, in (kW), f_{PV} is the derating factor in (%), G_T and $G_{T,STC}$ are the incident solar radiation on the PV array and the standard incident radiation, respectively, in (W/m2) α_p is the power temperature coefficient in (%/°C).

T_c and $T_{c,STC}$ are the PV cell temperature and the standard temperature, respectively, in (°C).[44]

II.5.2 Electrolyzer

Water electrolysis is a fundamental electrochemical process of water decomposition molecules into oxygen and hydrogen gases. This occurs in an electrolyzer cell that has two electrodes: an anode and a cathode. Hydrogen gas (H2) is generated at the cathode by the reduction reaction, while at the anode, oxygen gas (O2) is evolved by the oxidation reaction. These reactions may be written as: [45]

$$2H^+ + 2e^- \rightarrow H_2 \quad (2)$$

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \qquad (3)$$
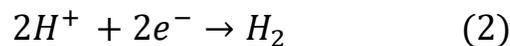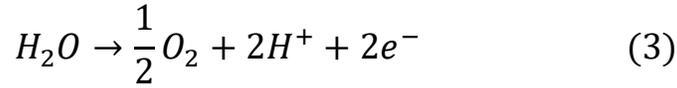
This electrochemical process is regulated by a number of factors including the electrolyte composition, electrode materials, applied voltage, and temperature. Understanding the water electrolysis complexity is vital for the optimization and design of efficient and sustainable hydrogen production technologies, with significant implications for the storage and use of renewable energy. The water electrolysis process is an established technological process for production of hydrogen, particularly from renewable electricity sources, because it is highly energy-efficient and has lower production costs. Alkaline and Proton Exchange Membrane (PEM) electrolyzers are the most common phase of commercialization and widely available types in the electrolysis market. [46] the energy consumption of an electrolyzer can be quantitatively characterized by the following:[47]

$$P_{EL} = \frac{\dot{m}_{H_2} \dot{H}HV_{H_2}}{\eta_{EL}} \qquad (4)$$

Where η_{EL} is the efficiency of the electrolyzer, HHV_{H2} is the higher heating value of hydrogen (MJ/kg) and m_{H2} m& is the hydrogen flow rate at the electrolyzer output (kg/s).

II.6 Economic model

Homer PRO's overall objective function is the minimization of the total net present cost (NPC) also known as as the life cycle cost (LCC) upon which the software ranks all the technically feasible configurations of the optimization result. The NPC of a system is the present value of all costs incurring over its life less the present value of all the revenues generated. It can be expressed as follows: [48]

$$C_{NPC,tot} = \frac{C_{ann,tot}}{CRF} \qquad (5)$$

Where $C_{ann,tot}$ is the total annualized cost ($/year) and CRF is the capital recovery factor expressed as:

$$CRF = \frac{i(1 + i)^N}{(1 + i)^N - 1} \qquad (6)$$

N is the number of years and i is the annual real discount rate (%).

Another important measure to determine a system's economic performance is the levelized cost

of energy (LCOE) which is the cost of producing 1kWh of useful energy. It can be calculated as

below: [49]

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \qquad (7)$$

Where $C_{ann,tot}$ is the total annualized cost ($/year) and E_{served} is the total electrical load served (kWh/year).

For hydrogen production systems, a second key parameter is the levelized cost of hydrogen (LCOH) that defines the average cost of one kilogram of hydrogen produced. For off-grid systems, the LCOH is given by: [50]

$$LCOH = \frac{C_{ann,tot}}{L_{H_2}} \qquad (8)$$

Where L_{H2} is the total annual hydrogen load, integrated over 8760 hours (one full year). It should be noted that the project under consideration is assumed to have a 25-year lifetime, reflecting the long-term feasibility and sustainability of the proposed infrastructure. Additionally, the simulation process is executed with a time step of 1 hour in order to facilitate precise and detailed analysis of system performance and operational dynamics over the life of the project. The real discount rate is assumed at 6%.

II.7. Conclusion

This chapter provided a comprehensive overview of HOMER Pro, a robust simulation and optimization tool for hybrid renewable energy system design. The key capabilities of the software from system configuration and economic analysis to sensitivity analysis were presented to form a clear picture of its contribution towards modeling solar-powered hydrogen production systems.

All the major components of a hybrid energy system can be realistically modeled within HOMER Pro's modular structure. Further, the ability of the software to carry out long-term simulations and optimize the solution based on minimum net present cost makes it highly qualified for techno-economic feasibility analysis, particularly in off-grid or variable-resource situations.

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Chapter III

Design and simulation of system studied

III.1 Introduction

This chapter explores the modeling, simulation, and analysis of a standalone hybrid renewable power system designed for green hydrogen production using HOMER Pro. The study aims to validate system performance, optimize component sizing, and evaluate the economic viability of powering an electrolyzer with solar energy. It provides a comprehensive overview of the system architecture, site selection criteria, input parameters, simulation setup, and interpretation of results.

