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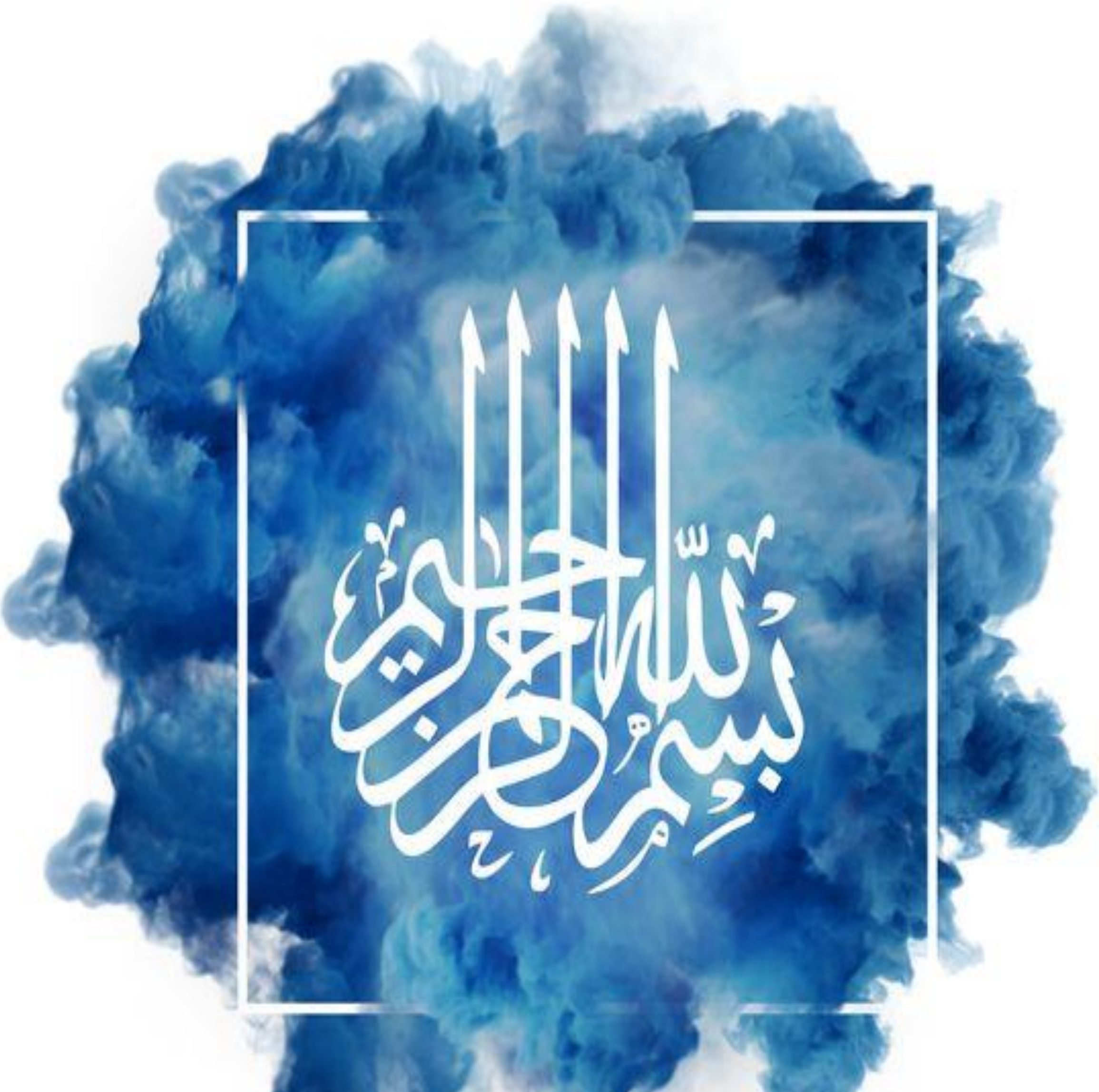
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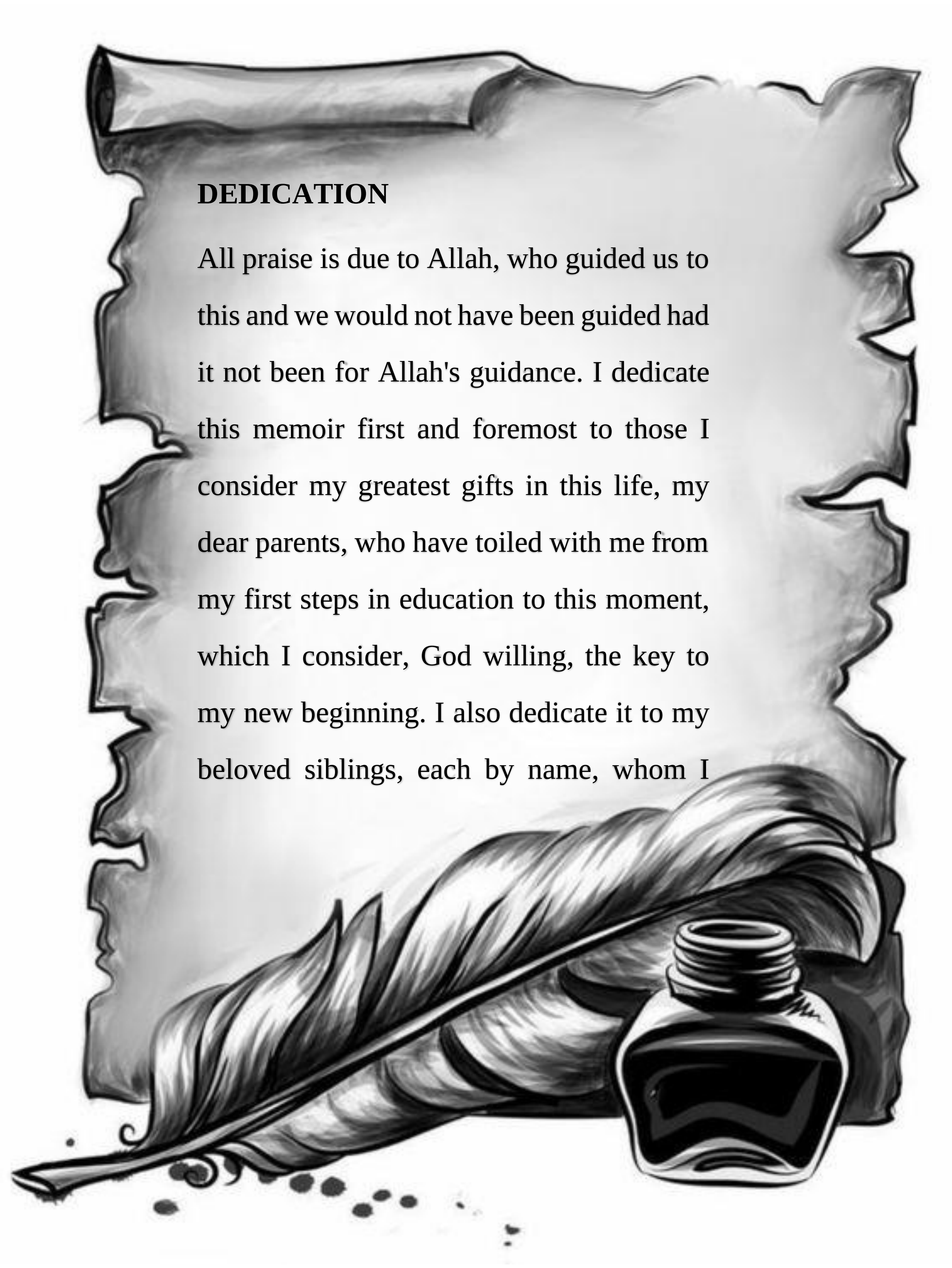

DEDICATION

All praise is due to Allah, who guided us to this and we would not have been guided had it not been for Allah's guidance. I dedicate this memoir first and foremost to those I consider my greatest gifts in this life, my dear parents, who have toiled with me from my first steps in education to this moment, which I consider, God willing, the key to my new beginning. I also dedicate it to my beloved siblings, each by name, whom I

Thanks

In the beginning of my speech, I would like to first thank Allah Almighty who guided me to reach this high academic level and paved the way for me to be among you today to discuss my master's thesis.

I would also like to extend my thanks and gratitude to:

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symbol	**Signification**
R	is the molar gas constant (8.314472 J/K.mol) (0.08314 bar.L/K.mol)
Tel	is the temperature of the electrolyzer in Kelvin (273+°C)
$PH2$	partial pressure of hydrogen
G	the gain of the speed multiplier
Cg	the torque of generator
Erev	is the reversible voltage
Ƞact	is the activation overvoltage
Co_2	the concentration (mol/m3) of oxygen in the physical zone of the reaction calculated by Henry's law
T_{pac}	Local temperature at the active layers of the electrodes (K)
Po_2	Partial pressure of oxygen at the active layers electrodes (Pa)
P_{H_2}	Partial pressure of hydrogen at the active layers electrodes (Pa)
j	Current density (A/m2)
α and β	Dimensionless constants used in the work of (Amphlett)
R_m	Membrane resistance (W.m2)
$T\Delta S$	Represents the reversible isothermal heat exchanged with the external environment
ΔS	Isothermal entropy change (J)
ΔG	Change in enthalpy free energy of the reaction (J)
We	Electrical work provided (J)
DH	Enthalpy of reaction Heat of reaction at pressure cte (J)
F	Faraday's constant (96500 C)
n	Number of electrons exchanged in electrochemical reactions
Eth	Cell potential at equilibrium
$Ƞ_E$	the potential performance of the battery under flow
$Ƞ_F$	the ratio between the current delivered I and the current maximum I_m of the overall reaction of the stack
j	current density
R_m	the resistance of the electrolyte between the two electrodes and the contact resistances
n_{exp}	is the experimental number of electrons actually exchanged
F_{H2}	Where $fH2$ is the molar flow of H2 per second for one electrolyzer cell
icell	is the current density (A/cm2)
Acell	is Effective cell area (cm2)
Z	is how many electrons are transferred, which for hydrogen is 2
F	is the Faraday constant of 9.6485*104 C/mol

P_{H_2O}	partial pressure of water
Po_2	partial pressure of oxygen
αan	is the anode charge transfer coefficient (0.433 p.u. at 60 C)
αcat	is the cathode charge transfer coefficient, assumed to be 0.5
$\alpha 1$	the cathodic charge transfer coefficient
$\alpha 2$	the anodic charge transfer coefficient
i	the electrode current density
io, an	are the anode exchange current densities, assumed to be 1*10-9 A/ cm2
io, cat	are the anode exchange current densities, assumed to be 1*10-3 A/ cm2
δ_m	is the membrane thickness in cm, (usually between 50-250 µm, assumed to be 125 µm)
σ_m	is the membrane conductivity (S/cm)
λ	is the membrane water content, with the equation for values around 20
Vt_h	Vth is the thermo neutral voltage which is 1.481 V at a standard state
V_{Rev0}	is the reversible voltage at atmospheric conditions (1.23 V), R is the molar gas constant
i_0	is the overpotential at the unit current density (1 mA cm $^{-2}$)
n_C	the number of PEM electrolyzer cell stacks
I	the current supplied to electrolyzer (ampere)
t	the period of time current supplied to electrolyzer (second)
p	the ambient pressure = 1.105 Pa
η_F	Faraday efficiency

GENERAL INTRODUCTION

General introduction

Algeria relies heavily on oil and natural gas revenues for its economy. However, fossil fuel reserves are limited, and their consumption causes environmental issues such as global warming. Burning fossil fuels releases greenhouse gases that contribute to global warming and climate change.

To address the problems associated with conventional energy, the focus has shifted to renewable energy sources such as photovoltaic solar energy, solar thermal energy, wind energy, and biomass energy. These sources are clean and abundant worldwide. Their technologies have now become cost-competitive with traditional sources. One of the challenges, particularly with wind and solar energy, is the variability in production due to fluctuations in wind speeds and solar radiation. This leads to a mismatch between production and load demand.

Solar and wind energy sources are intermittent, making them unreliable. Adding a storage system is essential to ensure production reliability. Using a system that produces hydrogen from clean energy can meet this requirement. Studies have shown that this approach is highly effective in improving the reliability of systems based on renewable energies. This system primarily relies on wind energy for power production, with excess electrical energy converted into hydrogen through electrolysis. The hydrogen is stored in tanks and used to power fuel cells to generate electricity when wind energy is insufficient. In isolated areas, hydrogen can be transported to other locations for use. The main objective of this type of system is to store energy long-term in the form of hydrogen, which can be easily transported and used. It also aims to reduce the size and cost of the storage system and replace generators that run on fossil fuels.

Many areas and homes are not connected to the national electricity grid and rely on diesel generators or mobile generators for power. The high cost and difficulty of transporting fuel to remote areas is the current situation adopted by the government to supply these regions. **[1]** Therefore, designing an independent system suitable for these areas is of great interest. The main goal is to provide a continuous and uninterrupted power supply using an independent system consisting of a wind turbine field, a fuel cell, and an electrolyzer.

We have developed this action plan to achieve the objectives outlined in this memorandum:

- Chapter I: This chapter delves into green hydrogen and its other types, In addition to types of electrolyzers, fuel cells, and hydrogen storage methods. We'll also explore wind turbines as a sustainable energy source.

- Chapter II: In this chapter, a general description of the proposed system is provided, along with modeling the system components, including fuel cell, water electrolyzer, renewable energy source, and hydrogen storage tank.
- Chapter III: This chapter provides the framework for building a hybrid system the objective is to produce hydrogen, and we will discuss components that meet the system's needs, and the sizing steps to achieve optimal design. It also includes a technical and economic analysis for supplying hydrogen fuel, which can be consumed directly or indirectly in various regions of Algeria using the HOMER Pro software.

CHAPTER I: OVERVIEW ON WIND TURBINE AND HYDROGEN

I.1 Introduction

Sustainable hydrogen offers a complementary solution for energy production, potentially becoming the most viable alternative considering economic and environmental factors. Its long-term storage capability and versatility as a vehicle fuel or fuel cell energy source further enhance its appeal.

While water electrolysis technology currently represents a small portion of hydrogen production, it holds immense promise for the future due to its clean nature. **[2]**

This chapter delves into green hydrogen and its other types, In addition to types of electrolyzers, fuel cells, and hydrogen storage methods. We'll also explore wind turbines as a sustainable energy source.

I.2 Understanding hydrogen

Hydrogen is a Greek word, where the first part (hydro) means water, and the second part (gen) means generate. Discovered by Henry Cavendish in 1776. Hydrogen is the simplest element, with just one proton and one electron. We often refer to hydrogen, but technically it's usually the two-atom molecule, dihydrogen (H2).

Hydrogen is abundant in the universe. However, it's mostly found combined with other elements, like in water and hydrocarbons. Even living organisms contain hydrogen, but separating it requires energy input. **[3]**

Hydrogen technology refers to all technologies for producing, storing and converting hydrogen for energy purposes **[4]**

I.3 Types of hydrogen

There are several types of hydrogen, which are classified according to the source of extraction:

- **Green hydrogen:** First referenced in 1995, green hydrogen is produced solely from water electrolysis using renewable electricity sources. **[5]** Europe's green hydrogen economy initiative marked its first official political mention in 2020. **[6]**
- **Gray hydrogen:** This method uses fossil fuels (coal or natural gas) and thermochemical processes for production. **[4]**
- **Blue hydrogen:** Similar to gray hydrogen, but the captured carbon dioxide is stored. **[4]**
- **Yellow hydrogen:** Nuclear power provides electricity for water electrolysis in yellow hydrogen production, similar to green hydrogen. **[4]**

Figure (I. 1) showing methods of hydrogen extraction

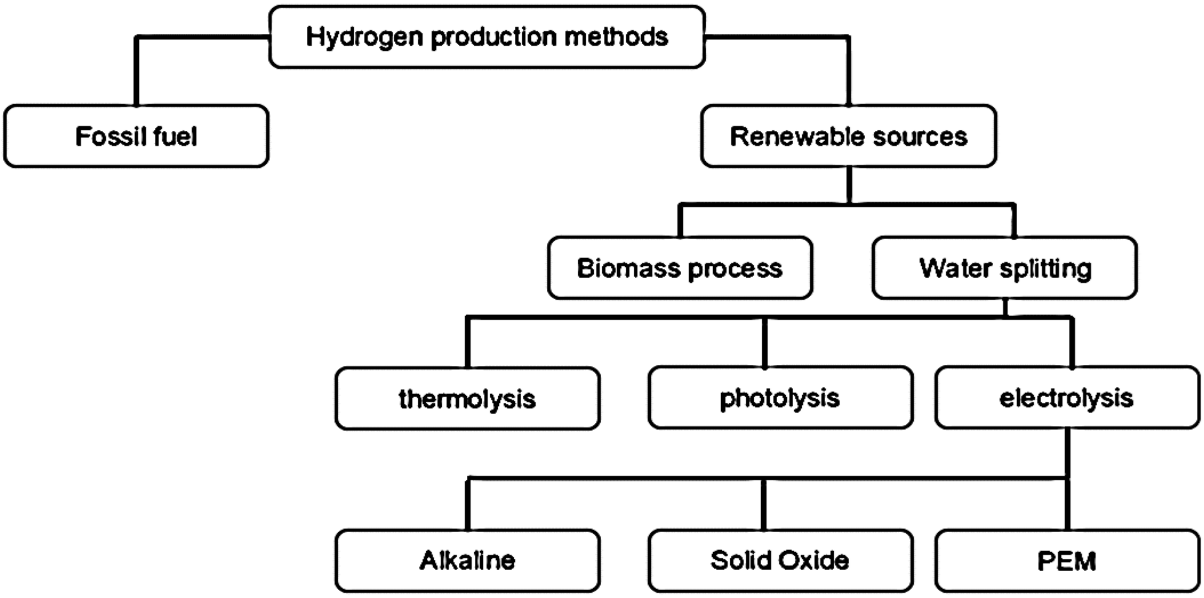


Figure I. 1: hydrogen production technology.

I.4 Technical description of the value chain of green hydrogen

This aspect of the thesis presents the hydrogen chain. It describes the various possible technologies for this chain, starting from production to conversion to storage until it ends with transportation. **[2]** As shown in the following Figure (I. 2)

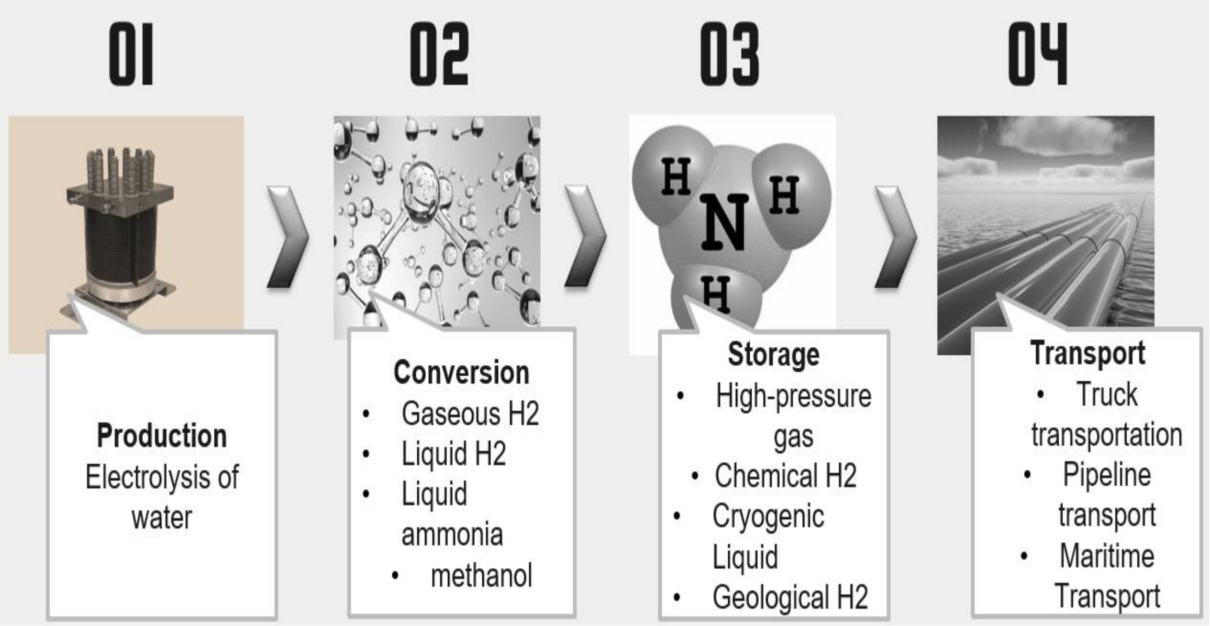


Figure I. 3: Technical description of the value chain.

