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**The influence of the electrolyte on the efficiency of
hydrogen production by water electrolysis**

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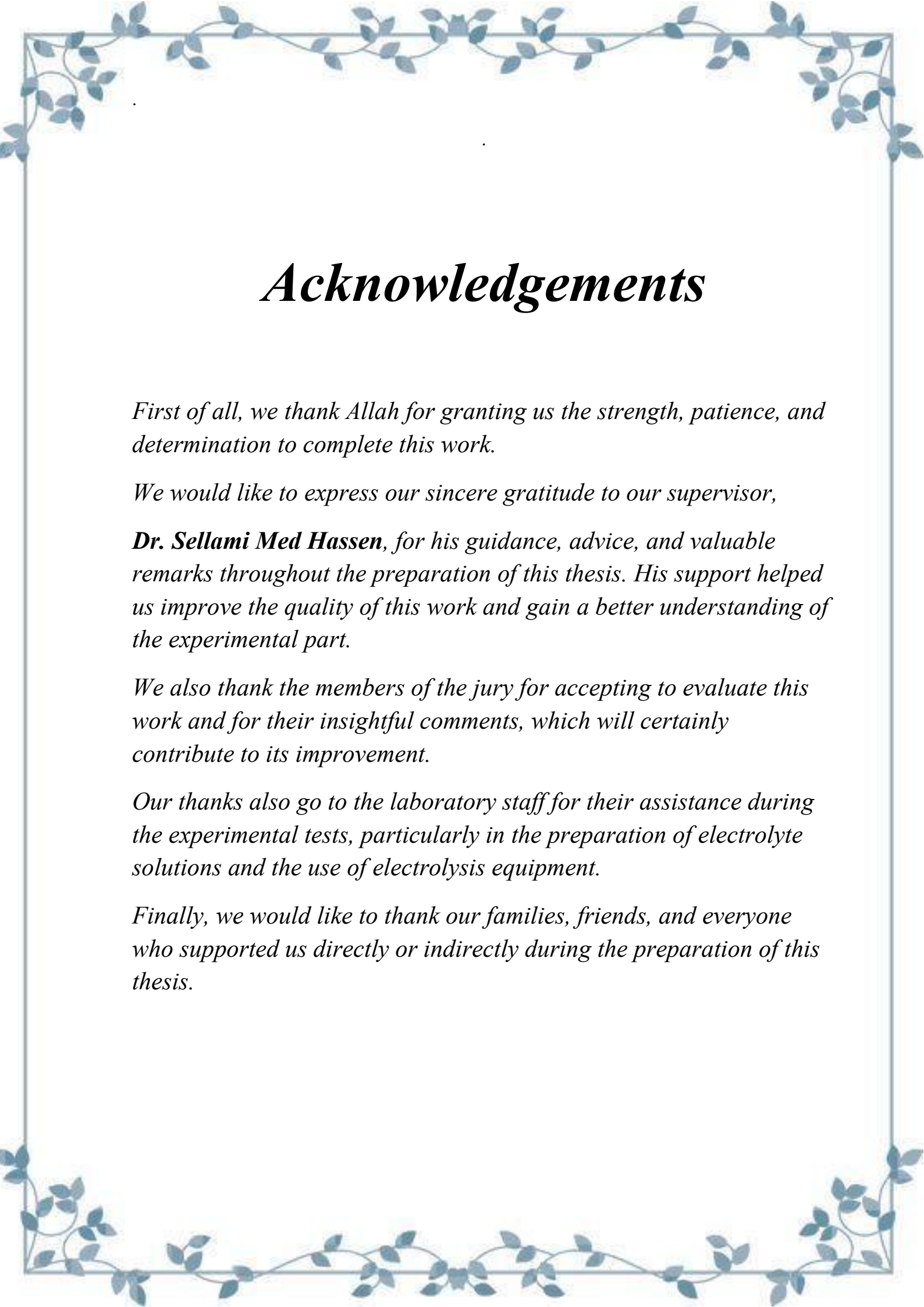
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First of all, we thank Allah for granting us the strength, patience, and determination to complete this work.