III.2 Hybrid System Description

The modeled system features a photovoltaic (PV) array as the primary power source, directly connected to an electrolyzer via a DC bus. A 1 kWh lead-acid battery mitigates short-term fluctuations in solar power, ensuring stable electrolyzer operation. The electrolyzer converts electrical energy into hydrogen, which is supplied to a hydrogen load for storage or end-use applications. Operating exclusively on DC, the system eliminates the need for inverters or AC-DC conversion, enhancing overall efficiency. This configuration is optimized for daytime hydrogen production while maintaining reliable performance under varying solar irradiation conditions.
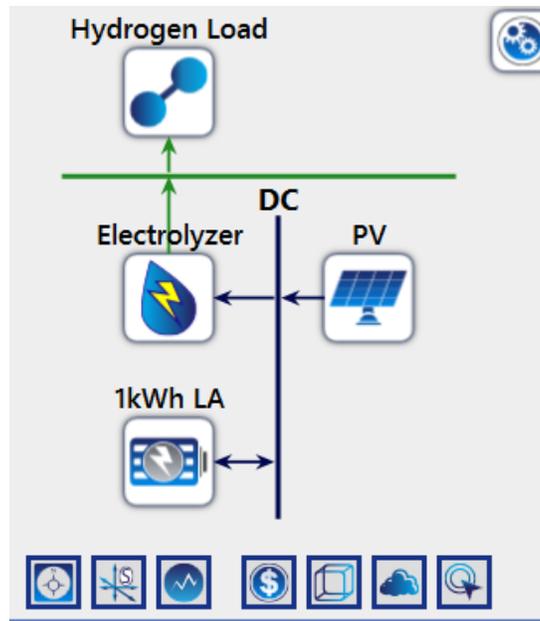

Figure III.1: Schematic of the proposed

Figure III.1 shows the schematic of the proposed renewable energy-based hydrogen production system that includes a photovoltaic (PV) array, an electrolyzer, a 1kWh lead-acid (LA) battery, and a hydrogen load arranged in a direct current (DC) bus.

III.3 Site Localization:

The selected location for this study is the region of Ouargla, situated in southeastern Algeria. Ouargla is at the heart of the Sahara Desert and is renowned for its abundant solar resources, and thus it is a best location to set up renewable energy schemes, particularly photovoltaic (PV) systems. The region enjoys extremely high solar irradiance values with mean annual global horizontal irradiation (GHI) rates above 2,200 kWh/m², and well over 3,500 sunshine hours annually. These outstanding solar conditions provide a strong foundation for efficient and continuous hydrogen production based on solar-powered electrolysis.

Ouargla's climate is hyper-arid, with very low annual precipitation, hot summer temperatures, and huge diurnal temperature ranges. The flat open landscape and large open areas enable the installation of large-scale solar arrays with low shading and good orientation. Additionally, the area's proximity to existing energy infrastructure and prospective hydrogen markets enhances its strategic significance for green hydrogen production.

For simulation and modeling of this study, meteorological data relevant to Ouargla-in terms of hourly solar irradiance and ambient temperature profiles-were sourced from reliable databases such as NASA's Surface Meteorology and Solar Energy (SSE) dataset. Localized data of this type ensures that system design and performance analysis adequately reflect the actual operating conditions of the region, thereby allowing the development of a robust and scalable hydrogen production system tailored to the unique environment of Ouargla
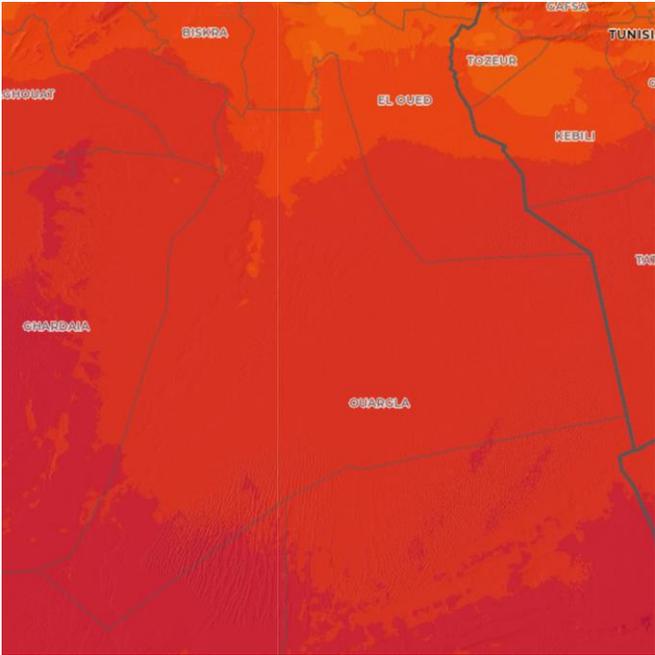
Figure III.2: Ouargla region [40]

Figure III.3 displays the geographical location of the Ouargla region of Algeria, highlighting its position and solar resource potential of interest to the study area.