I.4.1 Production hydrogen

Green hydrogen can be generated through various technologies, each dependent on its energy source. These include:

Hydrogen production from biomass: Hydrogen is generated from biomass through two distinct methods: thermochemical conversion (represented by techniques such as pyrolysis or gasification) and biological processes (including techniques like biophotolysis of water using microalgae, dark fermentation, and a two-stage process integrating dark- and photo-fermentation). **[7]**

Electrolysis of water using renewable energies Electricity sourced from solar, wind, or continuous energy sources like geothermal and hydraulic power is utilized for water electrolysis. **[2]**In this particular study, electrolysis powered by renewable energies was employed for hydrogen production. And as shown in the following Figure (I.3)

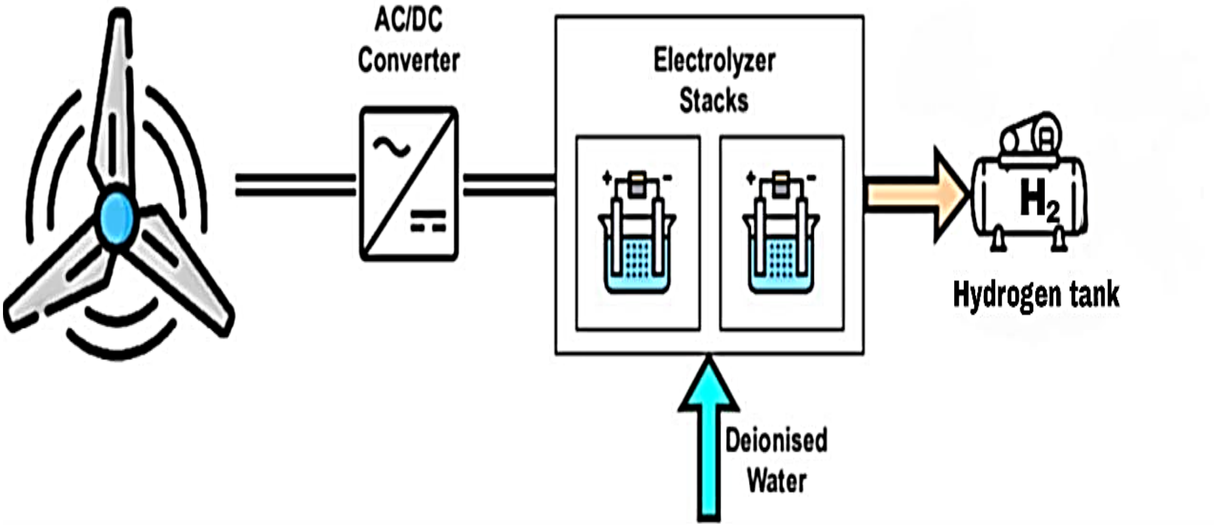


Figure I. 4: Schematic of the turbine-integrated hydrogen production configuration. **[8]**

I.4.1.1Water electrolyzers

In an apparatus for water electrolysis, a water molecule goes through a process where it is separated into hydrogen and oxygen atoms by applying direct electrical current from an external source. This process is essentially electrochemical in its essence. **[9]**

The equipment usually consists of two electrodes with opposing charges: the anode and the cathode. These electrodes are submerged in an electrolyte, which is a substance that conducts electricity through the movement of ions carrying electrical charges. The existence of these ions aids in facilitating redox reactions. **[2]**

In the electrolyte, ions like hydrogen ions (H^+) and hydroxide ions (OH^-) can move freely. When an electric current is applied, positively charged ions (H^+) move toward the negative electrode (cathode), while negatively charged ions (OH^-) move toward the positive electrode (anode). This ion movement leads to a flow of ions towards their respective electrodes.

As ions reach the electrodes, an exchange of electrons happens, resulting in chemical reactions producing new compounds or molecules, like hydrogen molecules (H_2) and oxygen molecules (O_2). This process is depicted in (Figure I. 5). **[2]**

Water electrolysis stands as one of the simplest and most efficient techniques for hydrogen production, renowned for its ability to yield high-purity hydrogen. **[10]**

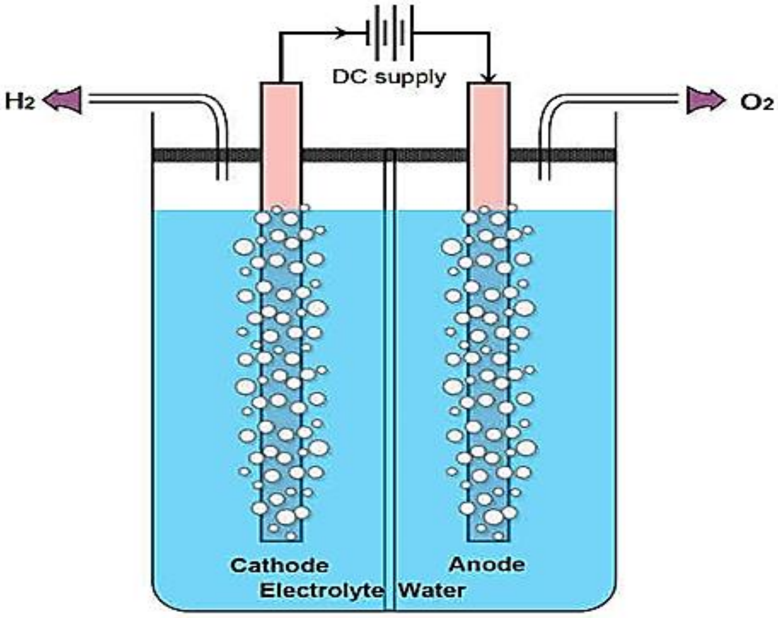


Figure I. 6: structure of electrolysis. [10]

I.4.1.2Type of water electrolyzers

We categorize water electrolysis devices into two types based on the electrolyte they use or structural differences.

A. Structure of electrolyzers

There are several water electrolysis technologies exist, differentiated by their internal structure. **[11]**

➢ Electrolyzers with parallel monopolar plates

Electrolysis devices initially relied on a monopole electrodes system, meaning that all the cell anodes were connected to the negative electrode, and vice versa, all the cell cathodes were connected to the positive electrode, so that the electrolysis cells worked in parallel.

The structure of the monopolar plates is shown in (Figure I.5). **[12]**

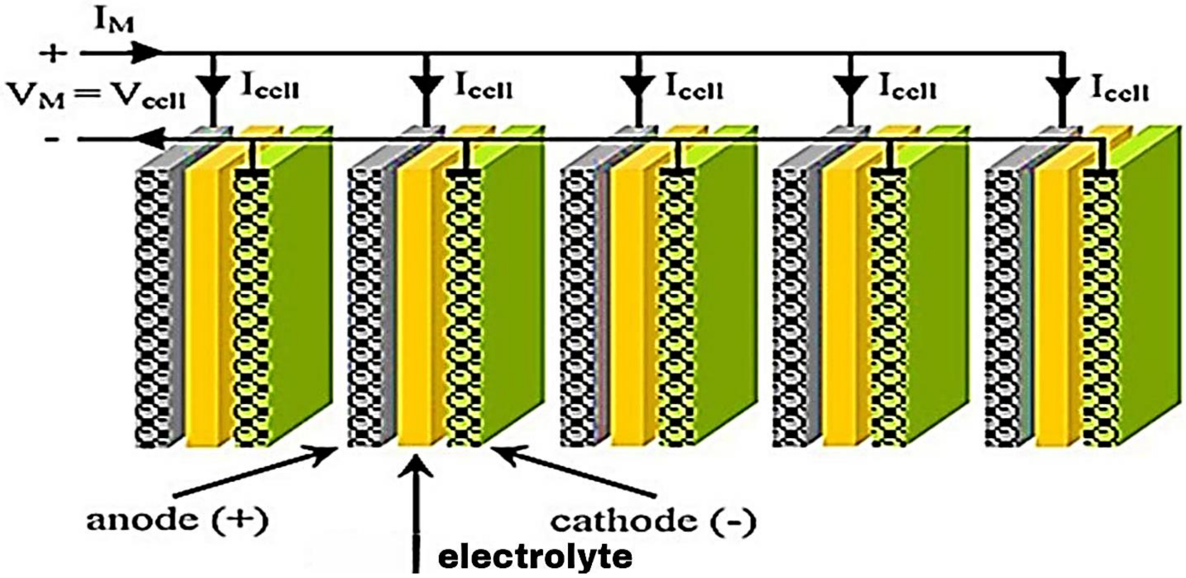


Figure I. 7: Structure of a monopolar electrolysis cell. [13]

➢ Electrolyzers with Series monopolar plates

Stacked plates have the anode on one side and the cathode on the other allowing the electrolysis cells to operate in series. Bipolar technology is almost currently adopted. **[12]** As shown in the following Figure (I. 6).

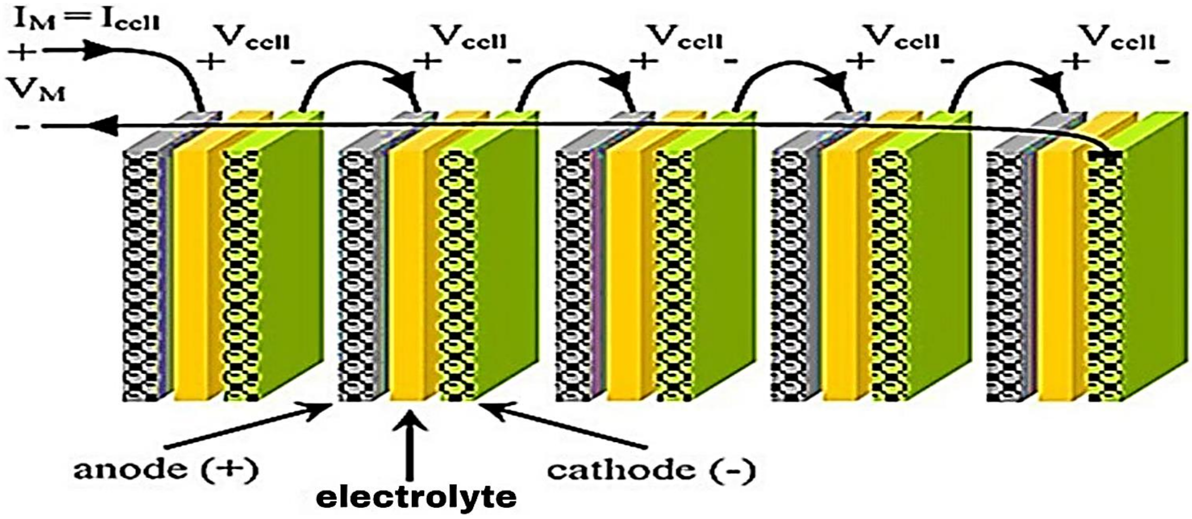


Figure I. 8: Structure of a bipolar electrolysis cell. [13]

B. State-of-the-art water electrolyzers

We classify the latest water electrolyzers based on the type of electrolyte they use. **[14]**

• Alkaline electrolyzers(AEC)

In this type, we use an alkaline aqueous solution (KOH) in the form of an electrolyte whose concentration ranges from 20% to 30%. **[15]**The chemical reaction occurs in an aqueous solution between two electrodes. These electrodes are located between a diaphragm(Anion Exchange Membrane (AEM)), Typically made of a polymer with positively charged functional groups that attract and allow OH^- ions to pass through.

The cathode in an alkaline electrolyzer is typically made of nickel, stainless steel, or other metals that do not react with the alkaline electrolyte. The cathode is also coated with a layer of platinum or ruthenium catalyst to enhance the hydrogen evolution reaction.

The anode in an alkaline electrolyzer is typically made of nickel oxide, iridium oxide, or other materials with high catalytic activity for the oxygen evolution reaction.

It is the most widely used technology in the electrolyte market**. [14]** It reaches the megawatt range for commercial purposes. This type operates at a temperature ranging from (65 to 100) Celsius. **[15]** In Figure (I.7)

Alkaline substances generally aid in the electrolysis of water, speeding up the generation of hydrogen and oxygen. This boosts process efficiency and fosters higher hydrogen production rates, setting this type apart. However, they are less efficient than PEM electrolyzers, and the alkaline electrolyzers are not able to absorb the energy during fast intermittent energy discontinuances.

We present the chemical equations as follows: **[16]**

Cathode $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ (I.1)

Anode $2OH^- \rightarrow 1/2\ O_2 + H_2O + 2e^-$ (I.2)

Global $2H_2O \rightarrow 2H_2 + O_2$ (I.3)

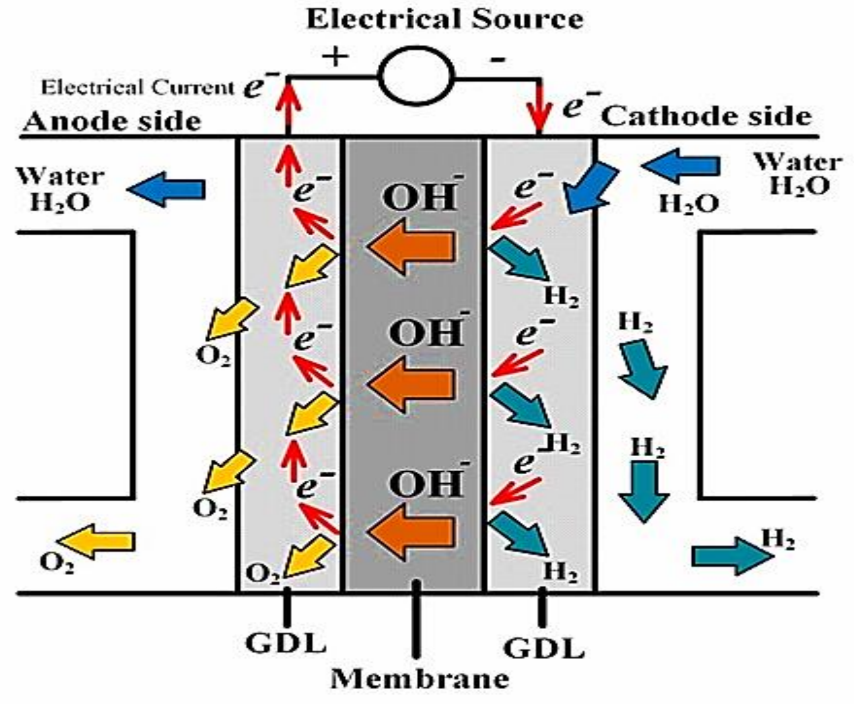


Figure I. 9: Principle of operation of alkaline electrolyzers. [16]

- ## Proton Exchange Membrane (PEM) electrolyzers

The PEM electrolyzer technology relies on low temperatures compared to other types. At its core is a polymer electrolyte membrane (also known as a proton exchange membrane) serving as an ionic conductor. This requires an acidic electrolyte solution, this acidic environment necessitates the use of expensive precious metal catalysts like platinum on the electrodes for efficient reactions. This membrane is typically thin and solid, often made of Nafion. The membrane transfers protons H+ from the anode to the cathode. It also separates the anode and cathode. This separation allows hydrogen and oxygen ions to flow freely without affecting the reactions in both the anode and cathode. In figure (I. 8)

This technology was developed to improve the disadvantages of alkaline electrolysis. This technology has many advantages (compact and efficient, making them suitable for small-scale applications), but it is expensive and remains in the development stage. **[14] [15] [17]**

We present the chemical equations as follows: **[16]**

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

Cathode $4H^+ + 4e^- \rightarrow 2H_2$ (I.5)

Global $2H_2O \rightarrow 2H_2 + O_2$ (I.6)

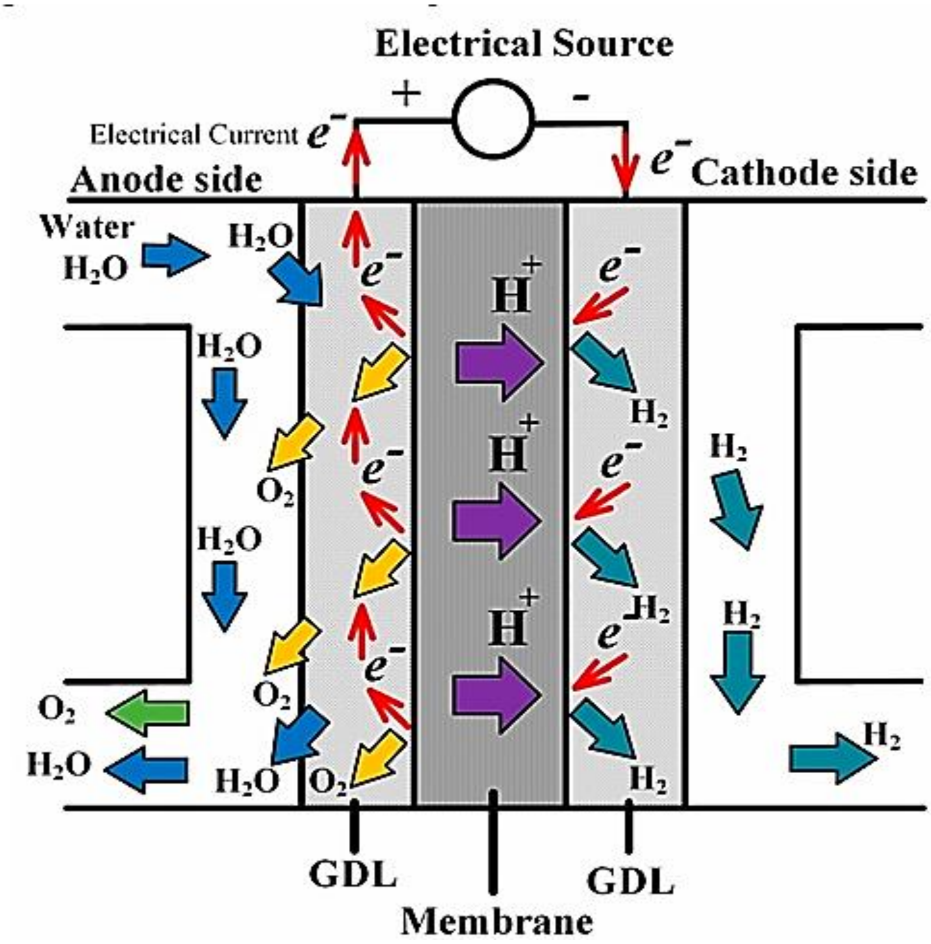


Figure I. 10: Principle of operation of proton exchange membrane (PEM) electrolyzers. [16]

- **Solid Oxide (SOEL) electrolyzers**

In this type, we utilize a ceramic electrolyte that conducts high temperatures. This variant operates within a high-temperature range of 800 to 1000 degrees Celsius. Water is split into hydrogen gas at the cathode, while oxygen ions (O2-) are extracted from the electrolyte at the anode and oxidized to form oxygen gas. State-owned enterprises have depended on materials and solid oxide fuel cell technology for this type. It boasts higher efficiency at elevated temperatures compared to alkaline or PEM (Proton Exchange Membrane), **[15]** types but encounters they require expensive materials and have longer startup times. In figure (I. 9)

We present the chemical equations as follows: **[18]**

Anode $2O_2^- \rightarrow O_2+4e^-$ (I.7)

Cathode $2HO_2 + 4e^- \rightarrow 2O_2^- + 2H_2$ (I.8)

Global $2H_2O \rightarrow 2H_2 + O_2$ (I.9)

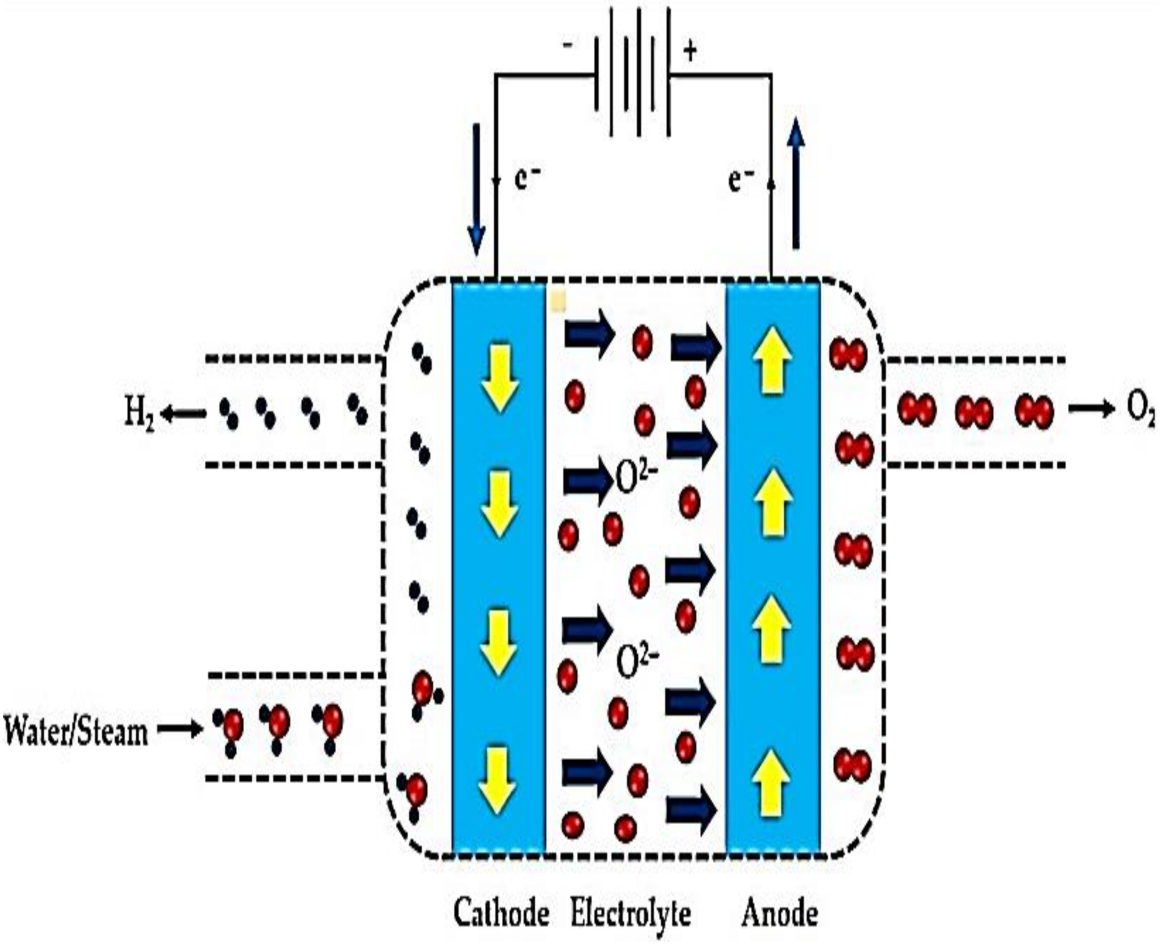


Figure I. 11: A conceptual drawing of a solid oxide water electrolyzer. [19]

And shown in the following table (I. 1) the most important differences between these types

Table I. 1: Technical data of electrolyze types. [14] [2]

Type	PEM	AEC	SOEL
Operating temperature (°C)	80-100	50-100	800-1000
Electric consumption Kwh/Nm3 of H2	6	4-5	3-3.5
Performance (%)	80-90	75-90	80-90
Electrolyzer	Polymer (Solid)	Hydroxide of potassium (KOH)	Ceramic (solid)
Lifespan of technology	10 — 20 ans	20 — 30 ans	20ans
Efficiency	61 — 67 %	55 — 63 %	90%
Water requirement 2	1,4 – 2 L/m3-H_2	1,5 – 2 L/m3-H_2	1,5 – 2 L/m3-H_2
Energy requirement2	52 - 60 kWh/kg-H_2	49 - 54 kWh/kg-H_2	37- 40 kWh/kg-H_2
Hydrogen production			

I.4.1.3 Positives and negative points of PEM electrolyzer

In our study, we focused on the PEM type of water electrolyzer, which has many the Advantages and Disadvantages, including: **[14]**

➢ **Advantages of PEM Electrolyzer**

- This technology provides high purity gases (greater than 99.99%).
- Water electrolysis technology is environmentally friendly.
- This technology has great productivity. **[14]**
- Fast response time can ramp up or down hydrogen production rapidly to match the fluctuating supply from solar and wind power.