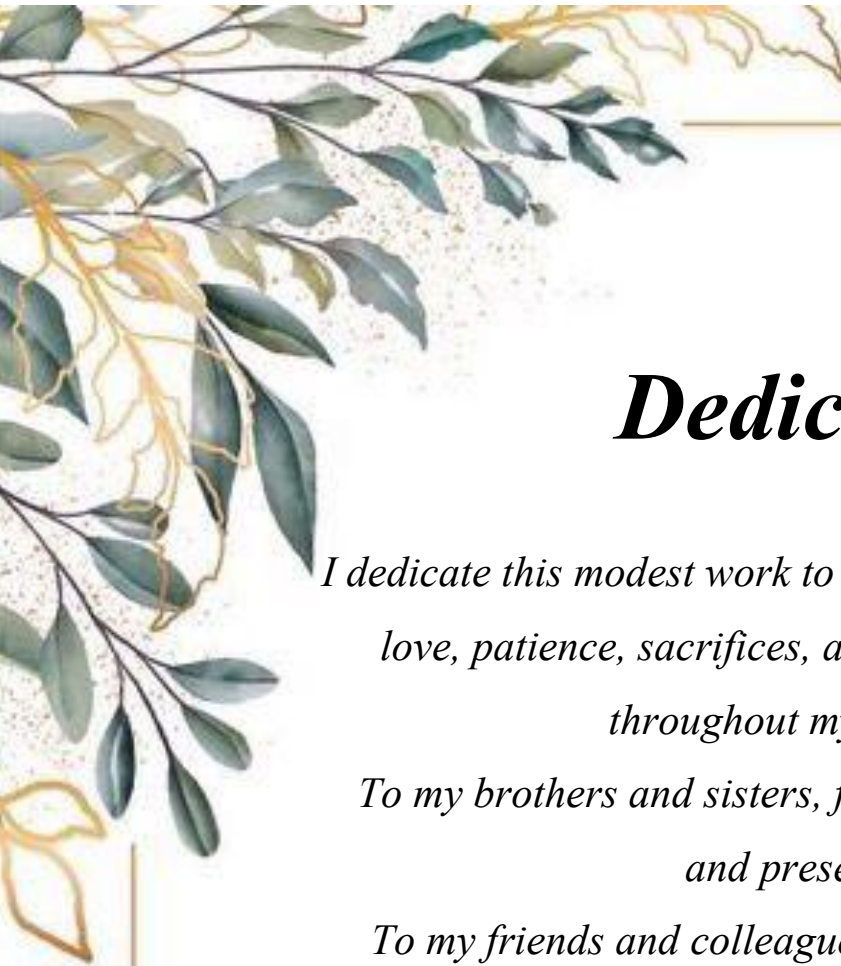
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Dedication

*I dedicate this modest work to my dear parents, for their
love, patience, sacrifices, and continuous support
throughout my studies.*