III.4 Solar Data of the Site

In the assessment of the solar resources available, HOMER® software uses NASA's surface meteorology and solar energy database to access detailed weather data relevant to the station coordinates.

Figure III.3: Monthly average solar radiation and clearness index of the site.

According to the study, the annual mean solar radiation at the site is estimated to be 5.71 kWh/m2/day, while the peak values are reached in July with a maximum of 7.70 kWh/m2/day.
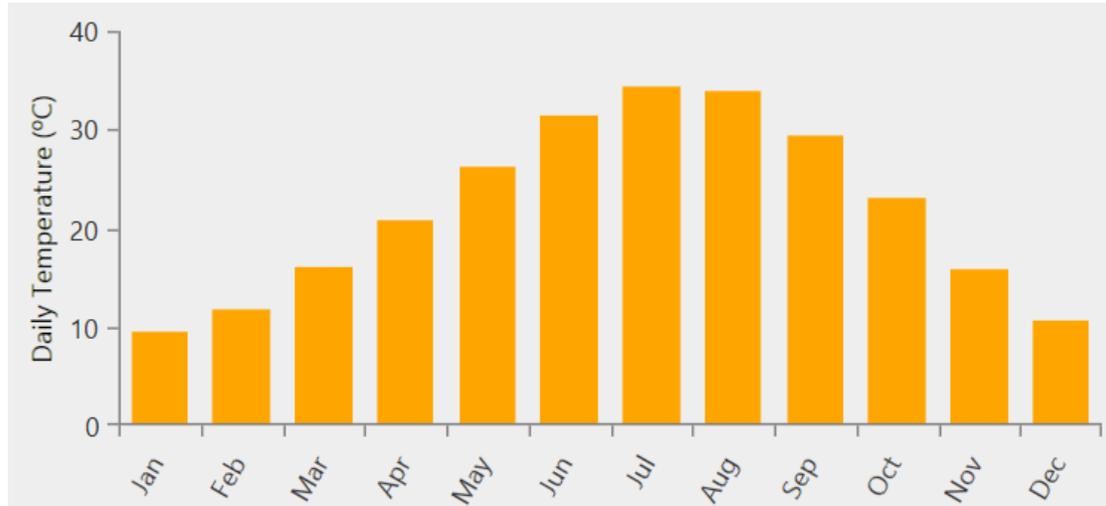
Figure III.4: Monthly average Temperature

This range indicates significant seasonal variation in the potential for solar energy. Similarly, mean annual temperature is noted to be 21.9˚C, with July reporting the highest temperature of 34.42˚C.

The assessment of solar potential shows the large renewable energy resources present at the study site, which points to the viability of integrating solar energy technology into the power supply system of the station.

III.5 Hydrogen Load

The hydrogen load in this case is the system daily volume of hydrogen generated. Figure III.5 displays the hourly hydrogen load, which defines the system output objective and also determines the capacity and functioning of the photovoltaic array, electrolyzer, and storage units to meet the desired production rate under variable solar radiation conditions.
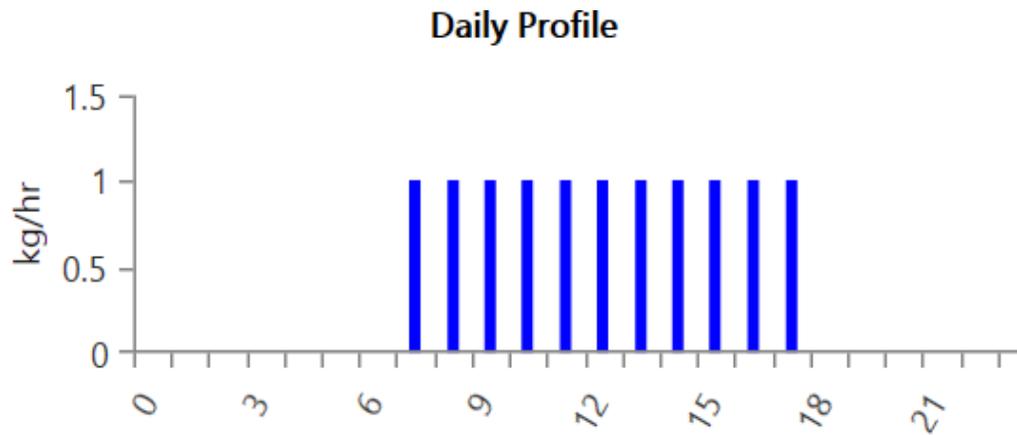
Figure III.5: The hourly Hydrogen load

III.6 PV System Modeling

The photovoltaic (PV) array is the principal source of renewable energy in the stand-alone hybrid system and delivers electricity directly to the electrolyzer and also to the storage battery bank to be charged.