- **Disadvantages of PEM Electrolyzer**

- The high initial cost can be a barrier to some applications.
- PEM electrolyzers are sensitive to impurities in the water feed. Contaminants like chlorides can degrade the performance and lifespan of the membrane and catalysts. **[20]**

I.4.2 Conversion

The hydrogen produced from the electrolysis process is in gas form at a low pressure of about 30 bar.

It is compressed, liquefied, converted into liquid ammonia, or converted into methanol, in order to facilitate its storage and transportation. In this section, we will study these various conversion. **[2]**

- **Gaseous Hydrogen**

The most productive way to produce pure gaseous hydrogen is through hydroelectrolysis, which splits water molecules into hydrogen and oxygen gases.

This method is the most widely used and widespread due to the method's simplicity, good effectiveness, and lowest cost

On the other hand, this method has disadvantages in terms of the chemical properties of hydrogen gas, as it can be explosive and must be handled with caution. Compressed gas poses a danger if it leaks, as well as in terms of energy consumption, as it consumes a lot of energy to operate the hydrogen gas compressor.

- **Liquid hydrogen**

Hydrogen gas is cooled to a very low temperature, causing it to contract at standard temperature and pressure. Strengths of the hydrogen liquefaction process include purity, versatility in final uses, and ease of conversion to gas. It requires less storage space and is distinguished by its high volumetric hydrogen density compared to other carriers. However, its drawbacks, compared to other carriers, include the difficulty of the process, resulting in high energy density start-up. **[21]**

- **Liquid ammonia**

Converting hydrogen (H_2) to ammonia (NH_3) is achieved through a process called the Haber-Bosch process. This industrial method combines hydrogen with nitrogen (N_2) from the air to produce ammonia under specific conditions.

Ammonia in its liquid form (LNH_3), acknowledged in agriculture as a constituent in fertilizers, is presently under scrutiny as an alternative due to its notable energy density and stability under ambient conditions. The amount of hydrogen present per cubic meter is twice as much when stored in the form of ammonia compared to liquid hydrogen.

- **Methanol (MeOH)**

This process involves reacting natural gas (methane) with steam at high temperatures to produce hydrogen and carbon dioxide.

Methanol ($CH3OH$) serves as a by-product under examination for the purposes of hydrogen storage and transportation. Its formation entails the interaction of hydrogen with carbon dioxide, facilitated by a copper catalyst. Methanol finds utility across diverse industrial sectors.

I.4.3 Hydrogen Storage Methods

storing hydrogen gas depend on several methods, including applying high pressure, liquefying the hydrogen, storing it with ammonia, or converting it to methanol and storing it. This section presents these techniques. **[2]**

- **High-Pressure Gas Storage**

This method involves storing hydrogen in compressed gas cylinders at high pressures, typically ranging from 350 to 700 bar (5,000 to 10,000 psi). While this method is relatively mature and cost-effective, the volumetric storage density of hydrogen is limited due to its compressibility. **[22]**

- **Liquid Hydrogen**

Although technology promises us a high density of hydrogen, its drawbacks include the significant energy demands necessary for this process, along with daily losses. This technology requires high energy input and operates at elevated temperatures, **[2]** thereby increasing its overall cost. Additionally, constant cooling is essential for its operation due to evaporation

- **Chemical Hydrogen Storage**

This method involves storing hydrogen in chemical compounds that can release hydrogen upon demand. **[23]** Examples include metal hydrides, ammonia, methanol, and boranes. While this method offers the potential for high gravimetric storage density, the release and storage processes may require additional energy input. **[24]**

- **Liquid ammonia**

It is called the organic hydrogen carrier due to the many advantages of this technology, but it has disadvantages, and the most prominent disadvantages are daily ammonia leaks during storage. This substance can pose harm to humans. **[2]**

- **Methanol**

This process requires conditions similar to ammonia, where hydrogen is converted into another substance through chemical bonding. **[25]** By adding carbon dioxide produced from organic materials. This technology contains fewer losses during the product storage stages compared to other technologies. **[2]**

- **Geological Hydrogen Storage**

This method involves storing hydrogen in underground formations, such as salt caverns or depleted oil and gas reservoirs. This method offers the potential for large-scale, long-term storage, but the suitability of geological formations and the environmental impact of leakage need to be carefully evaluated. **[13]** As shown in the following Figure (I. 10)

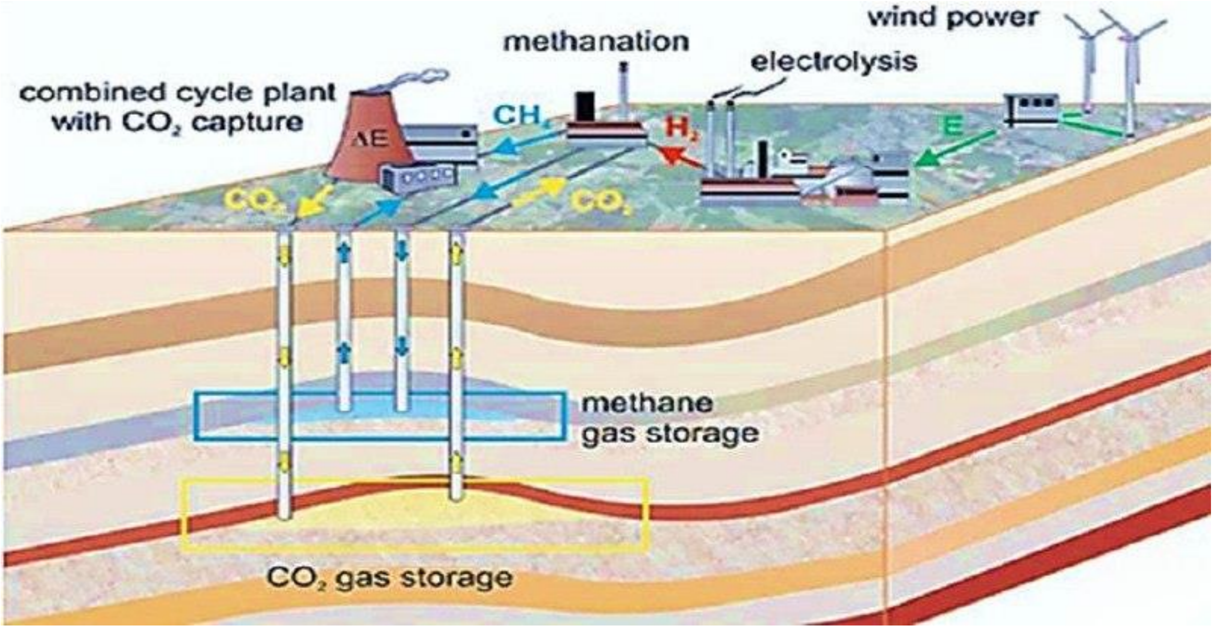


Figure I. 12: Geological hydrogen storage. [13]

I.4.4 Hydrogen transport methods

Currently we distinguish three ways to transport hydrogen: heavy trucks, pipelines and boats.

- **Truck transportation**

Land transport using heavy trucks can be done in gaseous or liquefied form through an assembly of tubes in a trailer or tanker trucks. At a pressure of 350 bar, the trailer's capacity is 1050 kg of hydrogen for 907 kg delivered.

This method is more flexible than pipelines but is less cost-effective for long distances. **[2]**

- **Pipeline transport**

Pipelines also enable intercontinental transportation, but the high Initial investment makes them less popular than heavy trucks. Transporting gaseous hydrogen through these conduits requires new installations or large-scale upgrades. The profitability of a pipeline network is achieved when large-scale utilization is realized. As of 2022, the maximum capacity of a 12-inch diameter pipeline is reached. **[2]**

- **Maritime transport**

Several studies are also underway for the maritime transport of hydrogen by ships in the form of liquid hydrogen and ammonia, or even methanol. This method is well-suited for transporting hydrogen over long distances, especially for maritime transport. However, it requires specialized liquefaction and regasification facilities. The development of hydrogen-fueled ships is also being studied, with typical tank capacities of 160,000 m3 per ship. **[2]**

I.5 Use of hydrogen

Hydrogen is an element with huge potential to be a clean and sustainable fuel for the future, with many current and future usese we present some uses of hydrogen:

- **Fuel**

Hydrogen gas is considered the most suitable alternative to natural gas, and studies have proven that its use helps reduce greenhouse gas emissions, thereby mitigating the phenomenon of global warming, especially when produced from renewable energies as a source. This significantly and effectively contributes to carbon elimination in the energy sector. Mentioning some uses of hydrogen as fuel, it can power gas turbines and be used as fuel for cars. Using hydrogen in heating systems as an alternative to natural gas has several advantages, including faster combustion and emissions reduction. Additionally, hydrogen is much more energy dense than fossil fuels, meaning more energy can be stored in the same volume, providing benefits such as longer driving range for vehicles and greater efficiency for energy systems. **[26]**

- **Energy**

Hydrogen technology holds significant potential for energy production centers through energy storage. Large quantities of hydrogen can be produced and utilized in two primary ways. Firstly, it can be directly consumed as a clean energy source. Alternatively, it can undergo chemical conversion for various industrial applications, including the production of ammonia, polymers, and resins, all of which are pivotal industries reliant on hydrogen.

Furthermore, the versatility of hydrogen extends to aerospace, where it can serve as both energy and fuel. Within industrial settings, hydrogen finds utility in processes within chemical and refining factories, particularly in fuel processing for sulfur removal.

Moreover, in the realm of infrastructure, there are opportunities to integrate hydrogen into existing natural gas networks and utilize hydrogen boilers within buildings, thereby expanding its reach and application. **[26]**

- **Hydrogenation Reactions**

Hydrogen has numerous applications within chemical factories, depending on the specific processes involved. Here are some key uses: **[26]**

Hydrogenation Reactions

Hydrogen undergo chemical conversion for various industrial purposes. Hydrogen gas (H2) is utilized as a reactant in diverse chemical reactions to add hydrogen atoms to molecules. This process, known as hydrogenation, is vital for the production of numerous essential chemicals, including ammonia, polymers, and resins—all of which are pivotal industries reliant on hydrogen. **[27]**

- **Selective catalytic reduction of NOx by hydrogen** NOx emissions have environmental implications, and efforts to reduce NOx are crucial for air quality and climate change mitigation. These emissions arise from both natural sources such as oceans, biological decay, and lightning strikes, and human activities including fertilized agricultural soils, livestock manure, and sewage treatment processes. The selective catalytic reduction of nitrogen oxides using hydrogen as a reducing agent (H2-SCR) has recently attracted extensive attention due to its inherently high activity at low temperatures. **[28]**
- **Hydrodesulfurization reaction HDS:** Is removes sulfur compounds from various petroleum fractions, such as gasoline, diesel, and jet fuel. **[5]**

  Sulfur in fuels can cause environmental issues like air pollution when burned. It can also damage catalytic converters in vehicles. **[28]**

  Overall, the hydrodesulfurization reaction plays a vital role in ensuring clean and environmentally friendly transportation fuels. Advancements in catalyst technology and hydrogen production methods will further enhance the sustainability and efficiency of this essential refining process. As shown in the following Figure (I. 11)

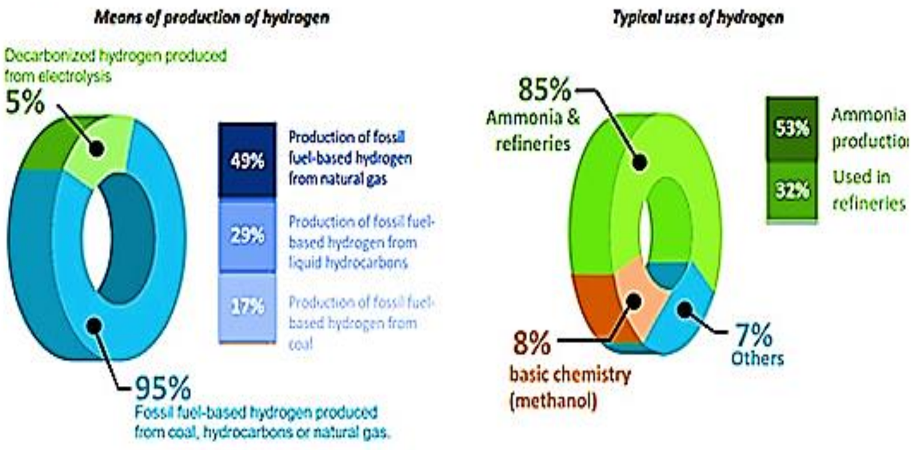


Figure I. 13: Production and current use of hydrogen. [29]

I.6 Fuel Cell technologies

I.6.1 Historical overview

Fuel cell technology dates back to Christian Friedrich Schönbein (1799-1868).

And Sir William Robert Grove (often called the Father of the Fuel Cell, 1811-1896). **[30]**

Developments in the fields of electrochemistry and chemical catalysts led to research on fuel cells beginning in the 18th and 19th centuries

It is emerging as an ideal solution that can be used to overcome the problems and needs of tomorrow's energy sources by exploiting the chemical reactions between hydrogen and oxygen. **[14]**

The real development of the fuel cell occurred in the year 1960, when NASA began searching for an efficient means of energy for spaceflight, in order to solve the problem of the weight of batteries and the expensive cost of the battery. **[31]**

I.6.2 Functional Principle

The fuel cell is a type of electrochemical technology that functions as a generator, producing electricity through the chemical reaction of hydrogen and oxygen. In this reaction, oxygen generates electricity and heat, which is the reverse process of electrolyzers **[15]**

Electricity is utilized directly, while heat can be stored, utilized across diverse sectors, or lost. The fuel cell comprises two electrodes, each with opposite charges (anode and cathode). Hydrogen gas is supplied to the anode, and oxygen to the cathode, alongside an ionic conductor, which may be solid or liquid, containing ions responsible for carrying the electrical charge. Here, hydrogen and oxygen undergo chemical reactions, generating electricity and heat.

Some fuel tanks operate at high temperatures and others at low temperatures Hydrogen has a higher electrochemical reactivity than other fuels, as for oxygen, it is characterized by its high reactivity and abundance in the air. **[31]**

I.6.3 Types of Fuel Cell

There are types of fuel cells, and these types differ according to the type of electrolyte used. [**31]** This section contains various types of fuel cell. As shown in the following table (I. 2)

Table I. 2: Main characteristics of fuel cells. [32]

Types / **Differences**	AFC	DMFC	PEMFC	PAFC	MCFC	SOFC
temperature	Low temperature	Low temperature	Low temperature	Low temperature	high temperature	high temperature
Electrolyte	Solution KOH (liquid)	Membrane In polymer (solid)	Membrane In polymer (solid)	Acid phosphoric (liquid)	Salt of carbonate molten(liquid)	Ceramic (solid)
Combustible	Hydrogen	Methanol	Hydrogen	Hydrogen/natural gas	Hydrogen/natural gas/Methanol…	Hydrogen/natural gas/ Methanol…
Operating temperature	50-250°C	70-90°C	70-100°C	150-220°C	600-800°C	700-1050°C
Power margin	1W-10KW	1Wplusieurs KW	1W-10MW	200KW-10MW	500KW-10MW	1KW-100MW
Performance (%)	55-60%	30-45%	30-45%	35-75%	50-60%	50-70%
Application Possible	Spatial, smashing, and portable equipment	Transport and portable equipment	Space, Transport, stationary, and portable equipment	Transportation, cogeneration, stationary	cogeneration, stationary	cogeneration, stationary

- **PEM Fuel Cell**

The fuel cell consists of two electrodes with opposite charges (the anode and the cathode). At the cathode level, where the hydrogen atom (in the gaseous state) is split into protons, positive ions and negative electrons. In the presence of an electron catalyst, it flows, forming an electric current outside the cell. As for the hydrogen protons, it allows them to pass through the polymer membrane but prevents the passage of electrons. The ions carry them towards the anode, where a reaction takes place between oxygen, protons, hydrogen and electrons, producing water in the form of droplets and heat. **[33]** In figure (I. 12)

We present the chemical equations as follows

At the anode Oxidation of hydrogen $H_2 \rightarrow 2H^+ + 2e^-$ (I.7)

At the cathode Reduction of oxygen $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ (I.8)

Overall reaction $O_2 + 4H \rightarrow 2H_2O$ (I.9)

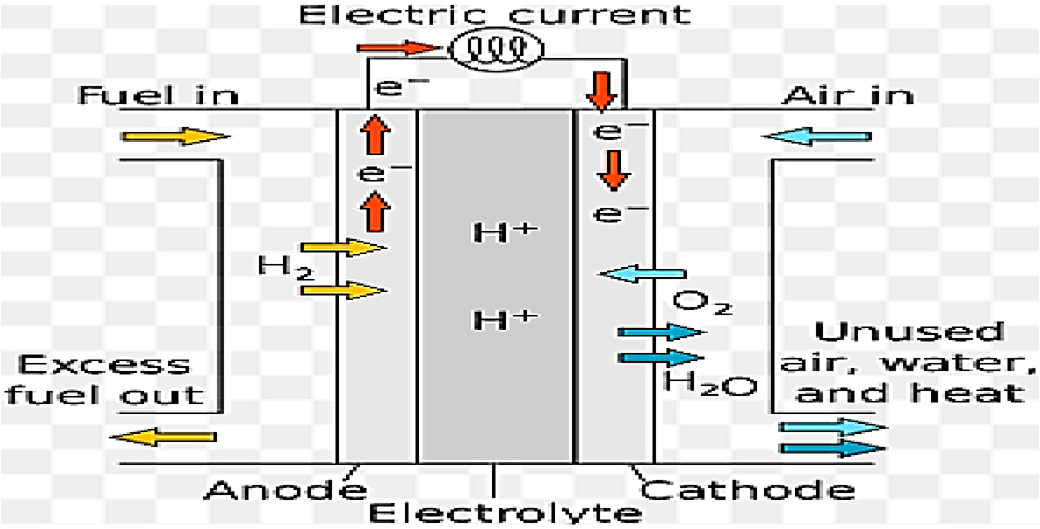


Figure I. 14: explain PEM fuel cell. [29]

I.7 Wind turbine technology

I.7.1 Operating principle of wind turbine

Wind turbine are a device that receive kinetic energy through the rotor convert it into **[34]** mechanical energy, after that transformed by the electrical generator into electrical energy. **[35]**Traditional wind turbine generally consist of three main parts (Tower/Nacelle

- **The rotor:** It consists of blades that capture wind speed and convert kinetic energy into mechanical energy.
- **The nacelle:** It is the heart of a wind turbine that combines a rotor with a generator. It consists of a speed increase gearbox and a generator that converts mechanical energy into electrical energy, along with a hydraulic system.
- **The tower:** Is the part that supports the wind turbine. Its role is to elevate the turbine to a certain level, so that as the height increases, the rotation level of the rotor axis also increases. **[36] [37]**

I.7.2 Wind turbine commend

The goal of control is to maximize and improved energy output at low wind speeds, where by controlling production-related elements for better efficiency and productivity. As shown in the following Figure (I. 13)

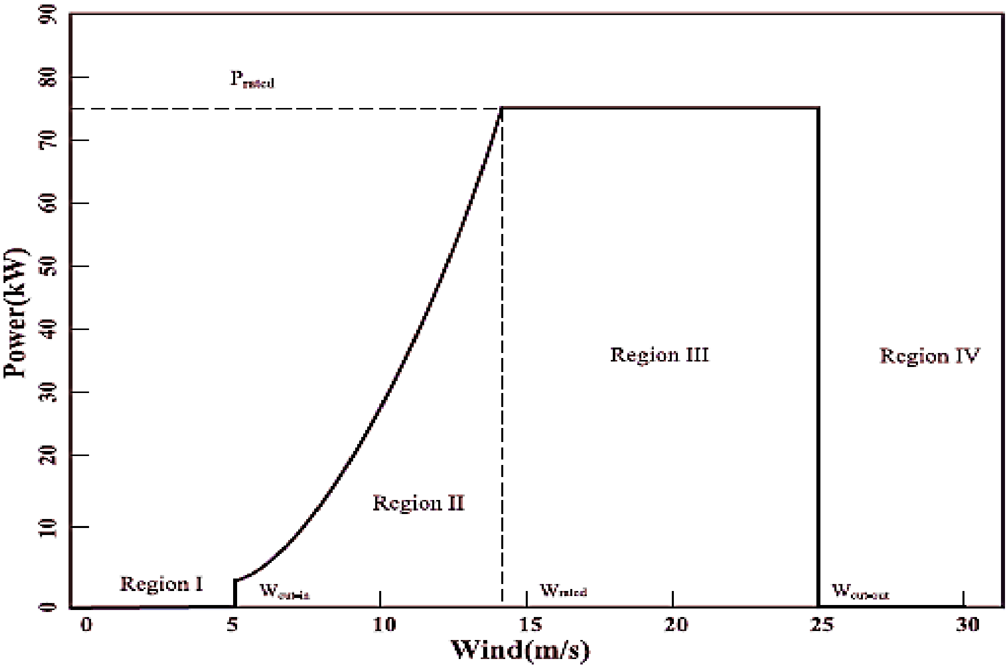


Figure I. 15: Ideal power curve and operating regions. [38]