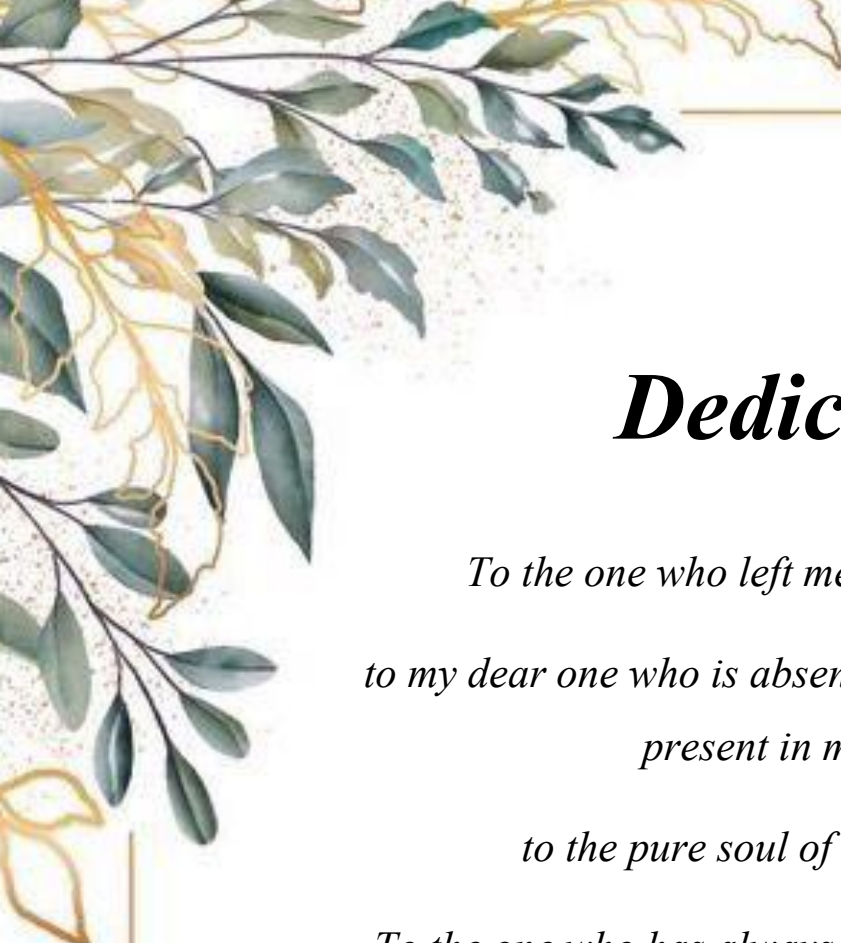
*To my brothers and sisters, for their encouragement
and presence.*

*To my friends and colleagues, who shared with me
many moments of work, stress, and motivation durin g
this academic journey.*

*And to everyone who helped me, even with a simple
word, to complete this work.*

Namarek





Dedication

*To the one who left me but never left me,
to my dear one who is absent in presence but always
present in my heart,*

to the pure soul of my dear father.

*To the one who has always been my first supporter,
to the pillar that never bends, my dear mother.*

*To those who strengthen my support, my brothers and
sisters.*

To all those who are dear to my heart.

I dedicate this humble work.

Djihad



Abstract:

Hydrogen is considered a clean energy source due to its ability to produce energy without harmful emissions to the environment, and it represents one of the main alternatives to fossil fuels. Among its production methods is water electrolysis, which relies on the use of an electrolyte that enables electrical current conduction within the solution.

This work aims to investigate the effect of electrolyte type and concentration on hydrogen production yield during the electrolysis process.

The experiments were carried out using an electrolysis setup assembled in the laboratory, consisting of an electrolytic cell connected to a direct current power supply. An electrolyte solution is first prepared and then introduced into the device. The experiment is then run for a given period, after which the volume of hydrogen produced is collected and measured. The experiments are repeated by varying the electrolyte type as well as the concentration of the optimal electrolyte.

The results show that the type of electrolyte has a direct influence on hydrogen production yield, which varies depending on the nature of the electrolyte used. It was also found that increasing electrolyte concentration improves the electrolysis process and thus increases hydrogen production yield. Therefore, the selection of the appropriate electrolyte and its concentration is a key factor for achieving optimal hydrogen production efficiency.

Keywords: Hydrogen, water electrolysis, electrolyte, potassium hydroxide, hydrogen production efficiency, electrochemical process.

المخلص:

يُعتبر الهيدروجين مصدرًا للطاقة النظيفة نظرًا لقدرته على إنتاج الطاقة دون انبعاثات ضارة بالبيئة، ويُعد من أبرز البدائل للوقود الأحفوري. ومن بين طرق إنتاجه التحليل الكهربائي للماء الذي يعتمد على استعمال الإلكتروليت الذي يساعد على نقل التيار الكهربائي داخل المحلول. يهدف هذا العمل إلى دراسة تأثير نوع الإلكتروليت وتركيزه على مردودية إنتاج الهيدروجين أثناء عملية التحليل الكهربائي.