The Kyocera KU325-8BCA PV module was chosen for the sake of this research due to its reliability, proven performance in high-temperature climates, and suitability for desert climates like Ouargla, Algeria. It offers the best balance between efficiency (14.8%), durability, and cost, and is widely recognized in the industry, making it a good and realistic option for achieving simulation accuracy with HOMER Pro.

Table III.1: Summary of the PV specifications

Parameter	Value
Model Name	Kyocera KU325-8BCA
PV Module	Multicristaline Silicone
Rated Capacity (per panel)	325 W
Efficiency	14.8%
Temperature Coefficient	-0.45 %/°C
Operating Temperature	45°C
Lifetime	25 years
Capital Cost	$150 per kW
Replacement cost	$150 per kW
O&M Cost	$10 per kW/year
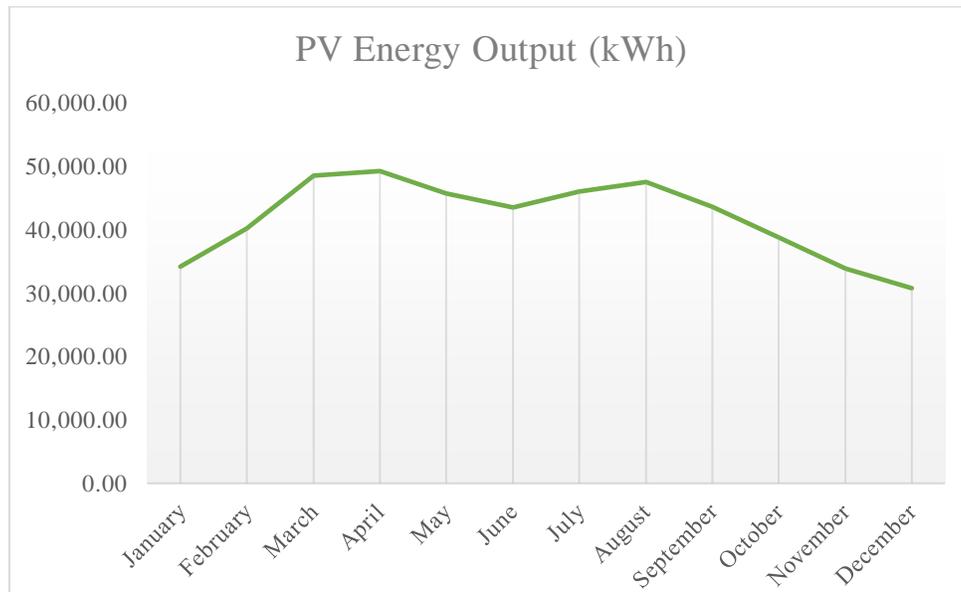
Figure III.6: PV panel power output

III.6.1 PV System Configuration

A DC configuration PV array was modeled in HOMER Pro with direct connection to the storage and the electrolyzer. System size varied at optimization levels in an effort to choose between optimal size configurations either for cost or performance.

III.6.2 Performance Modeling in HOMER Pro

HOMER Pro models on an hourly basis using solar irradiance and temperature data to estimate PV system performance over the course of a year. It calculates:

- Hourly energy produced (kWh)
- Renewable energy contribution to system load
- Energy supplied to the electrolyzer
- Energy supplied to battery storage
- Excess energy (curtailment)

The software also takes into consideration temperature coefficients, which affect PV output the hot climates of Ouargla.

III.6.3 PV Role in System Operation

Throughout sunny hours, the PV system powers the electrolyzer. If there is surplus energy apart from the amount the electrolyzer requires, it is fed into the battery bank. At cloudy days or early mornings, stored power can still be used to continue generating hydrogen.

III.7 Electrolyzer Modeling

The electrolyzer will operate whenever sufficient electrical power from the PV or battery is present. In HOMER Pro, it is modeled as a load generating hydrogen which consumes electricity based on its efficiency. The most significant function of the electrolyzer in this system is to meet a given hydrogen demand.

III.7.1 Electrolyzer Types Considered

The electrolyzer is the key unit of conversion of the hybrid renewable energy system where hydrogen is produced from water with the help of electricity from the PV array. Proper modeling of the electrolyzers in HOMER Pro is taken into consideration in order to provide hydrogen production estimation, system performance analysis, and also to provide component size recommendations in addition to being cost-effective.

Table III.2: Summary of Electrolyzer Types Considered

Electrolyzer Type	Efficiency (LHV)	Advantages	Challenges
Alkaline (AEL)	55–65%	Low cost, mature, long lifespan	Slow response time, less suitable for variable input
PEM	65–75%	Fast response, compact, good for PV coupling	High cost, uses rare metals (e.g., platinum)
SOEC	75–85% (high temp)	High efficiency, uses heat and electricity	Technically complex, still under development

III.7.2 Operation Logic in HOMER Pro

I configured the electrolyzer within HOMER Pro to operate according to the hydrogen load demand during my simulation. I had the electrolyzer operate whenever there was sufficient solar power available, producing hydrogen to meet the specified daily demand. I utilized a different parameter for each different type of electrolyzers and employed appropriate minimum load ratios to mimic real-world behavior. HOMER Pro enabled the electrolyzer to switch its operation dynamically based on available power, prioritizing hydrogen generation to achieve the system target output.