- **Zone01**: the turbine de not working due to the limited energy source.
- **Zone02**: the turbine operates progressively, as the speed increases, so does output. Therefore, it requires an MPPT (maximum power point tracking) controller unit to track the power to maximize production.
- **Zone03**: the production capacity of the turbine energy is maintained at the nominal level using a control unit, ensuring constant power output
- **Zone04**: at high wind speeds, the turbines rotor is separation from the nacelle. The turbine rotates independently to maintain the generator s safety. **[39] [40]**

I.7.3 Wind turbine in Algeria

➢ Wind speed atlas in Algeria

The Renewable Energy Development Center has developed numerous wind maps, which are continuously updated using the latest meteorological data collected from a larger number of measurement points. The presented wind maps represent the average distribution of wind speed (m/s) across Algerian territories at heights of 10 and 80 meters. **[41]**

The following figure depicts the wind map for Algeria estimated at 10 meters above ground and 80 meters above ground. The average annual speeds obtained range from 4.5 to 8.5 m/s. It is noted that the majority of the region falls within the speed range of 5.5 to 6.5 m/s (high plateaus and desert areas). Wind speeds increase to their maximum in the areas located in the middle of the Sahara Desert (Adrar, Ain Salah, Timimoun), as well as in the Ahaggar Mountains.**[41]**

There are several local climates around Oran, Tiaret, In Amenas, Tindouf, and Djelfa, where recorded wind speeds exceed 6 m/s. Finally, the western coast of the Mediterranean Sea enjoys the lowest average annual speeds (less than 5 m/s) (2019). **[41]** As shown in the following Figure (I. 14)

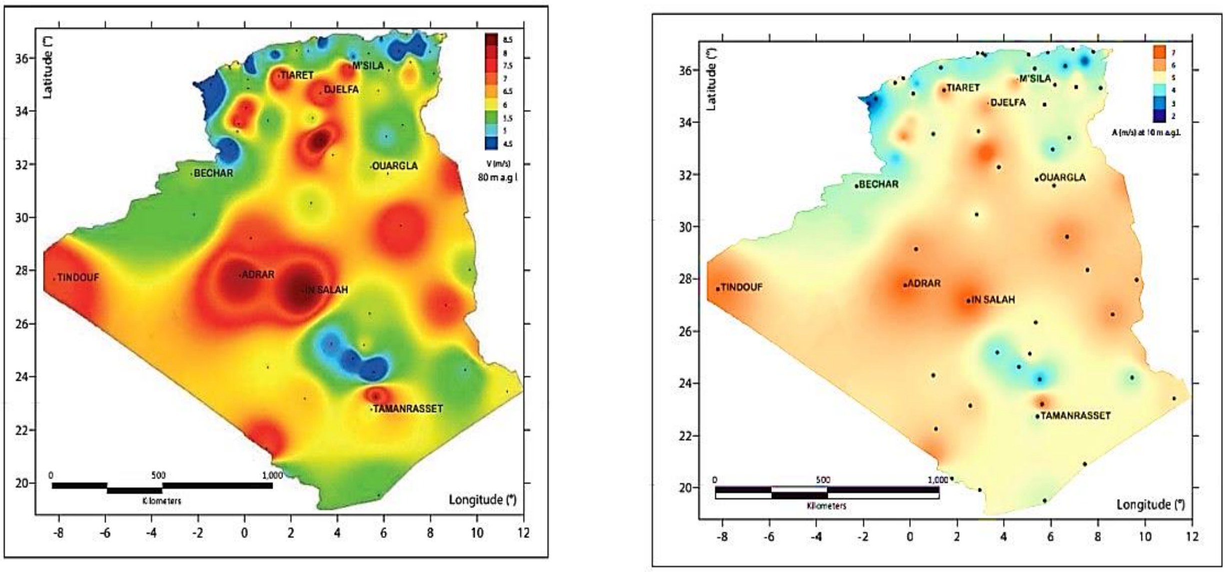


Figure I. 16: Atlas of the average wind speed of Algeria estimated at 10 and 80 m. [41]

- **The installed wind energy production capacity in Algeria**

For an optimal assessment of the wind resource available at a given site, it is necessary to calculate the average power density (W/m²) of the wind. This indicates the energy available on the site recoverable for conversion into electricity using wind turbines. At a height of 50 m, a site is considered eligible for wind farm installation if it has a power density between 300 and 400 W/m². **[41]** In figure (I. 15)

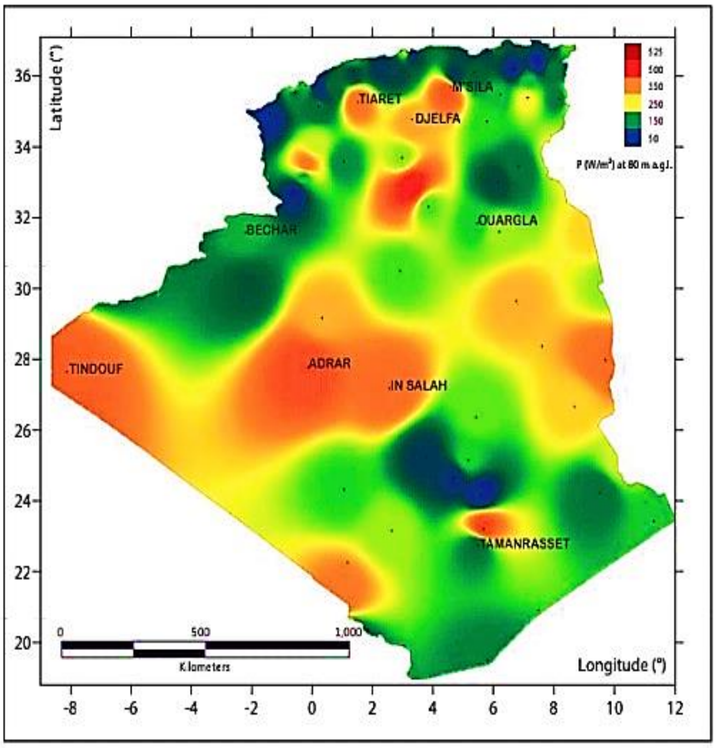


Figure I. 17: The seasonal variation of energy density. [41]

I.7.8 Potential for green hydrogen production from wind energy

The efficiency of wind energy for producing hydrogen in Algeria is notable and mainly centers on Sahara Desert in Algeria within the country. In the northern region, which encompasses the Saharan Atlas range, the Tell Atlas range, and the Mediterranean Sea area, hydrogen production ranges from 0.1 to 0.25 in areas characterized by low wind speeds.

In areas with moderate wind speeds, such as the Great Desert regions, hydrogen production ranges from 0.38 to 0.52. In regions experiencing high wind speeds, such as the Tademait Plateau, Tamanrasset, Tindouf, and Adrar, hydrogen production can range from 0.52 to 0.59. In the Tademait Plateau specifically, hydrogen production can reach levels between 0.59 and 0.66, indicating the most productive areas with the highest wind energy sources, as illustrated in the table below. **[42]** As shown in the following table (I. 3) and figure (I. 16).

Table I. 3: the regions with the greatest potential for production of green hydrogen in Algeria. [42]

the regions	production of green hydrogen(%)
Tamanrasset	26
Adrar	12
Illizi	13
Tindouf	8
Bashar	7
Ouargla	7

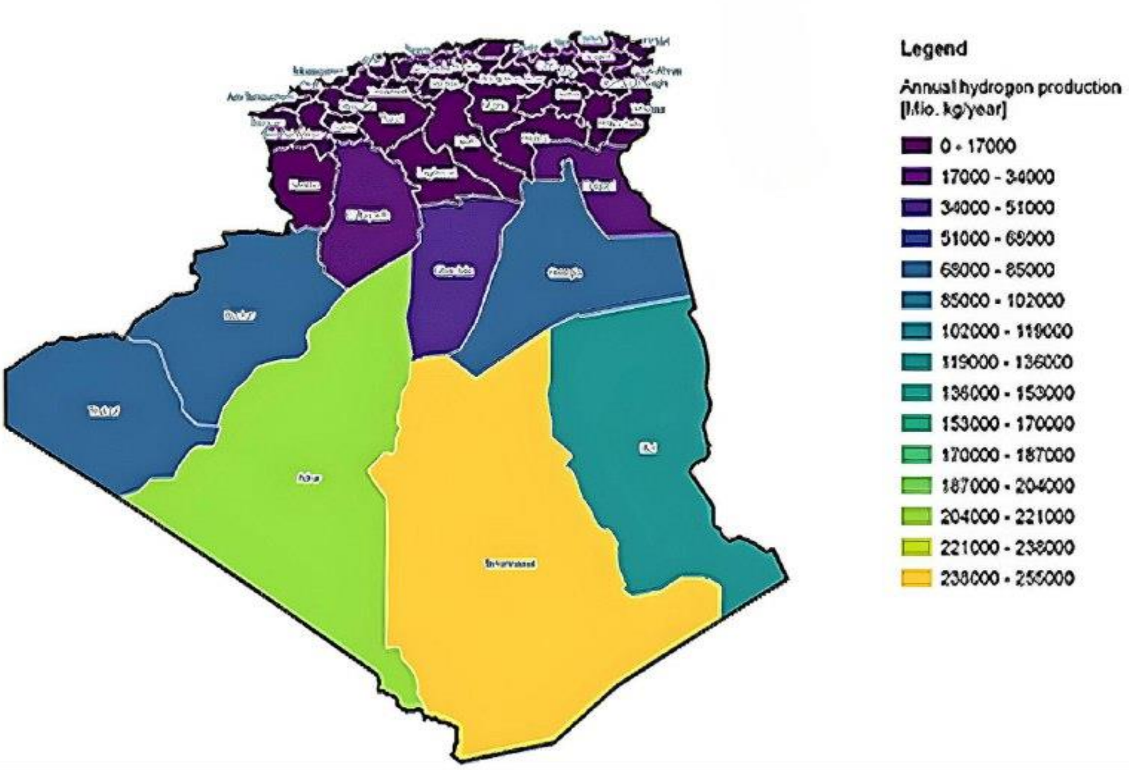


Figure I.16: Spatial overview of the technical potential for annual hydrogen production from wind power by region. [29]

I.8 Conclusion

Hydrogen has emerged as a promising contender in shaping the future energy landscape. Despite its environmental friendliness and biological benefits, hydrogen technology is still in its early stages of development, and the full potential of its exploitation has yet to be fully realized. In this chapter, we delved into the properties of hydrogen and the primary methods for its production using fossil fuels and renewable energy sources, with a particular focus on hydrogen production through water electrolysis. We also explored the diverse applications of hydrogen, including its utilization in fuel cells for electricity generation and its role as a clean energy carrier. Furthermore, we delved into the principles of operation and control of wind turbines.

The subsequent chapter will explore the modeling of the overall system.

Chapter II: Modeling of the system studied

II.1 Introduction

The hybridization of energies results in an independent, steady energy output. Controlling this output is considered important and complex, which is why researchers resort to modeling and simulation to control and understand their behavior and enhance their productivity. In this chapter, a general description of the proposed system is provided, along with modeling the system components, including fuel cell, water electrolyzer, renewable energy source, and hydrogen storage tank.

II.2 Architecture of the proposed system

Green hydrogen is considered environmentally friendly, as electricity generated from renewable energy sources such as wind energy is used to produce hydrogen. Figure (II.1) shows its general diagram. It consists of the following elements

Wind turbine: Considered a source of energy supply

PEM fuel cells: These are used as a backup system. They come into play in case of an energy deficit from the source mentioned above.

PEM Electrolyzer: A PEM hydrogen generator is used to convert surplus wind energy into hydrogen.

Hydrogen storage tank: Used to store the quantity of hydrogen produced from the electrolysis of water.

Power converters: AC-DC and DC-AC converters are used to achieve integration between systems.

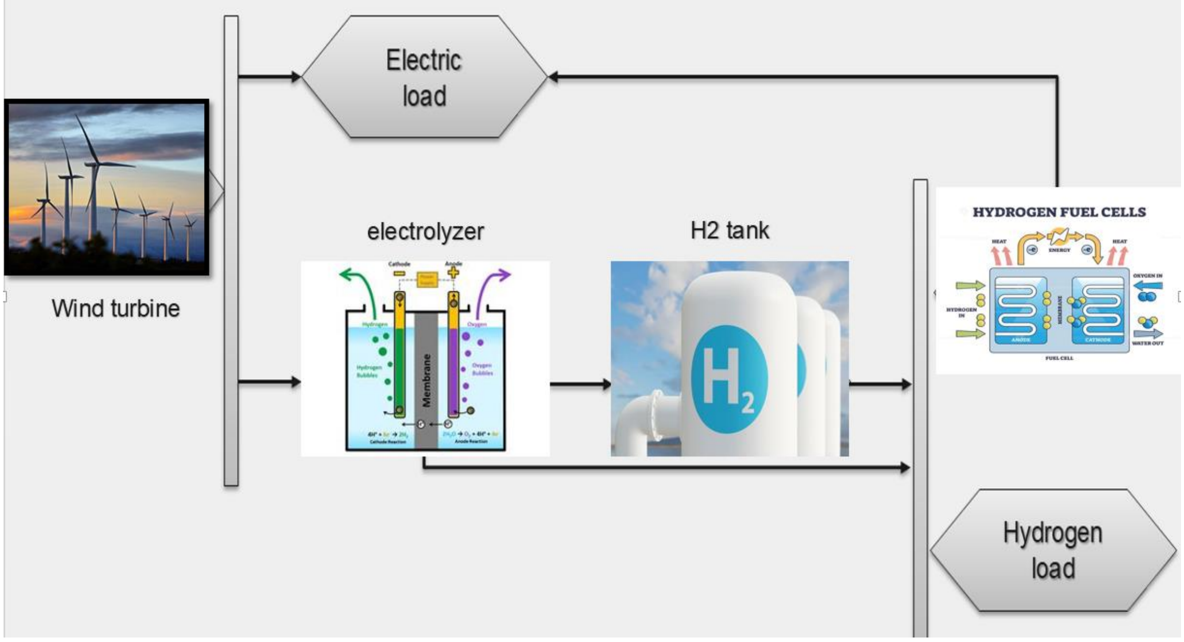


Figure II. 1: Composition of the proposed system

II.3 Modeling of renewable electricity source

II.3.1 Aerodynamic and Mechanical Model

a. Theoretical maximum rotor efficiency (Betze efficiency)

Betz's limit is a theory that represents the maximum theoretical energy that WT blades can capture from the wind. As wind passes with speed Vu from the WTs, **[43]** a portion of its kinetic energy is extracted, and the wind speed decreases to Vd after passing through the turbines Figure (II.2). **[44]**

Equation (II.13) shows how the power produced by a wind turbine can be calculated: **[45]**

$$P = 0.5\cdot\pi\cdot\rho\cdot R^{2}\cdot [Cp(\lambda,\beta)]\cdot V^{3}w \qquad \text{(II.13)}$$

Where, Cp is the coefficient of power 0.5, ρ is the density of air (1.225Kg/m ^{3}), λ is the tip-speed ratio, β is the pitch-angle, R is the radius of the wind wheel (m), Vw is the wind speed. **[45]**

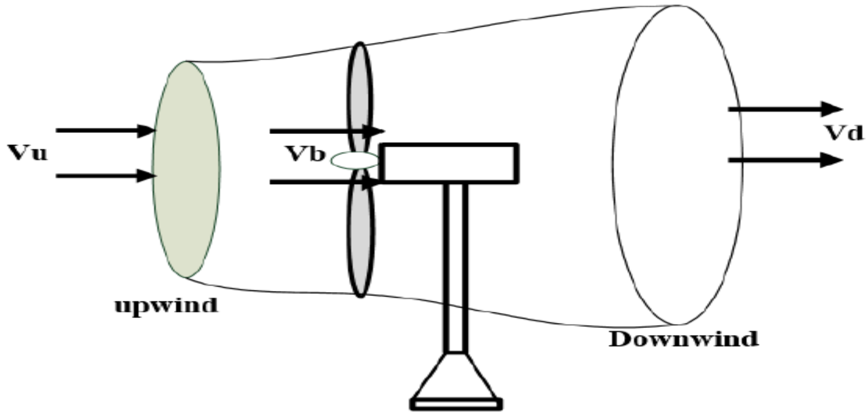


Figure II. 2: Stream tube due to the change in wind speed. [50]

b. Tip-speed ratio

Three subsystems make up the aerodynamic block: tip-speed ratio calculation, rotor power coefficient (Cp) calculation, and aerodynamic torque calculation. The input specified by user are wind velocity and pitch angle (β).

The tip speed ratio (λ) can be expressed as the ratio of speed at the tip of the blades to the wind speed, as represented by (II.14): **[45]**

$$\lambda = \frac{\omega R.R}{Vw} \qquad \text{(II.14)}$$

Here, ωR is the angular/rotational (rad/s) velocity of the wind turbine system, power coefficient (Cp) defines the efficiency of the entire wind power system, which is the ratio of power generated by the wind turbine and the wind power projected into the turbine. Mathematical formulation of wind turbine**. [46] [47]**

c. Rotor power coefficient (Cp)

Known as the fraction of wind energy extracted by the wind turbine, represents rotor efficiency. The equation of power coefficient is given in (II.15). **[48]**

$$Cp=\frac{\text{Extracted power}}{\text{power in wind}}=\frac{\text{Protor=Pm}}{\text{Pw}} \qquad \text{(II.15)}$$

Generally, the power coefficient (Cp) is highly nonlinear function of blade pitch angle (β) and (λ). In this study, the numerical (II.16) approximation of Cp is provided by: **[49]**

$$Cp\ (\alpha, \beta) = 0.22(\frac{116}{\lambda i}-0.4\beta -5) + e^{\lambda i-21} \qquad \text{(II.16)}$$

$$\frac{1}{\lambda i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \qquad \text{(II.17)}$$

Figure (II. 3) demonstrate the relation between Cp and λ with variable values for β. As illustrated in figure (I. 3), there are certain values of λ which, if held for corresponding wind velocities, will result in a maximum Cp curve and optimal wind power extraction. **[45]**

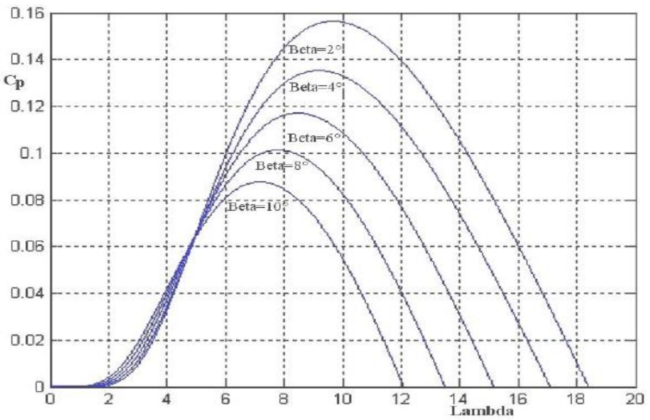


Figure II. 3: Power coefficient depending on speed ratio (λ) and pitch angle (β). [45]

d. Gearbox model

A gearbox is a critical component in a wind turbine drivetrain. It sits between the low-speed shaft connected to the turbine, and the high-speed shaft, connected to the generator. The function of the gearbox is to increase the rotational speed of the shaft from the rotor to a speed suitable for efficient electricity generation. Math equations define this multiplier:

$$Cg= \frac{Ct}{G} \qquad \text{(II.16)}$$

$$\Omega\ \text{turbine} = \frac{\Omega\text{mec}}{\text{G}} \qquad \text{(II.17)}$$

e. mechanical shaft

We find it between the Gearbox and power generator, it role is to conduct mechanical energy, it can represented by the following equations:

$$J\ \text{total}=\frac{J\text{turbine}}{G2} +\text{Jr} \qquad \text{(II.18)}$$

The fundamental equation of dynamics makes it possible to determine the evolution of the mechanical speed from the total mechanical torque (Cmec) applied to the rotor:

$$Cmec = Jtotal\times\frac{d\Omega mec}{dt} \qquad (II.19)$$

Where J represents the total inertia on the generator rotor, incorporating the electromagnetic torque (Cem) generated by the generator, the viscous friction torque (Cvis), and the torque (Cr).

$$C\,mec = Cr - Cem - Cvis \qquad (II.20)$$

The resistant torque due to friction is modeled by a viscous friction coefficient f:

$$Cvis = f \times \Omega mec \qquad (II.21)$$

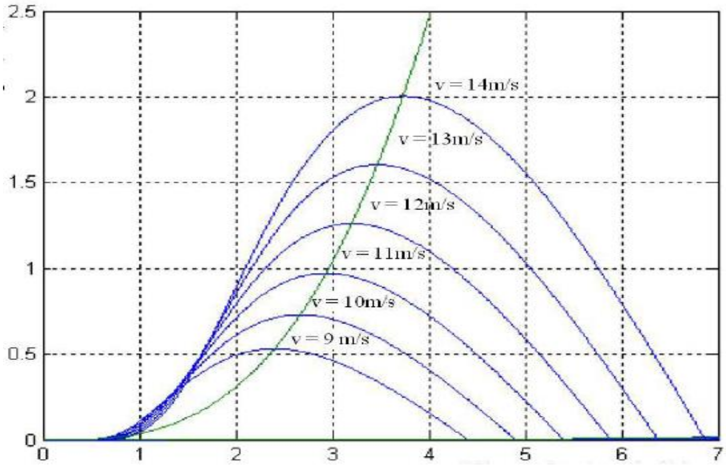


Figure II. 4: Theoretical power available for a given type of wind turbine. [45]

II.3.2 Electrical modeling of a wind turbine

The figures below represent various processes of converting wind kinetic energy into usable electrical energy.