تم إجراء التجارب باستعمال جهاز التحليل الكهربائي المركب داخل المخبر، والذي يتكون من جهاز تحليل كهربائي متصل بمزود طاقة مستمر، حيث يتم تحضير محلول إلكتروليتي ثم وضعه داخل الجهاز. يتم تشغيل الجهاز وترك العملية تتم لمدة معينة، بعدها يتم جمع وقياس حجم غاز الهيدروجين الناتج، وتعاد التجارب مع تغيير نوع الإلكتروليت وتغيير تركيز الإلكتروليت الأفضل.

أظهرت النتائج المتحصل عليها أن نوع الإلكتروليت يؤثر بشكل مباشر على مردود إنتاج الهيدروجين، حيث تختلف المردودية حسب طبيعة الإلكتروليت المستعمل. كما بينت النتائج أن زيادة تركيز الإلكتروليت تؤدي إلى تحسين عملية التحليل الكهربائي وبالتالي زيادة مردودية إنتاج الهيدروجين. ويُعد اختيار الإلكتروليت والتركيز المناسبين عاملاً أساسياً للحصول على أفضل مردودية في إنتاج الهيدروجين.

كلمات مفتاحية: الهيدروجين، التحليل الكهربائي للماء، الإلكتروليت، هيدروكسيد البوتاسيوم، مردودية إنتاج الهيدروجين، العملية الكهروكيميائية.

Résumé:

L'hydrogène est considéré comme une source d'énergie propre en raison de sa capacité à produire de l'énergie sans émissions polluantes pour l'environnement, et il constitue l'une des principales alternatives aux combustibles fossiles. Parmi ses méthodes de production, on trouve l'électrolyse de l'eau, qui repose sur l'utilisation d'un électrolyte permettant la conduction du courant électrique dans la solution.

Ce travail vise à étudier l'effet du type d'électrolyte et de sa concentration sur le rendement de production de l'hydrogène au cours du processus d'électrolyse.

Les expériences ont été réalisées à l'aide d'un dispositif d'électrolyse monté au

laboratoire, composé d'une cellule d'électrolyse reliée à une alimentation en courant continu. Une solution électrolytique est d'abord préparée puis introduite dans le dispositif. L'expérience est ensuite lancée pendant une durée déterminée, après quoi le volume d'hydrogène produit est collecté et mesuré. Les expériences sont répétées en variant le type d'électrolyte ainsi que la concentration de l'électrolyte optimal.

Les résultats obtenus montrent que le type d'électrolyte influence directement le rendement de production de l'hydrogène, ce dernier variant selon la nature de l'électrolyte utilisé. Il a également été démontré que l'augmentation de la concentration de l'électrolyte améliore le processus d'électrolyse et augmente ainsi le rendement de production de l'hydrogène. Le choix de l'électrolyte ainsi que de sa concentration constitue un facteur essentiel pour obtenir un rendement optimal de production d'hydrogène.

Mots-clés : Hydrogène, électrolyse de l'eau, électrolyte, hydroxyde de potassium, rendement de production d'hydrogène, procédé électrochimique.

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List of Abbreviations

List of Abbreviations:

AWE: Alkaline Water Electrolysis

CCS: Carbon Capture and Storage

CHP: Combined Heat and Power

DC: Direct Current

FCV: Fuel Cell Vehicle

HHV: Higher Heating Value

KOH: Potassium Hydroxide

LH₂: Liquid Hydrogen

LHV: Lower Heating Value

LOHC: Liquid Organic Hydrogen Carrier

NaOH: Sodium Hydroxide

PEM: Proton Exchange Membrane

PV: Photovoltaic

SMR: Steam Methane Reforming

SOEL: Solid Oxide Electrolysis

STP: Standard Temperature and Pressure

General Introduction

General Introduction

. Energy is an essential element in human life and a key factor in achieving economic and social development. For many decades, the world has relied on fossil energy sources such as oil, natural gas, and coal, which have significantly contributed to the growth of industry and transportation. However, the increasing dependence on these sources has led to several problems, most notably the depletion of natural reserves and the rise in environmental pollution caused by greenhouse gas emissions. In addition, these resources are non-renewable, raising concerns about their ability to meet future energy demands.