Technical and Economical Parameters Employed in Modeling

The following inputs and assumptions were employed in HOMER Pro for modeling electrolyzers:

Table III.3: Technical Parameters Employed in Modeling the electrolyzers

Electrolyzer	Type	Alkaline
	Efficiency	65%
	Capacity	Homer optimizer
	Minimum load ratio	5%
	Lifetime	15 years
	Capital Cost	$350
	O&M Cost	$20
Electrolyzer	**Type**	**PEM**
	Efficiency	70%
	Capacity Range	Homer optimizer
	Minimum load ratio	10%
	Lifetime	20 years
	Capital Cost	$600
	O&M Cost	$40
Electrolyzer	**Type**	**SOEC**
	Efficiency	85%
	Capacity Range	Homer optimizer
	Minimum load ratio	15%
	Lifetime	10 years
	Capital Cost	$1000
	O&M Cost	$60

III.8 Battery modeling

While having lower energy density and lifetime compared to newer technologies like lithium-ion, lead-acid remains economically and technically sufficient for this application to provide acceptable storage to manage solar variability in this stand-alone hydrogen production plant.

Table III.4: Battery specifications

Parameter	Value
Battery Model	1kWh Lead Acid Battery
Roundtrip Efficiency	80%
Capital Cost	$200/unit
Replacement Cost	$200/unit
O&M Cost	$10/year
Lifetime (years)	10 years
Throughput Lifetime	800 kWh
Initial State of Charge (SOC)	100%
Minimum State of Charge (SOC)	40%

III.9 Hydrogen Load Modeling

In this case, the hydrogen load is the desired daily output of hydrogen from the system based on an off-grid renewable energy source. Simulation of this load within HOMER Pro is necessary to determine if the hybrid system will be able to supply the hydrogen demand all year round in a continuous and reliable manner.

The hydrogen load was modeled as a constant daily requirement of 10.0 kg/day, uniformly distributed across a 10-hour day window, from 8:00 to 17:00.

Table III.5: Hydrogen Load Distribution Settings

Parameter	Value
Daily Load	10.0 kg/day
Hourly Load (8:00–17:00)	1.0 kg/hour
Load Type	Custom load profile
Maximum Unmet Load (%)	10%

III.10 Results of the Simulation

This section demonstrates and discourses on the result of simulating the standalone hybrid renewable power system for green hydrogen production using HOMER Pro. System configurations were taken into account to determine the optimal electrolyzer for this setup based on technical and financial performance criteria.
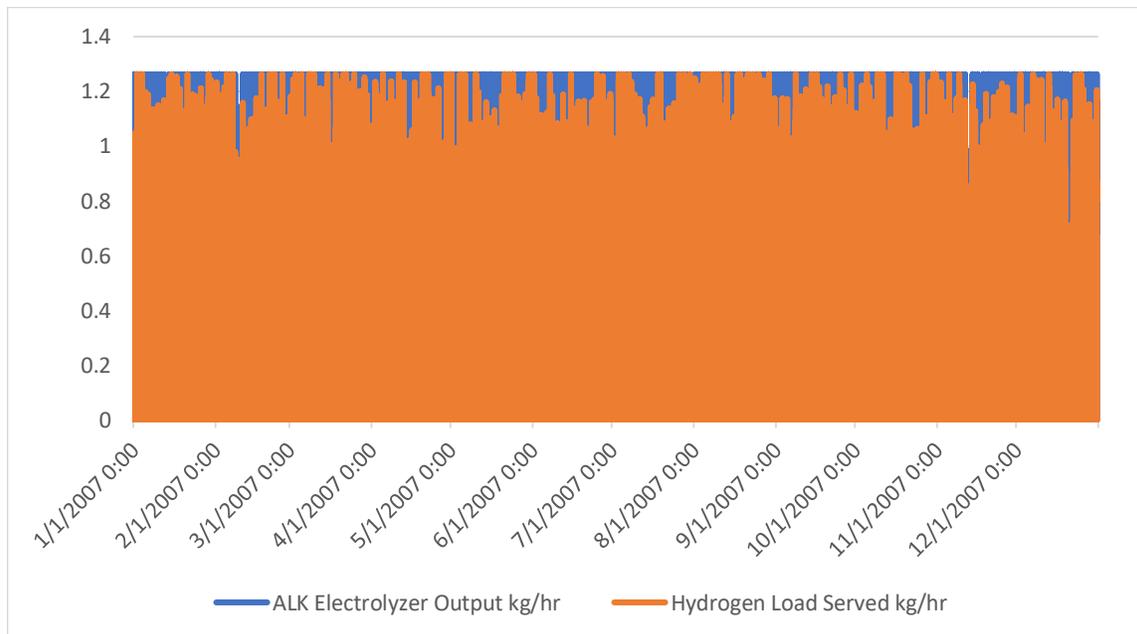
Figure III.7: Performance of ALK Electrolyzer Against Hydrogen Load