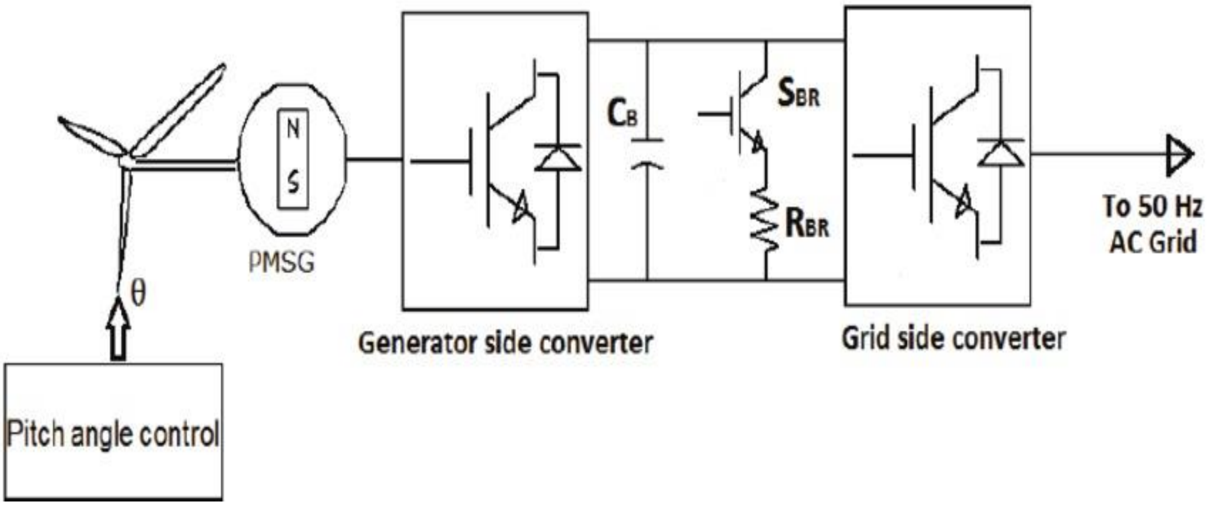


Figure II. 5: Wind power generation system. [50]

Wind speed plays a crucial role in various aspects of wind energy production. Especially at peak power, it's important to deal with and control fluctuations. Adjusting the blade pitch angle can assist in regulating wind turbine power by controlling either the rotor torque or generator speed to ensure maximum production across a wide range of wind speeds. This enhances reliability and protects mechanical components.

Wind energy conversion turbines rely on generators to convert mechanical energy from the wind into electrical energy. Two common types in this field are doubly fed asynchronous generators and permanent magnet synchronous generators. The advantage of permanent magnet synchronous generators lies in their ability to extract maximum energy by reducing mechanical constraints through eliminating the gearbox, thus improving speed. Additionally, increased reliability and decreased maintenance costs make them superior to other types of machines due to their ability to eliminate mechanical gearboxes. **[51]**

The illustrated system in Figure (II. 5) consists of a wind turbine connected to a permanent magnet synchronous generator without a mechanical gearbox. It also includes two transformers: one for converting the generator's AC output into direct current to improve current quality, and the other for converting AC current into DC current for connection to the grid. These transformers work to enhance current quality and also help match the power produced by the turbine with the required grid power. **[52] [50]**

II.3.3 Modeling of the generators permanent magnet synchronous generators (PMSG)

A Permanent Magnet Synchronous Generator (PMSG) is a type of electrical generator that uses permanent magnets to create the magnetic field required for generating electricity. This differs from traditional synchronous generators, which rely on electromagnets powered by an external source. **[53]** As shown in the following Figure (II. 6):

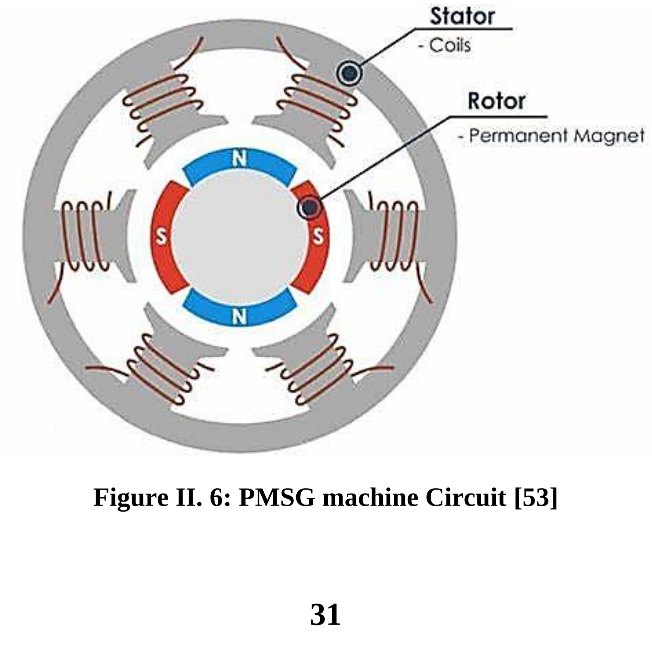


Figure II. 6: PMSG machine Circuit [53]

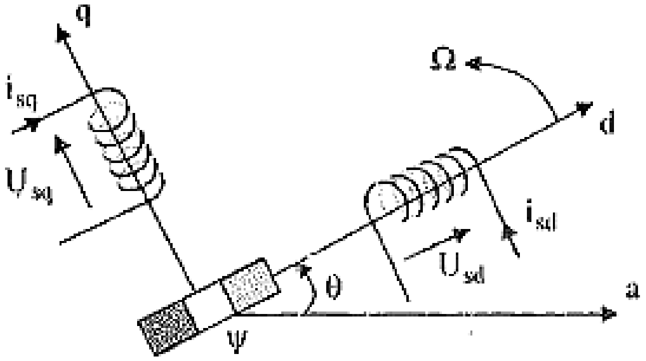


Figure II. 7: representation of the machine. [53]

The expressions for tensions in the XY axis system are of the form:

$$U_{sd}=R_s i_{sd}- \omega_e. \Psi_{sq}+ \Psi_{sd} \tag{II.22}$$

$$U_{sq}= R_s i_{sq}+\omega_e. \Psi_{sd}+ \Psi_{sq}$$

Expressions of flows in the same axis system:

$$\Psi_{sd}= L_d.i_{sd} + \Psi_{PM}$$

$$\Psi_{sq}= L_q.i_{sq} \tag{II.23}$$

The respective expressions of the torque and the dynamic rotor speed are:

$$P_{gem}=T_e\ \omega_m =\frac{3}{2}\,[U_{sd}i_{sd}+U_{sq}i_{sq}] \tag{II.25}$$

$$Ce = \frac{3}{2}\ [U_{sq}i_{sd}+U_{sd}i_{sq}] \tag{II.26}$$

II.4 Modeling of PEM Fuel Cells

II.4.1 Fuel cell characteristic curve

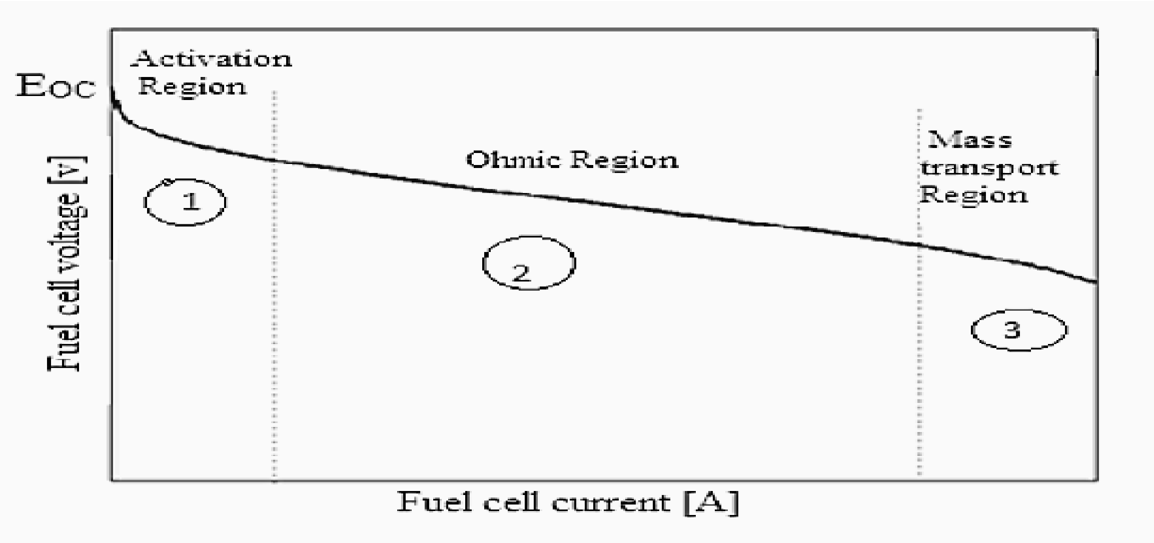


Figure II. 8: Polarization curve. [54]

Region 1 The first region represents the activation voltage drop due to the slowness of the chemical reactions taking place at electrode surfaces. Depending on the temperature and operating pressure, type of electrode, and catalyst used, this region is more or less wide. **[54]**

Region 2 The second region represents the resistive losses due the internal resistance of the fuel cell stack.

Region 3 Finally, the third region represents the mass transport losses resulting from the change in concentration of reactants as the fuel is used.

II.4.2 Voltage model

fuel cells are categorized into different types, In fact, the most suitable fuel cells for micro-cogeneration applications are the low temperature PEMFC working around 80 °C, This is attributed to its multiple benefits, mainly, high power density. less corrosion, and a low operating temperature

The used model is comprised of a controlled voltage source in series with a resistor, as presented in figure II. 9

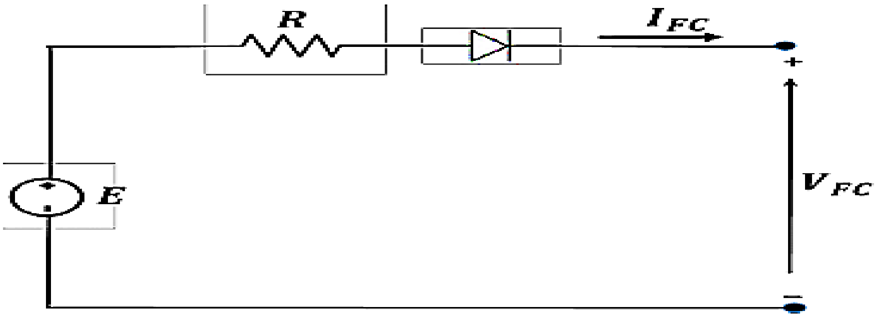


Figure II. 9: The fuel cell's equivalent circuit. [55]

Using Ohm's law, we can express the cell voltage as: **[56]**

$$E_{cell} = E_{rev} + \eta_{act} - R_m.\ J \qquad \text{(II.27)}$$

$$E_{rev} = \alpha_1 + \alpha_2.\ (T_{pac}-298.15) + \alpha.\ Tpac.\ (0.5.\ \text{In } Po_2 + \text{In } P_{H_2}) \qquad \text{(II.28)}$$

$$\eta_{act} = \beta_1 + \beta_2.\ T_{pac} + \beta_3.\ T_{pac}.\ \text{In}(j.\ 5.10^{-3}) + \beta_4.\ T_{pac}.\ \text{In } Co_2 \qquad \text{(II.29)}$$

$$Co_2 = \frac{Po_2}{5.08.10^6.\exp\left(-\frac{498}{Tpac}\right)} \qquad \text{(II.30)}$$

II.4.3 performance model

The efficiency of a battery operating at constant temperature and pressure under reversible conditions, that is, at equilibrium, is [Stevens]: **[56]**

$$\eta r\ (\text{pile}) = \frac{We}{-\Delta H} = \frac{nFEeq}{-\Delta H} = \frac{\Delta G}{\Delta H} = 1- \frac{T\Delta S}{\Delta H} \qquad \text{(II.31)}$$

$$\Delta G = \Delta H - T\Delta S \qquad \text{(II.32)}$$

This theoretical reversible yield is generally very high. For a hydrogen fuel cell (91% at 150°C and 83% at 25°C)

The overall efficiency of the stack is the product of the three previous efficiencies:

$$\eta_{pil} = \frac{nexpFE(j)}{(-\Delta H)} = \frac{nFEeq}{-\Delta H} \cdot \frac{E(j)}{Eeq} \cdot \frac{neq}{n} = \eta^{pil}{}_{r}\ \eta_{E}\ \eta_{F} \qquad \text{(II.33)}$$

$$\eta_{E} = \frac{E(j)}{Eeq} < 1 \qquad \text{(II.34)}$$

$$\eta_{F} = \frac{I}{\mathrm{Im}} = \frac{nexp}{n} \qquad \text{(II.35)}$$

II.5 PEM hydrogen generator model

PEM Electrolyzer is an electrochemical device that splits water molecules into hydrogen and oxygen molecules, consuming electrical energy in the process. **[57]** As shown in the following figure (II. 10)

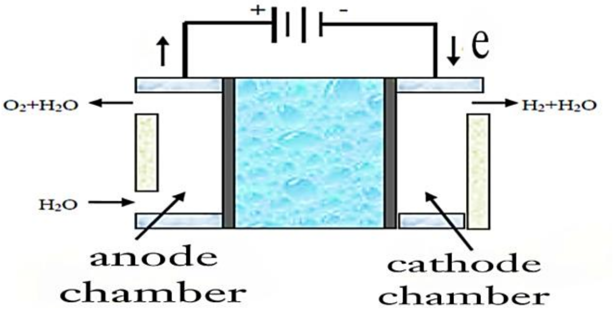


Figure II. 10: Internal diagram of the PEM electrolyzer

To obtain the amount of hydrogen produced from the electrolyzer, the following equation was used: **[58]**

$$F_{H2} = \eta_{F} * \frac{icell * \mathrm{Acell}}{Z * \mathrm{F}} \qquad \text{(II.36)}$$

The cell voltage was calculated according to the following formula [59] [60]:

$$\mathrm{Vcell} = V_{rev} + V_{ohm} + V_{act} + V_{com} \qquad \text{(II.37)}$$

V_{rev} was calculated thusly:

$$V_{rev} = V_{rev0} + \frac{R * \mathrm{Tel}}{2 * \mathrm{F}} * \left(\frac{pH2 * \sqrt{\mathrm{Po}_2}}{PH_2O}\right) \qquad \text{(II.38)}$$

V_{act} relates the current density to the activation over potential for each electrode, which takes into account the kinetics of the charge transfer reaction. Was calculated through this equation:

$$I = i_0 \left[\exp\left(\frac{\alpha 1.F}{R.T} Vact\right) - exp\left(-\frac{\alpha 2.F}{R.T}\right) Vact\right]$$

$$V_{act} = \frac{R*\mathrm{Tel}}{\alpha an*F} * \operatorname{asinh} * \frac{icell*\mathrm{Acell}}{Z*\mathrm{io,an}} + \frac{R*\mathrm{Tel}}{\alpha cat*F} \operatorname{asinh}\left(\frac{icell*\mathrm{Acell}}{Z*\mathrm{io,cat}}\right) \quad (II.39)$$

The ohmic resistance was calculated through this equation:

$$V_{ohm} = i.R_{ohm} \quad (II.40)$$

$$R_{ohm} = t_m / \sigma_m$$

The membrane conductivity was calculated thusly:

$$\sigma_m = 0.00514*\lambda m - 0.00326) * e^{1268*((1/303)-(1/\mathrm{Tel}))} \quad (II.41)$$

The membrane water content was calculated thusly

$$\lambda = \frac{(-2.89556+0.016*\mathrm{Tel})+1.625}{1875} \quad (II.42)$$

The electrolyzer efficiency was calculated thusly:

$$\eta_{elec} = \frac{\mathrm{Vth}}{Vcell} \quad (II.43)$$

The hydrogen production:

$$H2 \text{ production} = \eta_F \frac{\mathrm{nc(RITt)}}{Fpz}$$

The ratio between the actual and the theoretical maximum amount of hydrogen produced in the electrolyzer is known as Faraday efficiency. Assuming that the working temperature of the electrolyzer is 40°C

$$\eta_F = 96.5 e^{\left(\frac{0.09}{i} - \frac{75.5}{i^2}\right)}$$

II.6 Modeling of hydrogen storage systems

The storage tank intended to contain hydrogen at a certain pressure in liquid or gaseous form can be modeled. Note that hydrogen storage is done according to three main methods, high pressure for stable systems 120 bars, for 250-700 bars mobile systems, in liquid form (-259 ° C), then in hybrid metal form. **[59]**

$$Pt - Pti = \frac{P.Vm}{R.T} \frac{N_H{}^2.\ R.Tt}{M_{H_2}.\ Vt} \quad (II.44)$$

Pti is Initial pressure of the storage tank (pascal), Pt is Pressure of tank (pascal), R is universal (rydberg) gas constant (J/kmol K), Tt is Operating temperature (K), Vt is Volume of the tank, P is Pressure, M_{H2} is the molar mass of hydrogen gas, N is Number of hydrogen

The size of the hydrogen storage tank is determined by the amount of hydrogen consumed by the fuel cell. **[60]** The flow rate of the hydrogen is calculated at the operating pressure by:

$$P = Z.\ \frac{m_{H_2}.RTtank}{M_{H_2}.Vtank} + P_{initial} \quad (II.45)$$

Where P is the gas pressure in Pascal (Pa), mH2 is the mass quantity of hydrogen, R is the gas constant equal to 8.314 J/K.mol, T_{tank} is the absolute temperature of the gas (K), V_{tank} is the gas volume (m^3), and z is the compressibility factor

II.7 Modeling of power converters

II.7.1 converter bidirectinal AC-DC equations

A bidirectional converter is a power electronic device that allows the flow of energy in both directions between two different sources. This means it can convert AC power to DC power (rectification) and vice versa (inversion). **[61]** As shown in the following figure (II. 11)

For a single-phase AC system, the instantaneous voltage and current can be described as:

$$vac(t) = Vac.\ \sin.\ (Wt - \phi v)$$

$$iac(t)= Vmax.\ \sin.\ (Wt - \phi i) \qquad (II.46)$$

vac(t) is the instantaneous AC voltage, iac(t) is the instantaneous AC current, Vac is the peak AC voltage, Iac is the peak AC current, Wt is the angular frequency of the AC supply, ϕv and ϕi are the phase angles of the voltage and current, respectively.

The real (P) and reactive (Q) power can be calculated

$$P=Vrms.\ Irms.\ \cos(\phi v-\phi i)$$

$$Q=Vrms.\ Irms.\ \sin(\phi v-\phi i) \qquad (II.47)$$

Vrms is the root mean square (RMS) value of the AC voltage, Irms is the root mean square (RMS) value of the AC current.

For the DC side, the voltage and current can be expressed as:

$$Vdc=Vac,peak/\sqrt{2}$$

$$Idc=Pdc/Vdc \qquad (II.48)$$

Vdc is the DC voltage, Idc is the DC current, Vac,peak is the peak AC voltage, Pdc is the power on the DC side.

Bidirectional power flow:

The power flow between the AC and DC sides can be described as:

$$Pac=Pdc \qquad (II.49)$$

Taking into account the efficiency η\etaη of the converter, the power relationships can be written as:

$$Pac=\eta Pdc$$

$Pdc=\eta Pac$ (II.50)

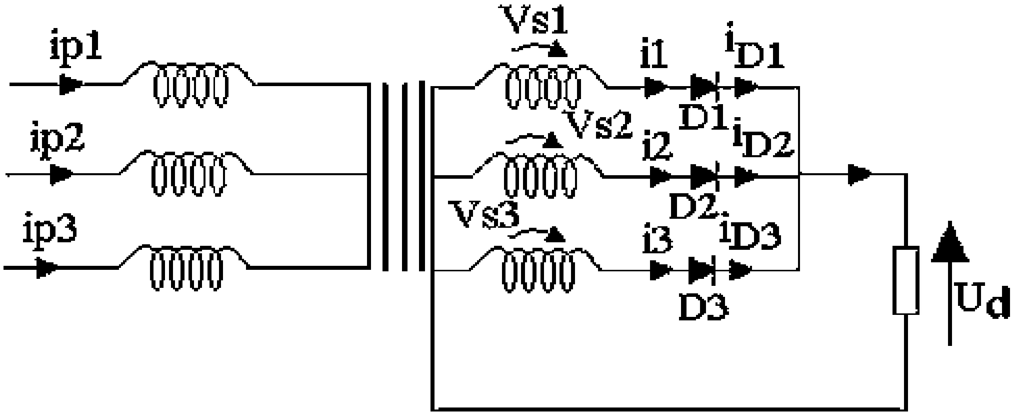


Figure II. 11: Single-phase half-wave rectification. [62]

The secondary windings of the transformer are connected in a star configuration, and the rectifier consists of three diodes mounted in common cathode (called the more positive switch). The load is placed between the cathode and the neutral.

II.8 Conclusion

In this chapter, we provided a general description of the proposed system and introduced a model of the system components, including fuel cells and wind energy, as well as storage systems. In the next chapter, we will delve into simulating the system and optimizing its control for improved efficiency.

CHAPTER III:

SIMULATION AND RESULTS

III.1 Introduction

Hybrid systems are power generation systems that incorporate multiple energy sources, whether conventional or renewable. The goal of integrating these energy sources is to increase efficiency, reliability, and production stability.

During our work, we studied the hydrogen production capacity of wind turbines located at the Adrar wind power plant. We also studied the same type of wind turbines in other regions of Algeria.

This chapter provides the framework for building a hybrid system the objective is to produce hydrogen, and we will discuss components that meet the system's needs, and the sizing steps to achieve optimal design. It also includes a technical and economic analysis for supplying hydrogen fuel, which can be consumed directly or indirectly in various regions of Algeria using the HOMER Pro software.

III.2 HOMER Pro overview

The HOMER software (Hybrid Optimisation Model for Electric Renewable) is designed to support researchers in the design and analysis of hybrid electrical systems. It simulates various systems, both production (wind turbine, generator...) or consumption, making it possible to evaluate the economic feasibility of renewable energy systems. It also allows for the understanding and improvement of system operations. In this study, the purpose of using HOMER is to determine the required energy from each generator and determine storage system which depends on hydrogen production to meet the imposed work requirements and to select the best design for the study.