To address these challenges, many countries have turned to the development and utilization of renewable energy sources such as solar energy, wind energy, hydropower, and biomass energy. These sources are considered clean and sustainable alternatives that contribute to environmental protection and energy security. Therefore, investment in renewable energy has become a strategic choice for achieving sustainable development and ensuring a more stable energy future [1].

Hydrogen is considered one of the most important energy carriers and has attracted increasing attention in recent years due to its potential applications in a wide range of industrial and energy-related sectors. It is currently used in the chemical industry and petroleum refining processes, and it is also gaining prominence in the transportation sector as a promising energy carrier. Since hydrogen does not exist naturally in its free form, it must be produced from various sources, the most important of which are fossil fuels, such as natural gas and coal, as well as renewable energy sources. Among the different hydrogen production methods, water electrolysis is regarded as a key technology for producing high-purity hydrogen.

Water electrolysis is an electrochemical process in which water molecules are decomposed into hydrogen and oxygen gases through the application of a direct electric current. Due to the low electrical conductivity of pure water, an electrolyte is added to enhance the transport of electric charge within the medium and facilitate the electrolysis process.[2]

Furthermore, both the type and concentration of the electrolyte have a significant influence on the water electrolysis process and, consequently, on the quantity of hydrogen produced.

The present work focuses on studying the influence of the electrolyte on the efficiency of hydrogen production by water electrolysis. The experimental study is divided into two main parts. The first part compares several electrolytes, including KOH, NaOH, CaO, NaCl, and citric acid, in order to determine which one gives the best hydrogen production yield.

General Introduction

The second part studies the effect of changing the concentration of the best electrolyte on the hydrogen production efficiency.

The main objective of this thesis is therefore to understand how the nature and concentration of the electrolyte affect hydrogen production during water electrolysis. This subject is important because improving electrolysis efficiency can help reduce energy losses and support the development of clean hydrogen production systems

This thesis is organized into three chapters. The first chapter presents the main energy sources, including fossil fuels and renewable energies, with a particular focus on the Algerian energy context. The second chapter deals with hydrogen, its properties, production methods, storage technologies, applications, and main challenges. The third chapter presents the experimental study, including the materials used, the experimental procedure, the obtained results, and their discussion.

Chapter I:

Energy Sources

Introduction:

Energy plays an essential role in modern society, since it supports industrial activity, transportation, electricity production, and daily human needs. For many decades, fossil fuels such as coal, oil, and natural gas have represented the dominant energy sources in the world. These resources contributed greatly to economic and technological development, but their intensive use has also caused major environmental problems, especially greenhouse gas emissions and air pollution.

In recent years, the need for cleaner and more sustainable energy systems has become more important. Renewable energies, such as solar, wind, geothermal, and biomass energy, are now considered practical alternatives that can reduce dependence on fossil fuels. In Algeria, this issue is particularly important because the country has significant fossil resources, but also a very high renewable energy potential, especially solar energy in the southern regions.

This chapter presents the main conventional and renewable energy sources. It first discusses fossil fuels, their formation, uses, and environmental impacts. Then, it introduces renewable energies and their potential role in supporting the energy transition, with a link to hydrogen production as a possible clean energy pathway.

I.1 Fossil Fuels (Coal, Oil, Gas)

Fossil fuels are one of the most important ways to get energy these days. Most of them are oil, coal, and natural gas. These are fuels that come from organic matter that has been around for millions of years and has changed because of heat and pressure in the Earth's crust [3].

Fossil fuels get their name from the fact that they come from the remains of living things that have turned into fossils, like plants, algae, and tiny marine organisms. Over time, this organic matter collected in sediments and then changed chemically and geologically. This made hydrocarbons that are high in carbon and hydrogen [1].