Figure III.8: Performance of PEM Electrolyzer Against Hydrogen Load

Figure III.9: Performance of SOEC Electrolyzer Against Hydrogen Load

➢ **Interpretation**

Figures III.7 (ALK), III.8 (PEM), and III.9 (SOEC) all demonstrate their respective electrolyzers satisfying a consistent hydrogen load over a year, but their operational profiles suggest varying advantages. While the PEM (Figure III.8) excels in precis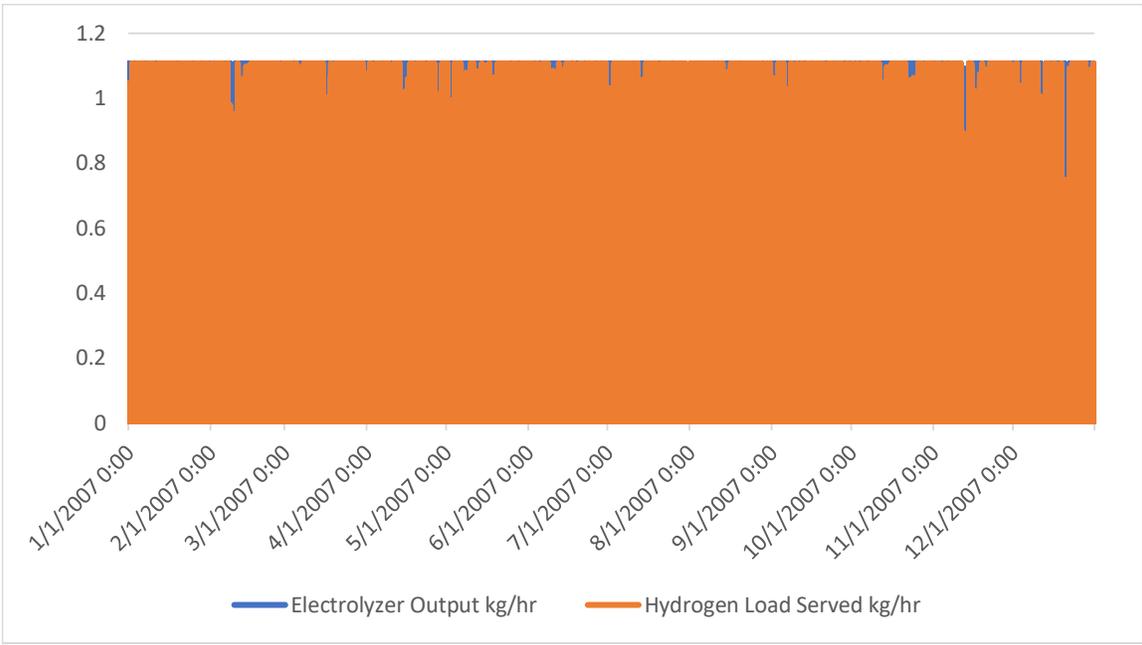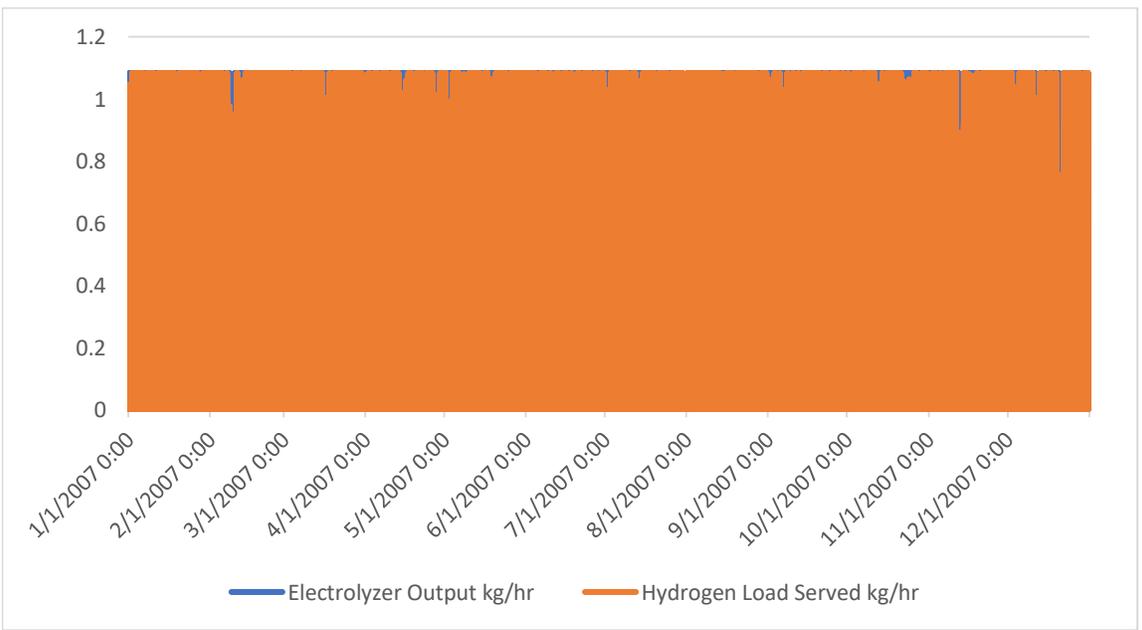e load-following with minimal overproduction, and the SOEC (Figure III.9) also shows the same with less production, Figure III.7 reveals the ALK electrolyzer as a robust solution by consistently producing a substantial surplus of hydrogen. This pronounced overproduction provides a strong buffer, ensuring high reliability in meeting demand and efficiently leveraging periods of abundant renewable energy for greater overall hydrogen output, ultimately positioning the ALK as a highly effective and potentially more resilient choice for large-scale green hydrogen production.