III.3 Energy balance of the chosen system

The general system contains a system of the power generation system with the hydrogen production system. This system can be divided into two parts:

Part 1: the basic unit of energy production is a wind turbine, where part of this energy is supplied directly to the electric load

Part 2: The surplus energy is directed to the storage system consisting of water electrolyzer and hydrogen tank, where it is converted into hydrogen using an electrolyzer. The hydrogen is then converted back to energy when needed using a fuel cell or consumed directly through the hydrogen load.

The figure (III. 1) shows the system Configuration in the HOMER Pro

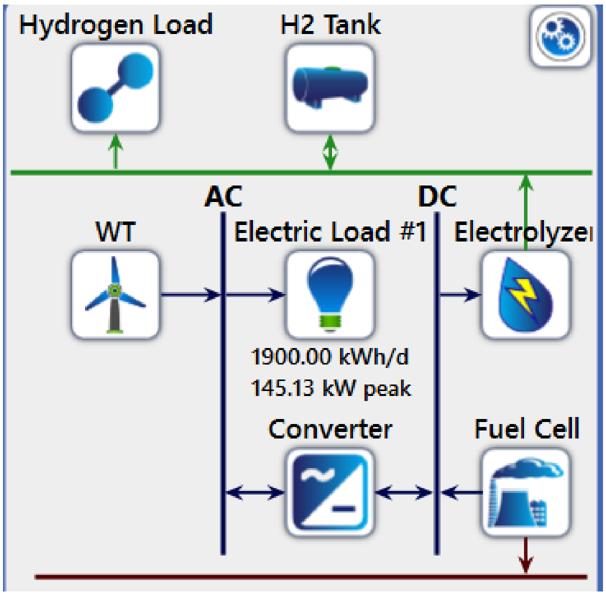


Figure III. 1: Schematic of the proposed system

III.4 Geographical and Meteorological characteristics of study sites

III.4.1 Input data Geographical

The study area is the geographic region that will be considered for the HOMER analysis. This could be a specific town, city, or region.

The Kaberten Wind Power Station is located approximately 70 kilometers north of Adrar City. It is the first wind power station in Algeria. The station began operations in 2014 and has a generation capacity of 10 megawatts. It was built by the French company Cegelec.

The Kaberten station consists of 12 wind turbines, each with a capacity of 850 kilowatts.

The subject of this study is the production of hydrogen using wind power plant equipment in Adrar in different regions of Algeria. The areas selected for the study are as follows Ouargla, Adrar, In Salah, Tiaret and Tindouf. With explanations shown in the atlas map these areas are characterized by medium and high wind speeds in different regions of the country:

III.4.2 Input data Meteorological

III.4.2.1 Wind speed data

- **Ouargla:** located in the Algerian Sahara, is characterized by a dry and hot climate. Wind is an important element in the region's environment, blowing almost continuously throughout the year. The figure (III. 2) shows the variation in wind energy annually in the Ouargla region

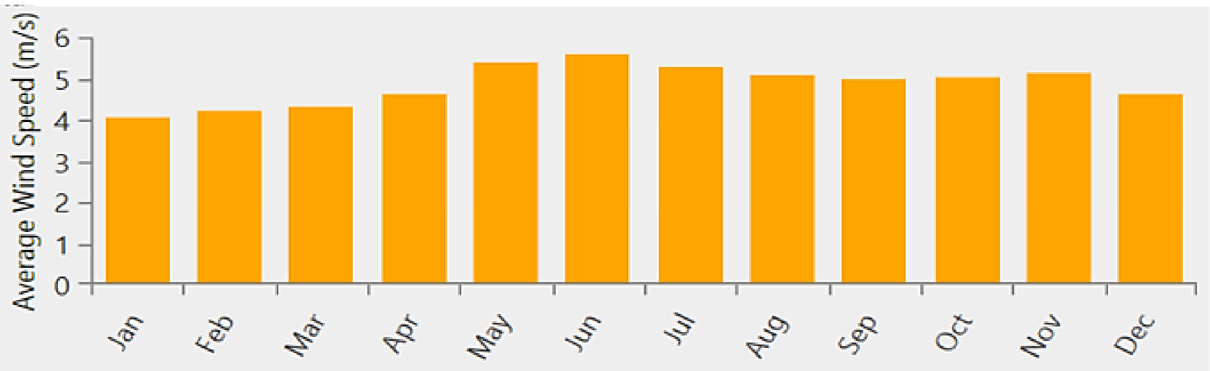


Figure III. 2: annual wind speed variation in Ouargla

Adrar: a wilaya (province) in southern Algeria, is characterized by its hot and dry desert climate, with strong winds being a common feature. The prevailing winds in Adrar are typically from the northeast and east directions. These winds can be quite strong, with average speeds ranging from 5 to 10 meters per second (m/s). The figure (III. 3) shows the variation in wind energy annually in the Adrar region

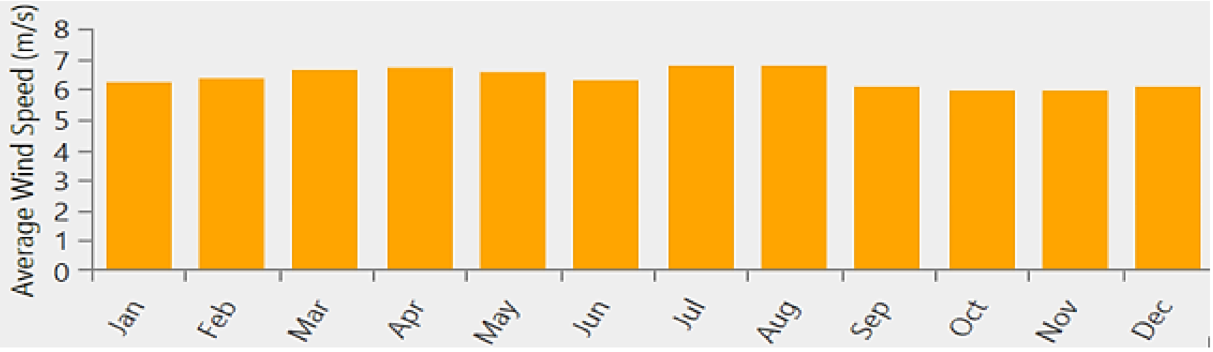


Figure III. 3: annual wind speed variation in Adrar

Tiaret: Wind speeds in Tiaret are generally moderate, with an average annual speed of around 6 kilometers per hour. However, wind speeds can increase significantly during thunderstorms and seasonal winds. The figure (III. 4) shows the variation in wind energy annually in the Tiaret region

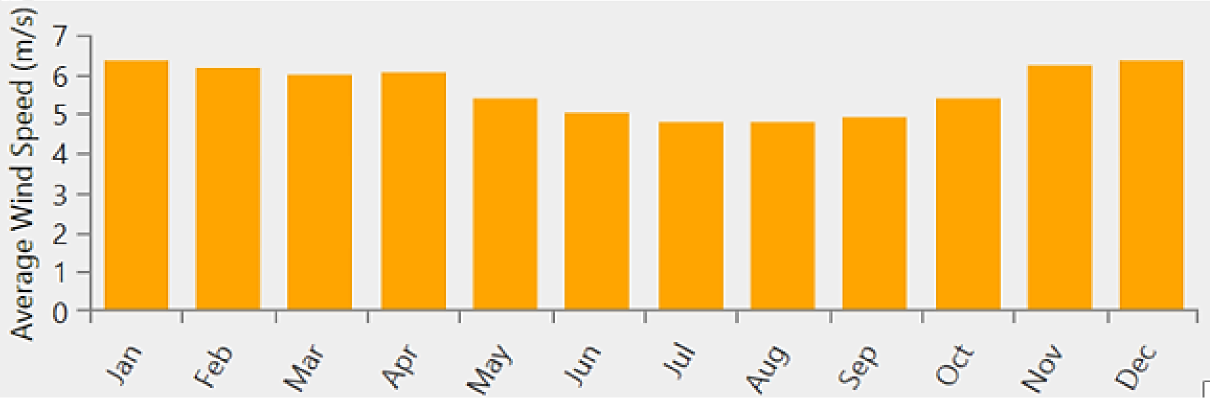


Figure III. 4: annual wind speed variation in Tiaret

Tindouf: is a city located in the far southwest of Algeria, in the Sahara desert region. The region is characterized by its dry and hot climate, with strong winds in general. Tindouf is considered one of the most promising areas in Algeria for wind energy potential. The figure (III. 5) shows the variation in wind energy annually in the Tindouf region

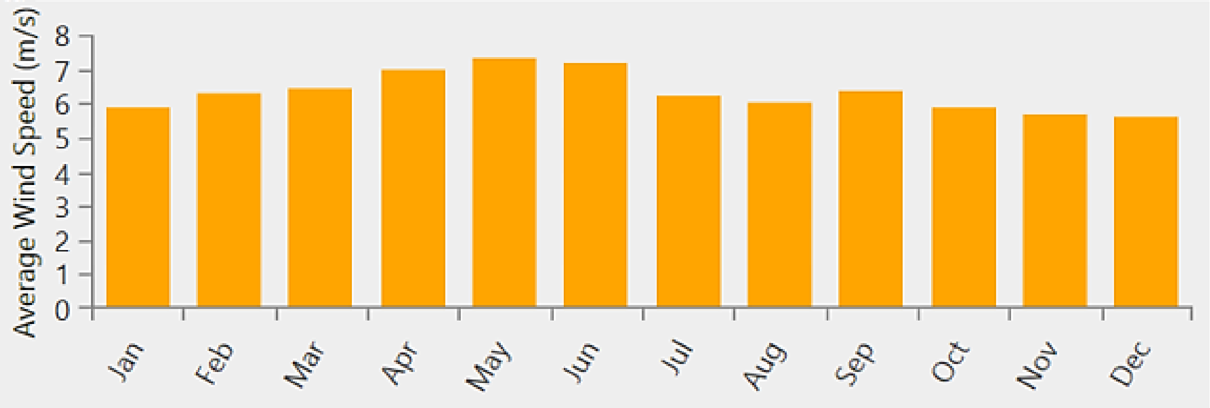


Figure III. 5: annual wind speed variation in Tindouf

In Salah: located in the Algerian Sahara, is characterized by moderate wind speeds and strong ranging from 10 to 20 km/h. The figure (III. 6) shows the variation in wind energy annually in the In Salah region

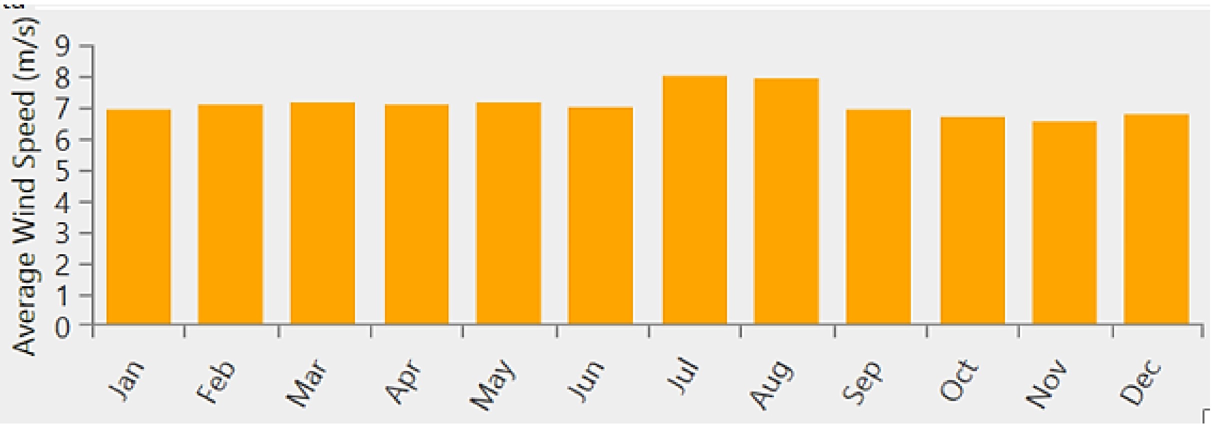


Figure III. 6: annual wind speed variation in In Salah

III.5 The load profile

Determining the size of hybrid renewable energy systems (RES) using HOMER requires knowledge of the site's geographical and meteorological conditions. In this work, wind data and electric load is obtained from the HOMER software. The plant was chosen to be electric and hydrogen load type. It is noted that the daily electrical peak of the load is 1000 KW

As shown in the figure (III. 7) and figure (III. 8)

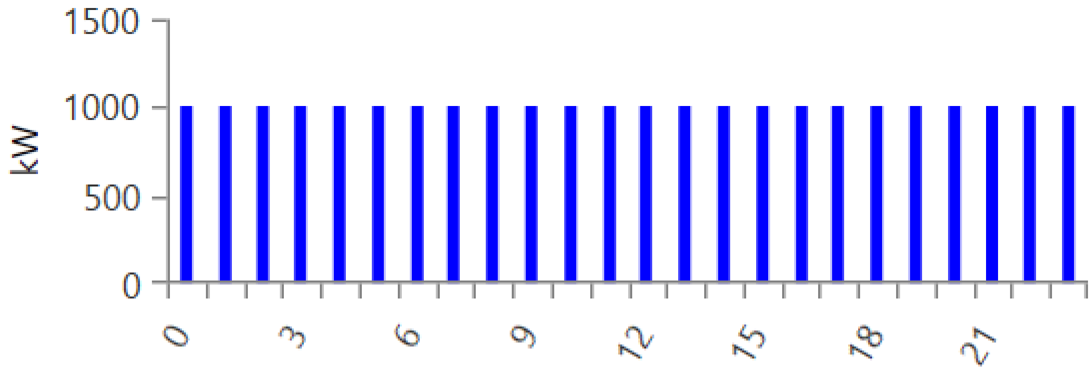


Figure III. 7: an hourly average electric load variations.

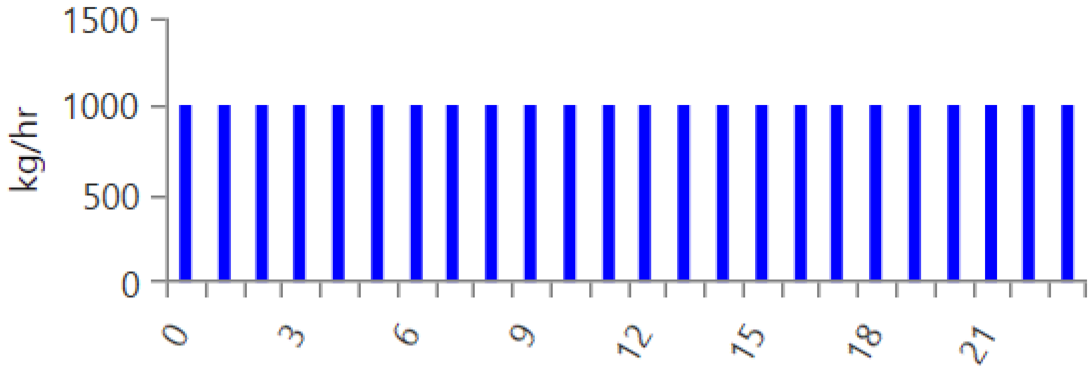


Figure III. 8: an hourly average hydrogen load variations.

III.6 selection of components

III.6.1 Choice of wind turbine

The Gamesa G58 is a wind turbine well-suited for high-wind areas around the world. These wind turbines can provide power to off-grid areas, . They have the following characteristics the table (III. 1) shows, and the figure (III. 9) shown the power turbine as a function of wind speed:

Table III. 1: wind turbine system specifications

Setting	value
Capital cost($/KW)installed	55.546,57
Operation and maintenance cost($/KW/year)	10
Replacement cost($/KW)	55.546,57
Lifespan	30
Rotor diameter	58m
Type generator	Asynchronous
Rated power	850 kW

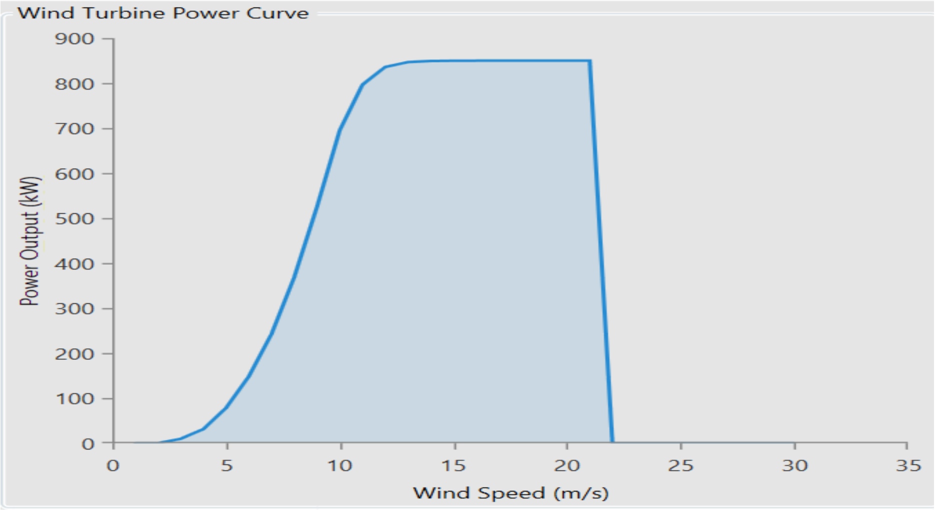


Figure III. 9: wind turbine power curve

III.6.2 Bidirectional converter choice

A bidirectional inverter is a device that can convert direct current (DC) electricity to alternating current (AC) electricity, and vice versa. It is an essential component of renewable energy systems, as it allows for the integration of power sources, such as solar panels and wind turbines, with AC or DC load. Shown in the following table (III. 2) specifications

Table III. 2: Bidirectional converter specifications

Setting	value
Capital cost($/KW)installed	300
Operation and maintenance cost ($/KW/year)	0
Replacement cost($/KW)	300
Lifespan	15
Efficiency(%) at nominal power	95

III.6.3 Fuel cell Choice

Since the fuel cell can operate the load by itself during a shortage in primary source production, its power must be sufficient to meet the peak load demand. This generator automatically sizes itself to meet the load. It also adjusts its fuel curve to match its size

The specification of the selected electrolyzer are detailed in table (III. 3):

Table III. 3: Fuel cell specifications

Setting	Value
Capital cost($/KW)installed	500
Operation and maintenance cost ($/KW/year)	0.030
Replacement cost($/KW)	500
Lifespan(h)	15,000.00

III.6.4 Electrolyzer choice

In this study, a polymer electrolyte membrane (PEM) electrolyzer was selected due to its technological maturity and acceptable efficiency under different load conditions. And PEM technology has the advantage main which lies in the fact that its response is instantaneous and very rapid to the variation of the current entry. The specifications of the selected fuel cell are detailed in table (III. 4).

Table III. 4: electrolyzer specifications [63]

Setting	Value
Capital cost($/KW)installed	2000
Operation and maintenance cost ($/KW/year)	10
Replacement cost($/KW)	2000
Lifespan(year)	15
efficiency	85

III.6.5 Choice of hydrogen storage tank

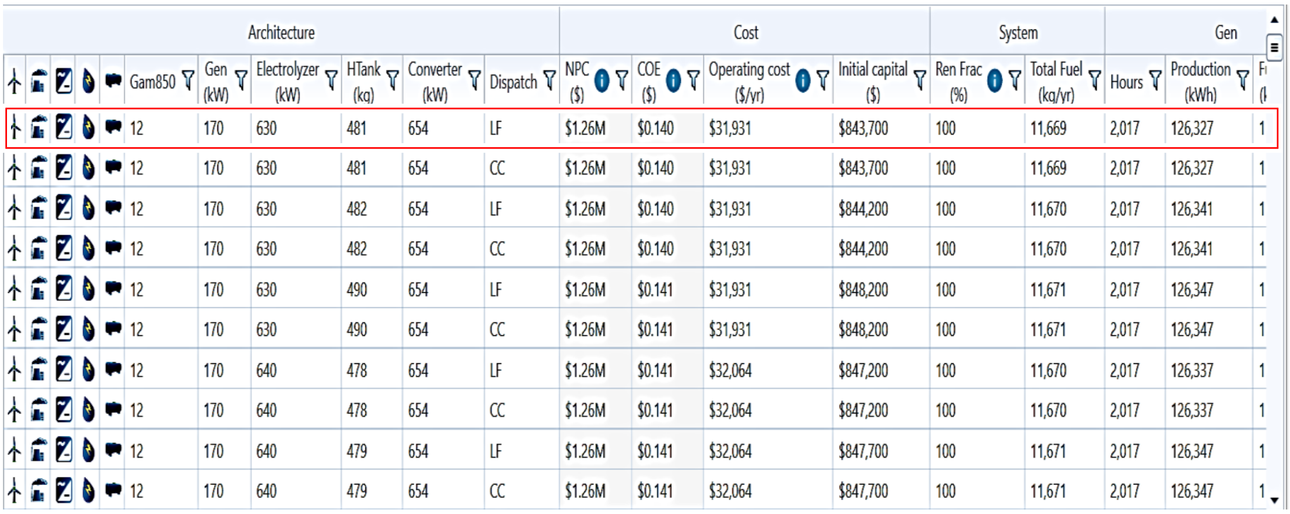
In this study, the storage of hydrogen in the form of compressed gas in sustainable tanks was studied. A description of the specifications of the specified hydrogen tank is given in table (III. 5).