Fossil fuels have been very important for the growth of the economy and industry since the Industrial Revolution [4]. They still make most of the energy in the world today, especially for transportation, making electricity, and industry.

But you can't get these resources back, and using them has a big impact on the environment. For instance, they pollute the air and let out greenhouse gases [5].

I.1.1 Geological Formation of Fossil Fuels**I.1.1.1 Accumulation of Organic Matter**

In aquatic or swampy environments, living organisms such as plants, algae, and microorganisms die and accumulate at the bottom of sedimentary basins [1].

I.1.1.2 Burial and Sedimentation

Over time, these organic remains are covered by layers of sediment like clay, sand, and rocks. As the temperature and pressure rise, more and more chemical changes take place [6].

I.1.1.3 Transformation into Hydrocarbons

When you heat and press organic matter, it becomes hydrocarbons. The kinds of fossil fuels that are made depend on the kind of organic matter and the geological conditions.

- Coal
- Oil
- Natural gas [1]

Sedimentary basins are good places to collect organic matter, and these changes usually happen there.

I.1.2 Main Types of Fossil Fuels**I.1.2.1 Petroleum**

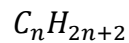
Crude oil is a natural liquid composed mainly of a complex mixture of hydrocarbons. It is formed from the decomposition of marine microorganisms and algae deposited at the bottom of oceans millions of years ago [7].

After extraction from the subsoil, crude oil is transported to refineries where it is separated into different fractions through fractional distillation [8].

Table I.1: Petroleum Derivatives and Their Uses [7]

Product	Use
Gasoline	Automotive fuel
Diesel	Road transport
Kerosene	Aviation
Fuel oil	Electricity generation
Naphtha	Petrochemical industry

The hydrocarbons present in oil can be represented by the general formula:



This formula corresponds to the alkane family, which constitutes a large portion of the hydrocarbons in fossil fuels [8].

I.1.2.2 Coal

Coal is a combustible sedimentary rock rich in carbon, formed from the fossilization of plants in ancient swampy environments [3].

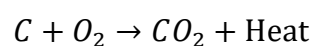
Coal formation occurs through a process called carbonization, which includes several stages:

1. Peat
2. Lignite
3. Bituminous coal
4. Anthracite (coal with the highest carbon content) [3]

Coal is mainly used in:

- Electricity production
- Steel industry
- Coke manufacturing [5]

The combustion of carbon in coal can be represented by the chemical equation:



This reaction releases a large amount of heat used in thermal power plants [4].

I.1.2.3 Natural Gas

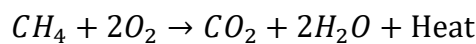
Natural gas is a gaseous fossil fuel mainly composed of methane (CH₄). It is often associated with oil fields and can also form independently in certain geological formations [7].

Methane has a high energy density and burns relatively cleaner than coal or oil [7].

Table I.2: Typical Composition of Natural Gas [7]

Component	Approximate Percentage
Methane (CH₄)	70–90 %
Ethane (C₂H₆)	5–15 %
Propane (C₃H₈)	1–5 %
Other gases	Traces

The combustion of methane is represented by the chemical equation:



This reaction produces a large amount of thermal energy with relatively lower CO₂ emissions than coal or oil [4].

I.1.3 Role of Fossil Fuels in the Energy System

Fossil fuels remain the primary energy source worldwide. They are used in:

- Electricity generation
- Transportation
- Chemical industry
- Domestic heating [5]

Estimates suggest that oil, coal, and natural gas account for more than 80% of global energy consumption [6].

Their high energy density and ease of transport and storage have enabled the industrial and technological development of many societies [5].

I.1.4 Environmental Impact of Fossil Fuels

I.1.4.1 Greenhouse Gas Emissions

Combustion of fossil fuels produces carbon dioxide (CO₂), the primary greenhouse gas responsible for global warming [4].