III.10.1 Technical Performance

HOMER Pro simulated hourly performance for a full year (8,760 hours) and provided detailed information regarding energy flows, rates of hydrogen production, and battery operation.

Table III.6: Technical comparative results

Metric	Alkaline case	PEM case	SOEC case
Annual Hydrogen Production	4,415 kg/year	4,042 Kg/year	3,987 Kg/year
Unmet Hydrogen Load	368 kg/year	368 kg/year	369 kg/year
Excess Hydrogen Load	1,133 kg/year	760 kg/year	706 kg/year
Electrolyzer capacity Factor	39.9%	41.7%	42%
PV rated capacity	285 KW	274 KW	257 KW
Battery usable nominal capacity	0.6 KWh	0.6 KWh	0.6 KWh

III.10.2 Economic Performance

The financial viability of the system was determined using primary cost indicators provided by HOMER Pro.

Table III.7: Economical comparative results

Economic Metric	Alkaline case	PEM case	SOEC case
Net Present Cost (NPC)	$130,819	$144,698	$236,526
Levelized Cost of Hydrogen (LCOH)	$2.29/kg	$2.77/kg	$4.59/kg
Capital Cost (initial)	$69,677	$76,232	$129,270
Operating Cost (annual)	$4,730	$5,296	$8,297

The simulation results confirm that the production of a 10 kg/day hydrogen target is technologically and economically feasible through a solar-powered independent hybrid system in Ouargla. The system was very reliable, free from any fossil fuel dependency, and provided competitive cost of hydrogen production for off-grid or remote applications. The economic viability remains sensitive to PV capital cost and electrolyzer efficiency, which are areas of future cost and technology optimization.

III.10.3 Analysis of the Winning Case: Alkaline Electrolyzer System

Among the three choices, the alkaline electrolyzer configuration was the most cost-effective option from the economic feasibility and stability of the system perspective. While PEM and SOEC are more efficient, with their much higher capital investment, they have higher LCOH and NPC.

Some major benefits of the alkaline system include:

- Reduced capital cost and long operational life
- High reliability during varying solar input
- Compatibility with simpler control systems
- Satisfactory hydrogen production with minimal unmet demand

Hydrogen Produced (kg)

Figure III.10: Monthly Hydrogen Production – Alkaline
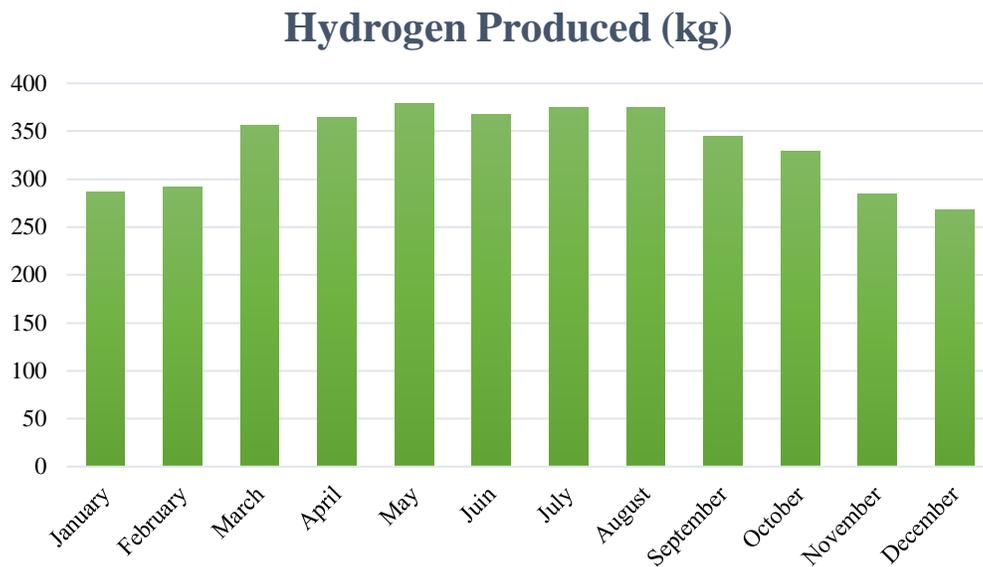
Figure III.10 shows the monthly actual hydrogen production by alkaline electrolysis. The plot demonstrates the capability of the system to fulfill the hydrogen demand most of the months, with particularly good performance during summer periods when maximum solar irradiance is experienced.