Table III. 5: hydrogen storage tank specifications [63]

Setting	Value
Capital cost($/KW)installed	1500
Operation and maintenance cost ($/KW/year)	30
Replacement cost($/KW)	1500
Lifespan(year)	25
Relative to tank size (%)	50

III.7 Sizing results

The purpose of using HOMER is to obtain the optimal energy from the entered components, where the energy source is a wind turbine and the green hydrogen source is an electrolyzer. The hydrogen ratio should be sufficient to meet the needs of both the hydrogen load and the electricity load when needed. The latter comes from an optimal mix of components. As shown in the following figure (III. 10)



Architecture						Cost				System		Gen		
Gam850	Gen (kW)	Electrolyzer (kW)	HTank (kg)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (kg/yr)	Hours	Production (kWh)	F
12	170	630	481	654	LF	$1.26M	$0.140	$31,931	$843,700	100	11,669	2,017	126,327	1
12	170	630	481	654	CC	$1.26M	$0.140	$31,931	$843,700	100	11,669	2,017	126,327	1
12	170	630	482	654	LF	$1.26M	$0.140	$31,931	$844,200	100	11,670	2,017	126,341	1
12	170	630	482	654	CC	$1.26M	$0.140	$31,931	$844,200	100	11,670	2,017	126,341	1
12	170	630	490	654	LF	$1.26M	$0.141	$31,931	$848,200	100	11,671	2,017	126,347	1
12	170	630	490	654	CC	$1.26M	$0.141	$31,931	$848,200	100	11,671	2,017	126,347	1
12	170	640	478	654	LF	$1.26M	$0.141	$32,064	$847,200	100	11,670	2,017	126,337	1
12	170	640	478	654	CC	$1.26M	$0.141	$32,064	$847,200	100	11,670	2,017	126,337	1
12	170	640	479	654	LF	$1.26M	$0.141	$32,064	$847,700	100	11,671	2,017	126,347	1
12	170	640	479	654	CC	$1.26M	$0.141	$32,064	$847,700	100	11,671	2,017	126,347	1

Figure III. 10: solution found by HOMER

III.7.1 Energy production from each source

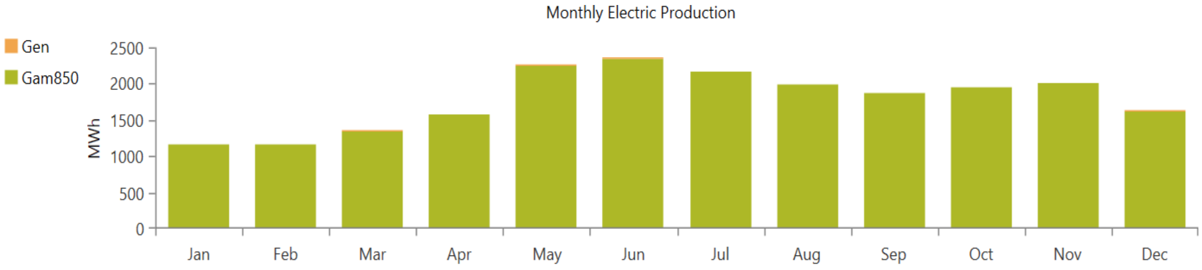


Figure III. 11: Energy part of each source in Ouargla

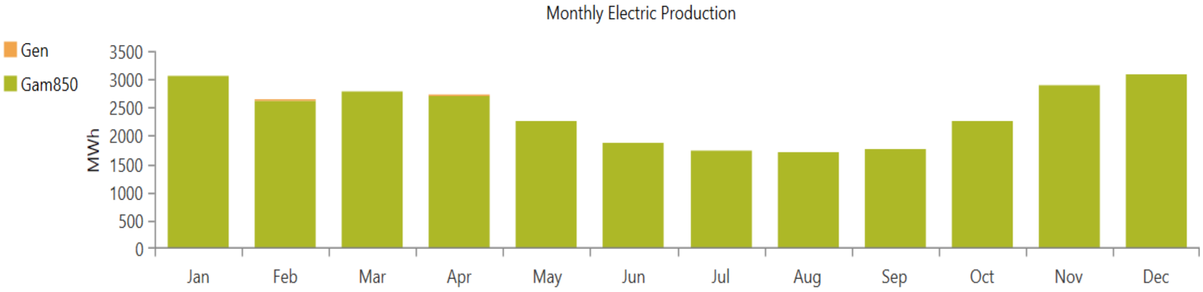


Figure III. 12: Energy part of each source in Tindouf

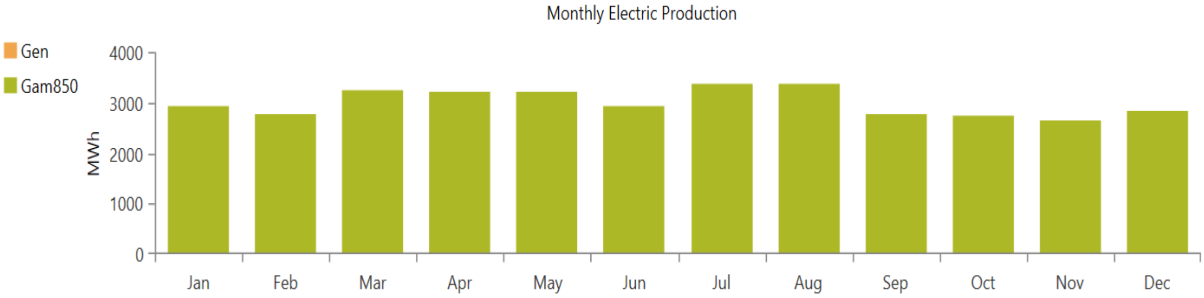


Figure III. 13: Energy part of each source in Tiaret

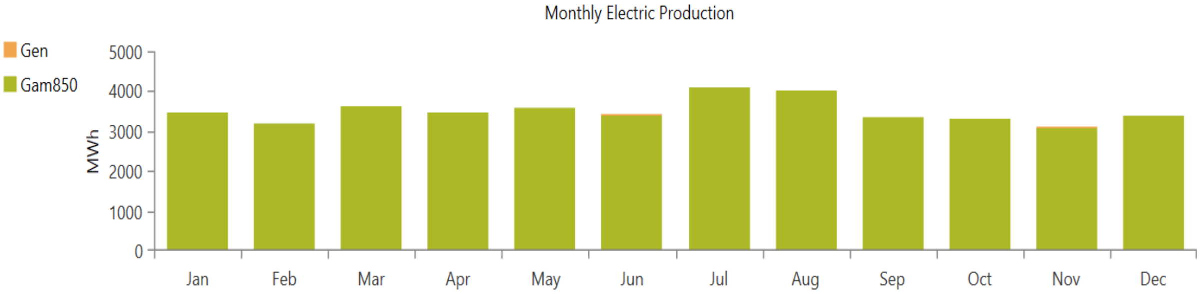


Figure III. 14: Energy part of each source in Adrar

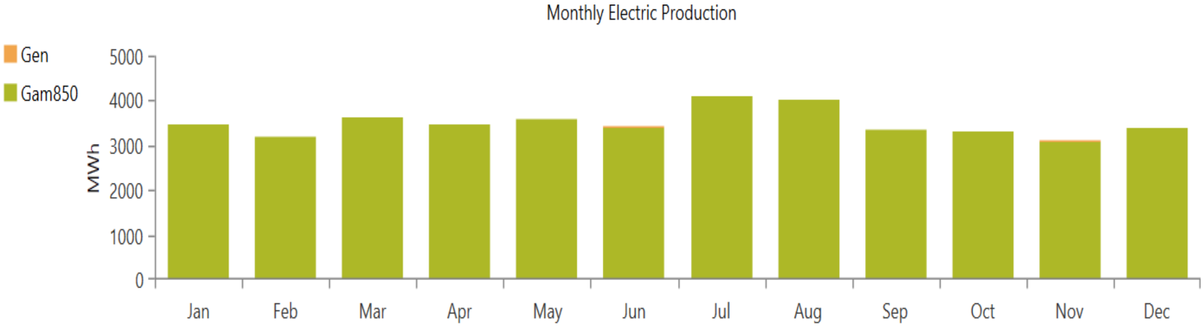


Figure III. 15: Energy part of each source in In Salah

It can be observed that the wind turbine has the highest share in production, as it is the main energy producer. And the highest percentage was recorded in In Salah and Adrar by 99.8% of the total production

It is expected that the fuel cell will produce a minimum amount of energy accounting for especially during seasons when wind speeds are high.

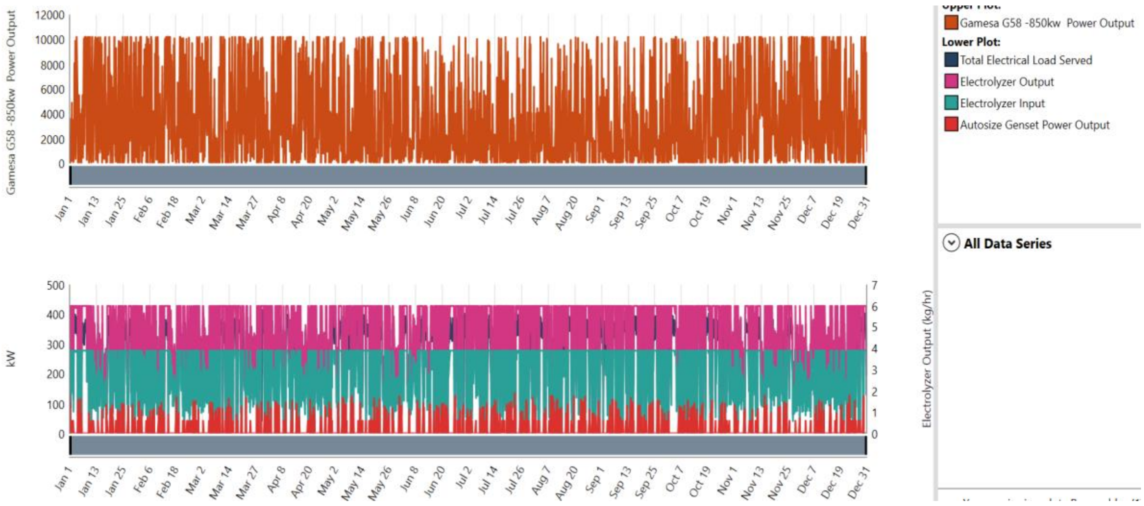
These ratios vary from region to region in the country, with Adrar and Ain Saleh regions having the highest energy production rates due to their favorable wind speeds. We can see detail in the table (III. 6).

Table III. 6: the energy production in the study region

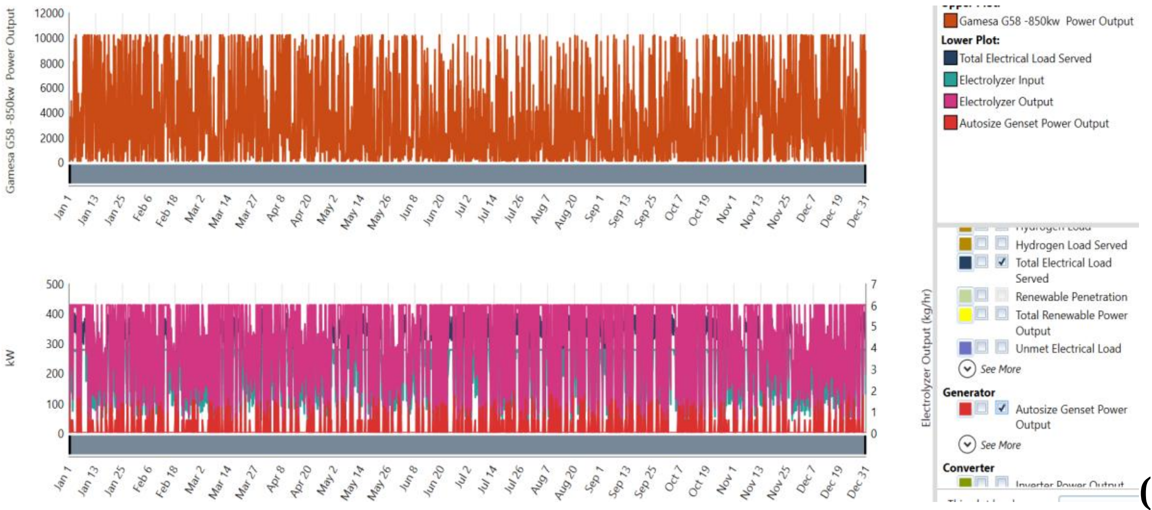
The region	Energy Production (KW/yr)			
	Wind turbine output		**Fuel Cell output**	
	value	**percentage**	**value**	**percentage**
Ouargla	28,713,465	99.7 %	89,568	0.311%
Adrar	36,022,829	99.8%	75,945	0.210%
Tindouf	35,405,469	99.8%	78,591	0.221%
Tiaret	28,713,465	99.7%	89,568	0.311%
In Salah	41,891,072	99.8%	64,209	0.153%

III.7.2 Operation the components of the seasonal production hydrogen system

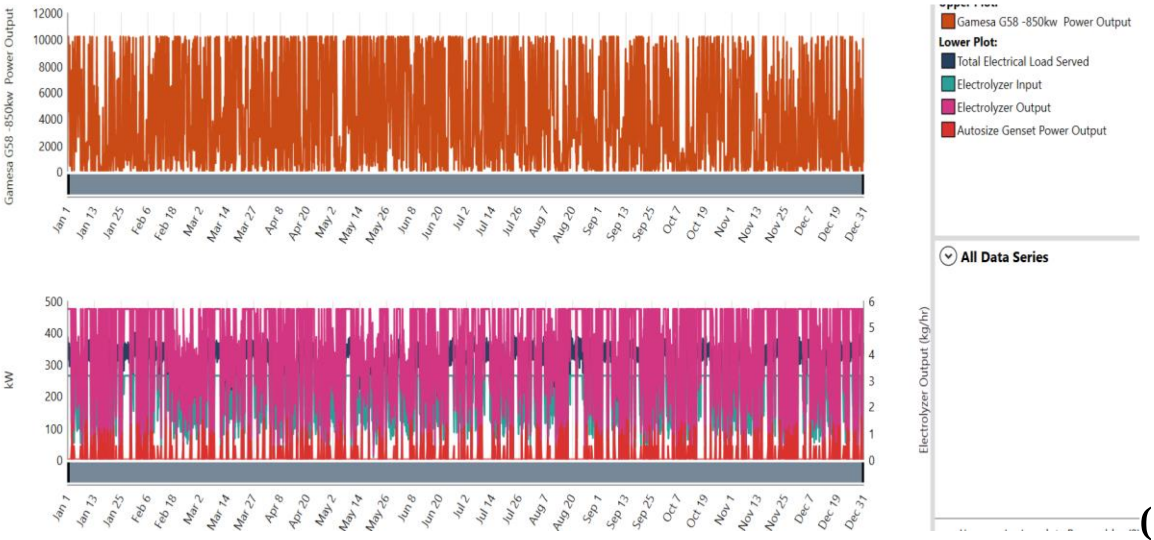
- **In the year**



(A)



(B)



(C)

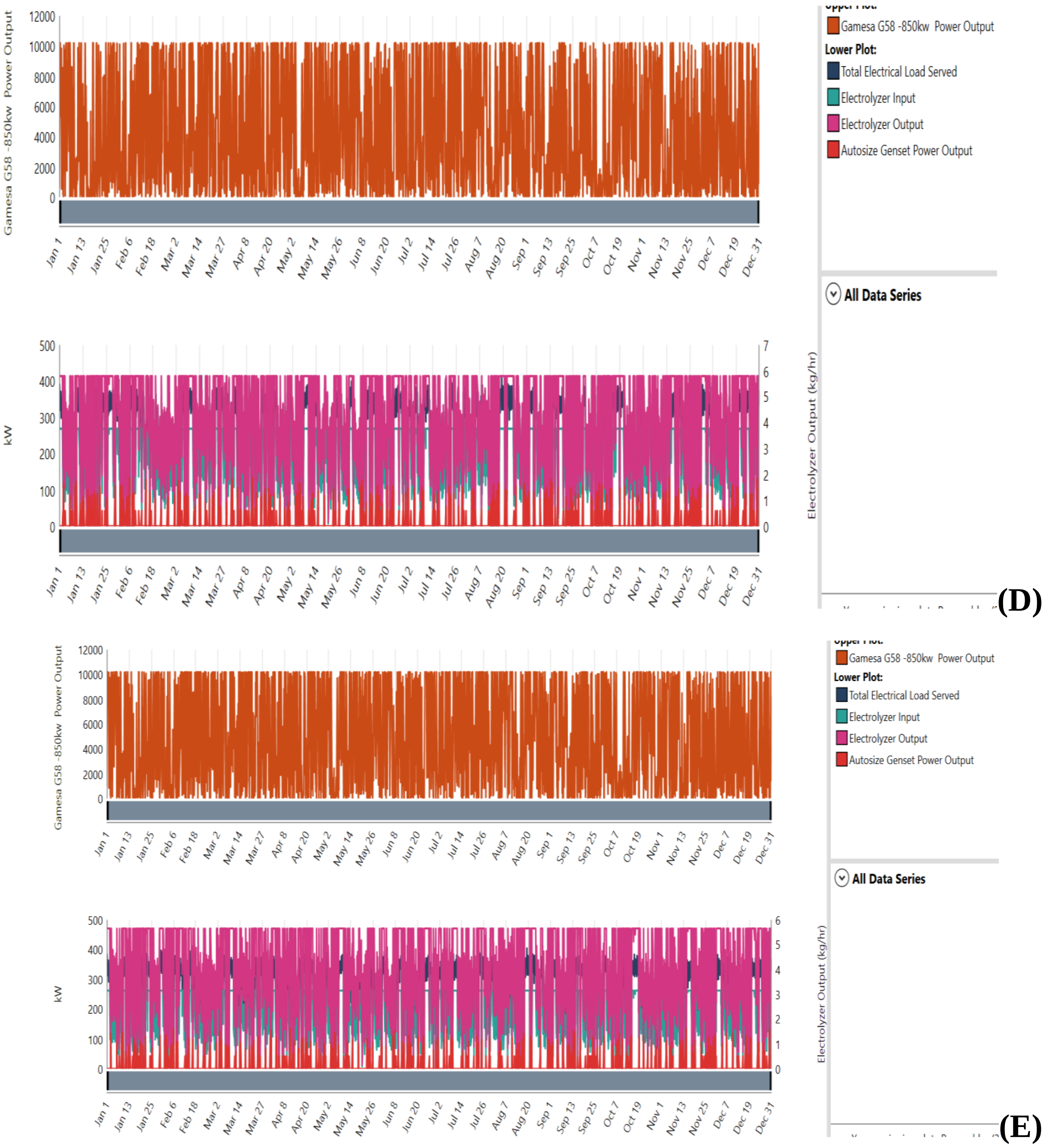


Figure III. 16: operation of the components of the system for different regions in the year (A) Ouargla, (B) Tiaret, (C) Tindouf, (D) Adrar, (E) In Salah

The curves in figure (III. 16) illustrate the relationship between wind turbine power generation and hydrogen production rate, along with load value, fuel cell production capacity. Fluctuations can be observed in the wind turbine power generation curve. Wind turbine power generation is variable and depends on wind speed. When wind speeds are high, wind turbines generate more power. When wind speeds are low, wind turbines generate less power, and this varies from one region to another. The highest recorded value was around 10,200 kW.

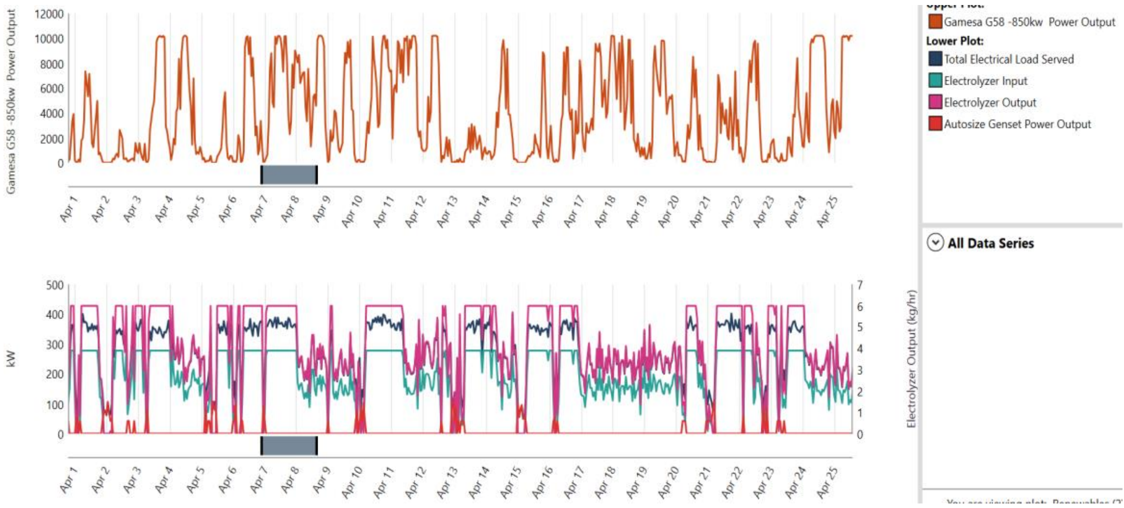
This is accompanied by a change in hydrogen production, as its production also varies like wind power, depending on the amount of energy generated by wind turbines. Electrolyzers use electricity to split water into hydrogen and oxygen. When there is more power generation from wind turbines, more electricity becomes available to electrolyzers, which can produce more hydrogen.

In terms of fuel cell operation, hydrogen is used to generate electricity. The amount of electricity that fuel cells can generate depends on the amount of hydrogen available. When more hydrogen is available, fuel cells can generate more electricity.