I.1.4.2 Air Pollution

Burning coal and oil also produces:

- Nitrogen oxides (NO_x)
- Sulfur dioxide (SO₂)
- Fine particulate matter [4]

These pollutants can negatively affect human health and the environment.

I.1.5 Fossil Fuels and Energy Transition

Rising greenhouse gas emissions and the gradual depletion of fossil resources have led many countries to consider a transition to cleaner energy sources [6].

In Algeria, isolated energy systems in desert regions still rely heavily on diesel generators and gas turbines for electricity production [6].

According to this study, the total installed capacity in isolated networks in southern Algeria reached approximately 528 MW, with about 60% from diesel generators and 39% from gas turbines [6].

This strong dependence on fossil fuels poses several challenges:

- High fuel cost
- Greenhouse gas emissions
- Vulnerability to energy market fluctuations [6]

Several energy transition projects propose combining solar energy with hydrogen production to reduce dependence on fossil fuels and improve the sustainability of the energy system [1].

I.1.6 Link with Hydrogen Production

Currently, much of industrial hydrogen is produced from fossil fuels via:

- Natural gas reforming
- Coal gasification [7]

However, these processes emit carbon dioxide.

To reduce emissions, water electrolysis powered by renewable energy is a promising alternative for producing clean hydrogen [1].

Fossil fuels—oil, coal, and natural gas—have played a decisive role in global industrial and economic development. Their high energy density and availability supported economic growth and the expansion of modern energy systems [5].

However, these resources are limited, and their exploitation causes significant environmental impacts. Transitioning to cleaner and sustainable energy sources, such as renewables and hydrogen, represents a major challenge for the future of global energy [1].

I.2 Renewable Energy (Solar, Wind, Geothermal, etc.)

Algeria has significant renewable energy potential due to its geographic location, abundant solar irradiation, wind availability, and groundwater reserves. Renewable energy is considered a strategic solution for sustainable development and energy transition in Algeria [9].

I.2.1 Definition and Types of Renewable Energy

I.2.1.1 Definition of Renewable Energy

Renewable energy refers to sources naturally replenished at a rate equal to or greater than their consumption. They include sunlight, wind, geothermal heat, water, tidal energy, and biomass. These sources generate little or no pollution and are essential for environmental sustainability [10].

I.2.1.2 Types of Renewable Energy

The main renewable energy sectors in Algeria are:

- **Solar Energy:** Conversion of sunlight into electricity using photovoltaic cells or solar thermal systems. Southern Algeria receives up to 3,500 hours of sunshine annually [11].

- **Wind Energy:** Kinetic energy captured from wind using turbines, mostly in coastal and highland areas [2].
- **Hydropower:** Small-scale hydroelectric plants utilize river flow for electricity in selected regions [12].
- **Geothermal Energy:** It is the energy put away in the rough layers that comes from the deterioration of radioactive components in the earth's crust and the heat latent in molten rocks due to the decay of uranium, potassium and other radioactive materials [1].
- **Biomass Energy:** refers to energy obtained from plant and animal materials, as well as organic waste, which is converted into usable forms such as gas for the effective utilization of organic residues. This conversion can be achieved through various processes, including pyrolysis, chemical treatment, or complete combustion. Biomass energy is utilized on a relatively limited scale, accounting for approximately 15% of global energy consumption [1].

Table I.3: Renewable Energy Types and Applications [11]

Type	Application
Solar	Electricity, water heating, industrial heat
Wind	Electricity generation
Hydropower	Small-scale electricity, irrigation
Geothermal	Heating, electricity
Biomass	Heat, electricity, biofuel

I.2.2 Renewable Energy Potential

I.2.2.1 Solar Potential

The Sahara region has one of the highest solar irradiations worldwide, making it ideal for large-scale photovoltaic and thermal plants. Average sunshine duration reaches 3,500 h/year in southern Algeria [11].