Cash Flow Summary
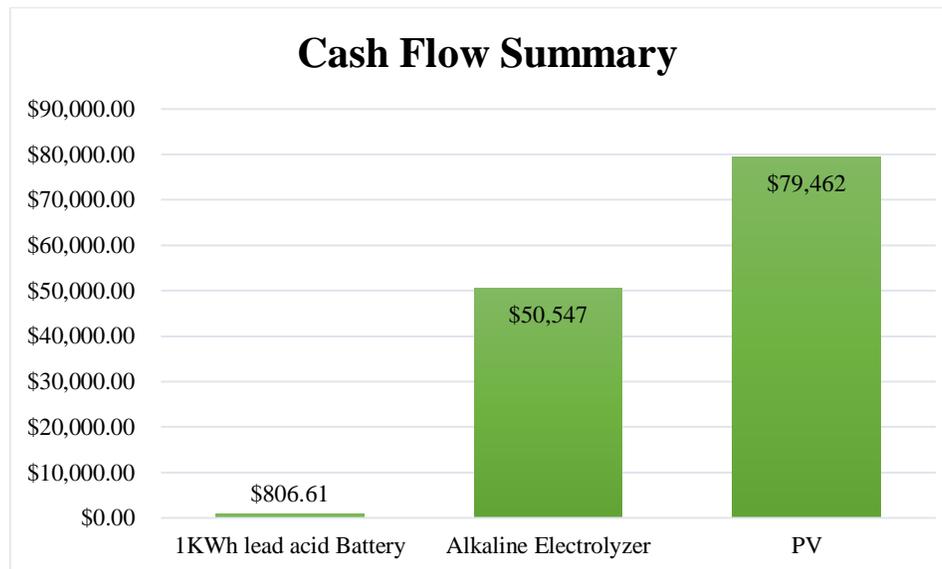
Figure III.11: Cash Flow Of The system components Net

Figure III.11 provides a step-by-step decomposition of the net cost of the system and shows the capital cost required for major components: the PV array ($79,462), alkaline electrolyzer ($50,547), and 1 kWh lead-acid battery ($806). From this economic analysis, it can be concluded that the suggested system configuration is economically feasible.

III.11 Conclusion

This chapter demonstrated the modeling and simulation of a hybrid solar hydrogen system in Ouargla using HOMER Pro. Results showed that with proper sizing of PV and electrolyzer systems, it is feasible to meet daily hydrogen demands using locally available solar resources. System performance is very sensitive to PV sizing and electrolyzer efficiency. These results are a strong foundation for future work involving detailed control strategies, seasonal hydrogen storage, and economic scaling.

General Conclusion

This thesis provides a thorough investigation into the design, simulation, and optimization of a solar-powered hybrid standalone system for the production of green hydrogen in the Ouargla region, Algeria. The system included an electrolyzer with a daily objective of producing 10 kg of hydrogen, a PV array, and battery storage. With the aid of site-specific technical and environmental data, HOMER Pro was used to carry out the simulation and optimization activities. An overview of green hydrogen, its production methods, its main benefits, and its place in the global energy transition was given at the outset of the study. Along with the applications and storage systems, the methods of producing hydrogen particularly electrolysis with renewable energy have been explained and demonstrated.

When the site's solar potential was taken into account, it was discovered that Ouargla's high solar irradiation made it a highly suitable location for powering off-grid hydrogen systems. The operation of electrochemical storage, the challenges of solar-based systems in arid environments, and the fundamentals of PV technology were all closely examined.

Three case studies were simulated in the work's practical section employing various electrolyzer types: solid oxide electrolyzer cell (SOEC), proton exchange membrane (PEM), and alkaline (ALK). System performance, hydrogen yield, component sizing, and economic feasibility were evaluated for each scenario using HOMER Pro. With the lowest Levelized Cost of Hydrogen (LCOH) and a 100% renewable fraction, the alkaline electrolyzer system was the most technically and economically balanced of the three options.

The simulation's main findings showed that a design consisting of a 1 kWh battery bank, 76.6 kW electrolyzer, and 285 kW PV array was sufficient to meet the hydrogen target. Based on Ouargla's solar and climatic profile, optimization also provided a ballpark estimate of each component's contribution and cost-effectiveness.

 Lastly, the present study suggests comparing the performance of the same systems in different Algerian regions in order to advance this research. In order to determine the best places to install

solar-hydrogen infrastructure around the nation, a map of hydrogen potential generation would be useful.

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