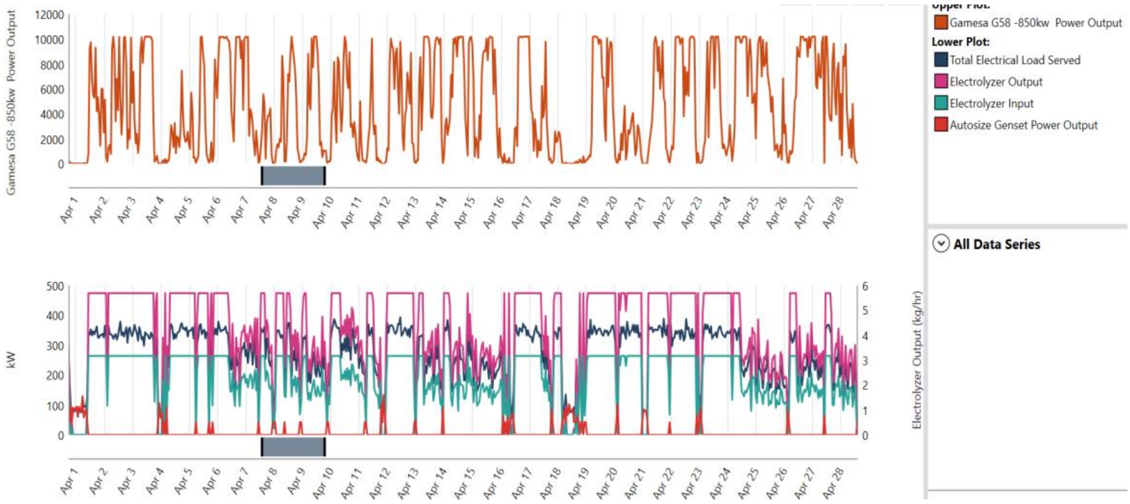
We note during spring and autumn hydrogen production was higher in different regions, with hydrogen values close to each other, reaching a maximum value of 6 kg/hour. The controlling factor hydrogen production through the curves is the wind value. If it increases, the hydrogen production rate also increases, as in Adrar and Ain Saleh.

Load value also plays a role in determining the amount of hydrogen produced and the amount of electricity generated by fuel cells.

- **In the month**



(A)



(B)

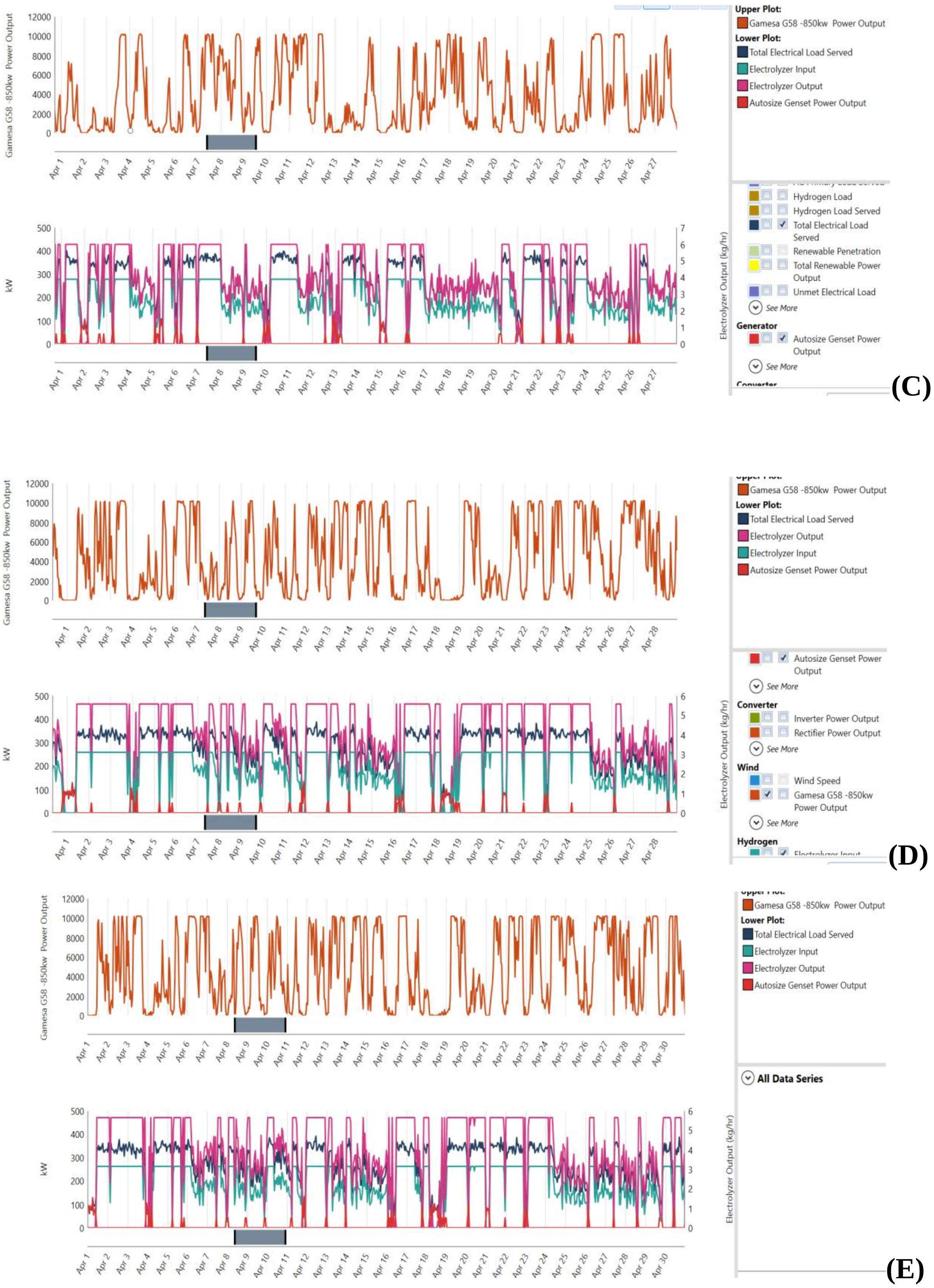
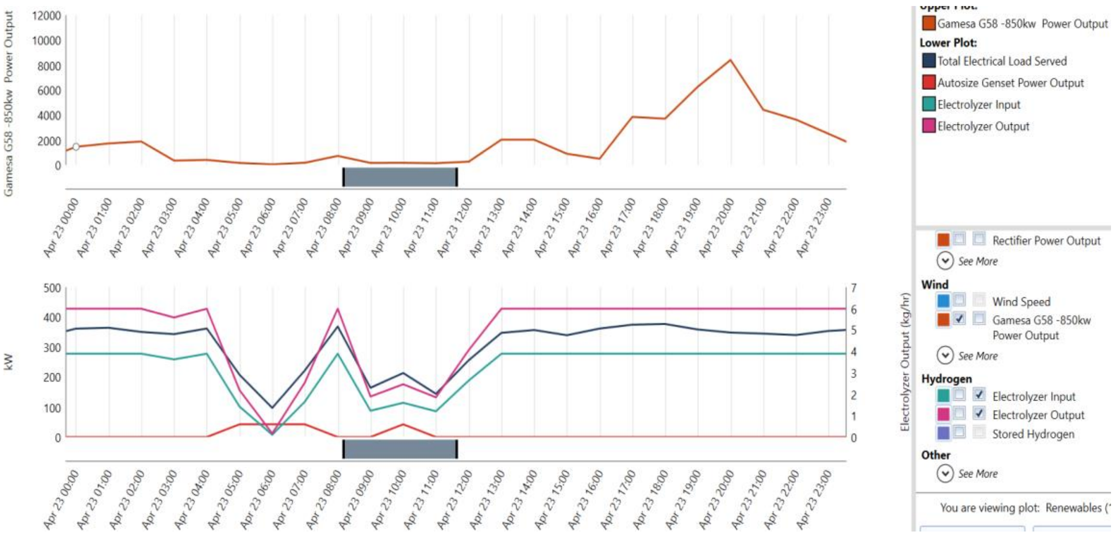


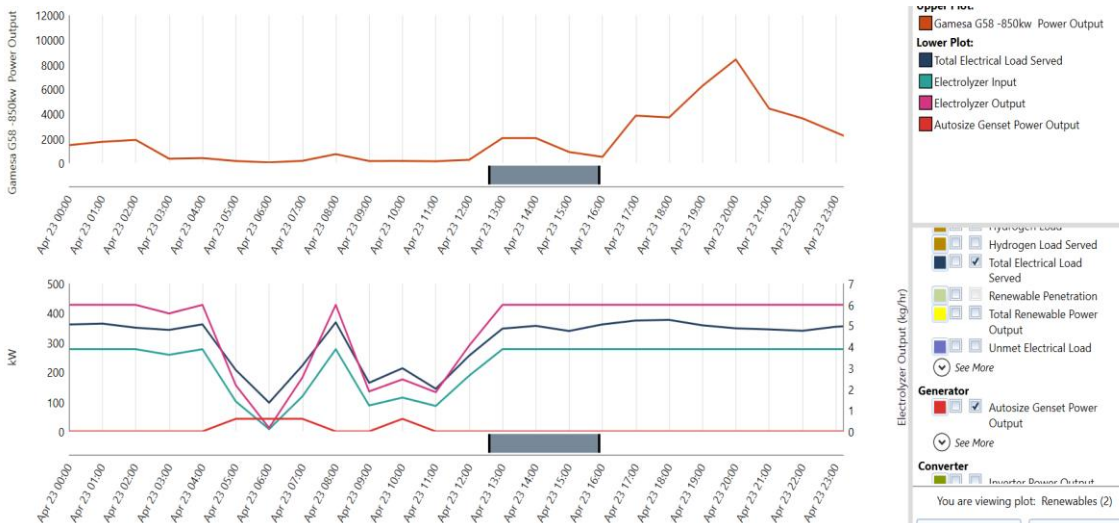
Figure III. 17: operation of the components of the system for different regions in the month
(A)Ouargla, (B)Tiaret, (C)Tindouf, (D)Adrar, (E) In Salah

In the figure (III. 17) We observe fluctuations in wind power production, accompanied by fluctuations in hydrogen production. Since a large portion of the energy produced often exceeds the load, a significant part of it goes to the electrolyzer for hydrogen production, as seen on days 11 and 12 in Ouargla.

- **In the day**



(A)



(B)

(C)

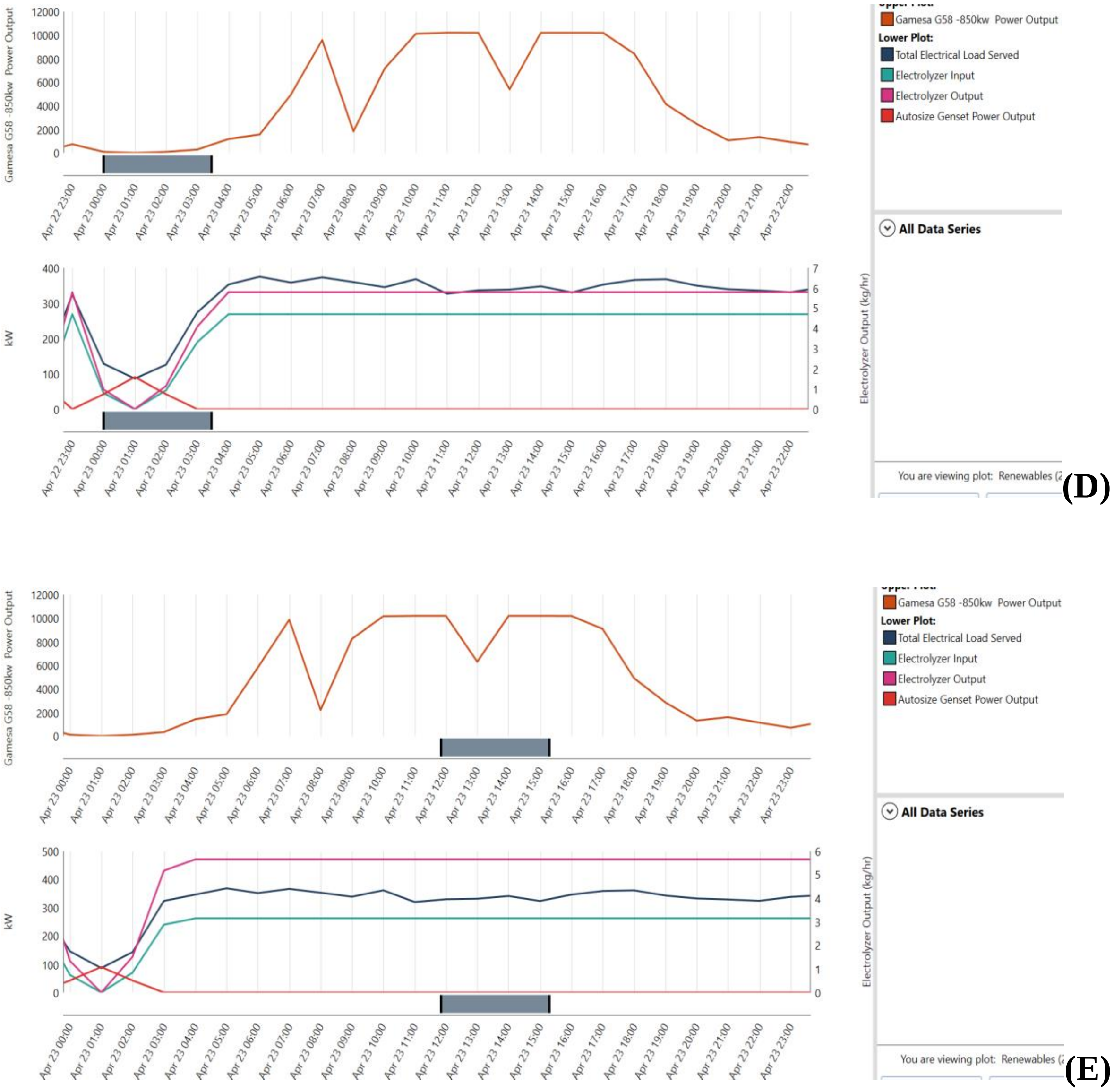


Figure III. 18: operation of the components of the system for different regions in the day
(A)Ouargla, (B)Tiaret, (C)Tindouf, (D)Adrar, (E) In Salah

In the figure (III. 18) The current system efficiently meets load requirements; however, we notice that a decrease in hydrogen consumption corresponds to a decrease in power production from the fuel cell, and vice versa. This variation is compensated when wind speeds are high, resulting in high energy production from the wind turbines. Conversely, when wind speeds are low and the wind turbines are out of service, the hydrogen-based system takes over to meet the electricity demand in an integrated manner, utilizing available resources according to changes in wind speeds.

Hydrogen production rates vary across regions depending on wind resource availability. The highest production values are observed in regions with the highest wind potential, such as Adrar and Ain Saleh. In these areas, hydrogen production chains are more integrated and efficient, relying more heavily on wind energy compared to other regions.

The combination of wind turbines and hydrogen fuel cells, powered by hydrogen produced from the electrolyzer, ensures more stable production. This enables fuel cells to operate even in the absence of wind.

The primary storage system, consisting of an electrolyzer, hydrogen tank, and fuel cell, provides long-term energy storage in the form of hydrogen gas.

The system is also versatile and multi-purpose.

Despite its advantages, the system also has drawbacks, including high cost, complex control requirements, and the need for a secondary storage system such as batteries. This is because during periods of low wind energy production, there is no source to power the electrolyzer, leading to a disruption in the primary storage system's hydrogen supply and a lack of power to meet demand. Therefore, a secondary storage system is essential for this system.

And from him, the hybrid wind-hydrogen system offers several advantages, including stable energy production, long-term energy storage, and versatility. However, its high cost, complex control requirements, and the need for a secondary storage system pose significant challenges that need to be addressed for widespread adoption.

III.8 Cost optimization

In price optimization, HOMER simulates each system design and shows the net cost regularization probabilities. This is illustrated in the equation:

$$C_s = C_{WT} + C_{elect} + C_{H2T} + C_C$$

C_s: cost of the system (the total price of its elements)

C_{WT}: the cost of the wind turbine system

C_{elect}: he cost of the PEM electrolyzer

C_{H2T}: the cost of the H2 tank

C_C: the converter cost

The following formula gives the cost of every part:

$$C_i = N_i \left[C_{Cap,i} + (C_{Rep,i} * N_{ri}) + C_{OM,H}\right]$$

N_i: is the number of the element of the HES

$C_{Cap,i}$: is the capital cost of each component

$C_{Rep,i}$: is the replacement cost of each component

N_{ri}: number of replacements suffered

$C_{OM,H}$: the operation and maintenance price of each component

The figure (III. 19) summarizes the related costs of each system component

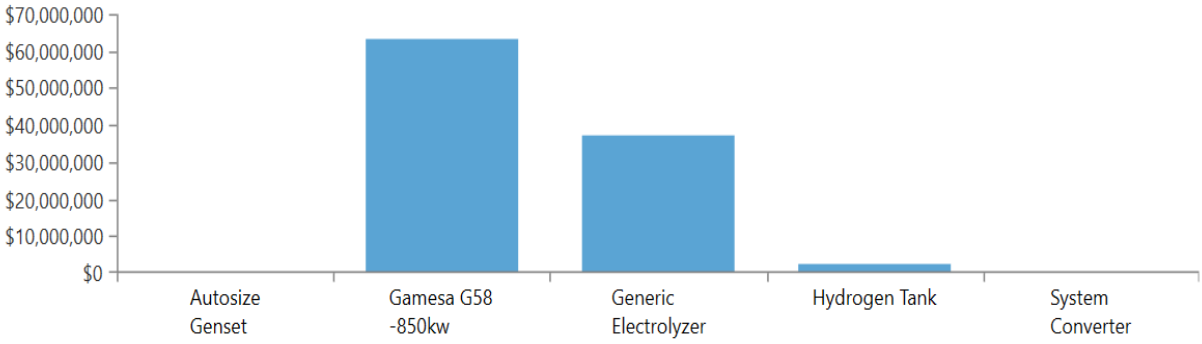


Figure III. 19: Net Current Cost by Cost Type for Scenario

III.9 Conclusion

This chapter presents the optimal design of a standalone wind energy system with a hydrogen production source. This configuration powers a hydrogen fueling station and consumption energy. HOMER Pro was used to optimize system behavior. Was studied The Adrar wind energy production center, which has a set of 850 kW wind turbines, and applied in several Algerian states with high wind speeds.

The program compared the results to determine the optimal system size. The results showed the best values that can be used in each system and varied according to the selected region. It can be noted that the energy price from this system is very high, but it is expected to decrease significantly in the future. Finally, this system is considered effective in terms of production, independence, and energy stability due to the use of renewable energy and green hydrogen

General conclusion

The aim of this study is to evaluate the hydrogen production rate of an off-grid wind-hydrogen hybrid system. Wind and hydrogen have great advantages as energy sources for such systems. However, off-grid wind systems have their own limitations and production fluctuations. Integrating these systems with hydrogen systems provides a promising solution to enhance system efficiency and reliability.

In this study, several locations in the south and north of the country with high wind speeds were identified. The Adrar Wind Energy Center model was applied to these sites, and the results were analyzed and compared to determine the best sites for hydrogen production when combined with wind energy.

HOMER Pro software was used to simulate the system and obtain the following conclusions:

* The system can meet power requirements reliably by operating synchronously. When wind speeds are low or non-existent, the secondary hydrogen production system generates power to cover the load deficit. Conversely, when wind speeds are high, the wind turbines meet the load, and any excess hydrogen production is stored and used elsewhere. This enhances the reliability of the system by ensuring continuous hydrogen production.

*The amount of hydrogen produced per kilowatt of wind energy depends on several factors, including system configuration, component efficiency, and operating conditions.

* Batteries or other secondary storage systems are still necessary for off-grid systems with intermittent power sources.

* Hydrogen production from renewable energy sources provides a solution for long-term energy storage. Hydrogen can be transported and used in various applications and has excellent environmental properties and efficiency.

Finally, the integration of wind and hydrogen systems represents a promising approach to off-grid power generation while enhancing efficiency, reliability, and long-term energy storage capabilities. More research is needed to improve system design and operation for specific sites and applications.

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Summary

We propose creating a small, independent grid that combines different renewable energy sources (wind turbines/full cell). To ensure efficient energy production, we aim to improve system components and control, and carefully size them through a meticulous selection process. This studies evaluates the performance of this system, aiming to minimize total net cost, energy continuity, and unmet loads. The HOMER Pro simulation software was used to perform this analysis. In general, the proposed system shows positive results in electrifying remote areas, ultimately leading to the creation of sustainable areas.

Keywords: Wind energy, green hydrogen, electrolyzer, system sizing, Homer Pro, fuel cell

الملخص

يهدف هذا العمل إلى إجراء دراسة حجمية لنظام توربينات الرياح بهدف تشغيل محلل كهربائي لإنتاج الهيدروجين الأخضر .وأحمال التغذية، في المناطق النائية ذات سرعات الرياح الكبيرة في الجزائر.

نقترح إنشاء شبكة صغيرة مستقلة تجمع بين مصادر الطاقة المتجددة المختلفة (توربينات الرياح/الخلية الكاملة). لضمان إنتاج الطاقة بكفاءة، نهدف إلى تحسين مكونات النظام والتحكم فيه، وحجمها بعناية من خلال عملية اختيار دقيقة. تقوم هذه الدراسات بتقييم أداء هذا النظام، بهدف تقليل إجمالي صافي التكلفة، واستمرارية الطاقة، والأحمال غير الملباة. تم استخدام برنامج هومر لمحاكاة و لتنفيذ هذا التحليل. بشكل عام ، يُظهر النظام المقترح نتائج إيجابية من حيث كهربة المناطق النائية، مما يؤدي في النهاية إلى إنشاء مناطق مستدامة

الكلمات المفتاحية: طاقة الرياح، الهيدروجين الأخضر، المحلل الكهربائي، تحجيم النظام، هومر برو، خلية الوقود

Résumé

Nous proposons de créer un micro-réseau autonome combinant différentes sources d'énergie renouvelable (éoliennes/panneaux photovoltaïques). Pour assurer une production d'énergie efficace, nous visons à optimiser les composants du système et leur contrôle, et à les dimensionner soigneusement par un processus de sélection rigoureux. Cette étude évalue les performances de ce système, avec pour objectif de réduire le coût net total, d'assurer la continuité de l'énergie et de minimiser les charges non satisfaites. Le logiciel de simulation HOMER Pro a été utilisé pour réaliser cette analyse. Globalement, le système proposé montre des résultats positifs en matière d'électrification des régions reculées, conduisant finalement à la création de zones durables.

Mots-clés : L'énergie éolienne, hydrogène vert, électrolyseur, dimensionnement du système, Homer Pro, pile à combustible