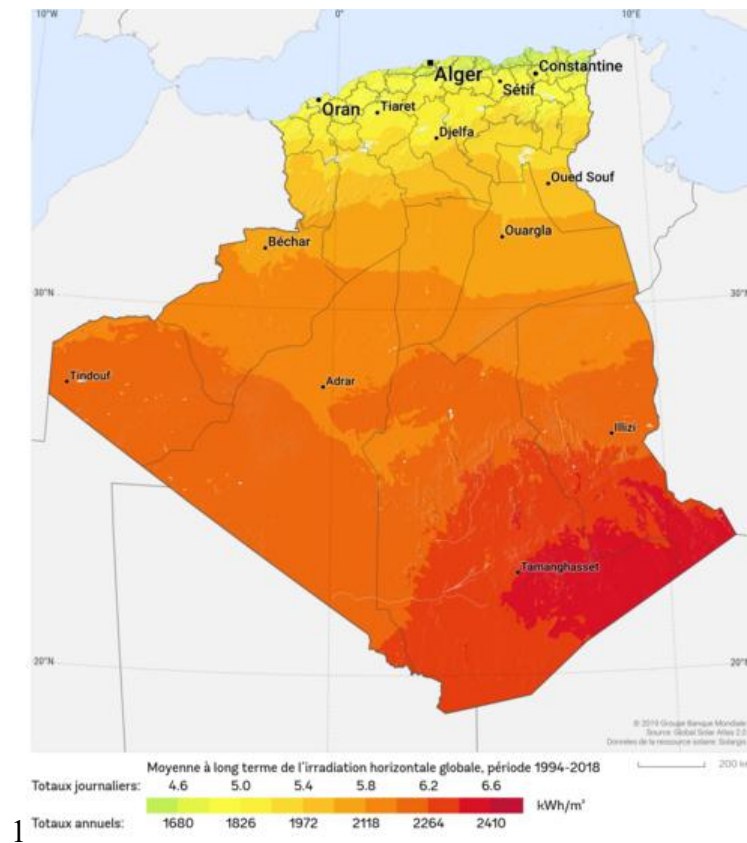


Figure I.1 : Annual Solar Irradiation Map of Algeria [11]

Table I.4: Solar Energy Potential by Region in Algeria [11]

Region	Sunshine Duration (h/year)	Energy Received (kWh/m ² /year)
Coastal	2,650	1,700
Highlands	3,000	1,900
South (Desert)	3,500	2,650

I.2.2.2 Wind Potential

Wind energy is region-specific, with the highest potential along the coast and highlands. Measurement stations identify optimal wind farm locations [2].

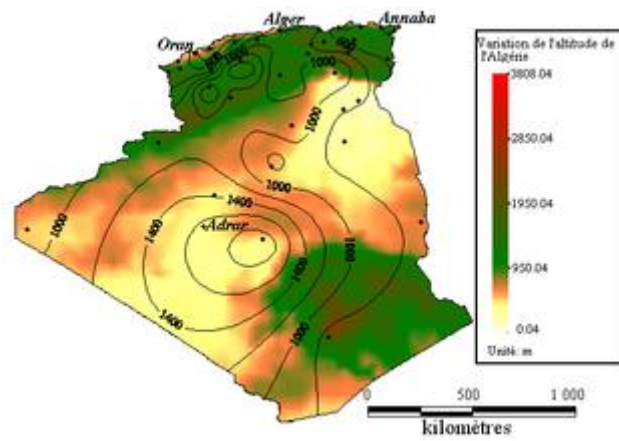


Figure I.2: Wind Potential Map of Algeria [2]

I.2.2.3 Other Renewable Potentials

- Groundwater can complement solar-hydrogen hybrid systems.
- Biomass and hydropower provide localized energy solutions for rural areas [13].

I.2.3 Advantages and Limitations

I.2.3.1 Advantages

- Sustainable and inexhaustible energy supply.
- Reduction of greenhouse gas emissions and pollution.
- Energy independence and rural electrification.
- Potential for economic growth and investment opportunities [9]

I.2.3.2 Limitations

- Intermittency of solar and wind energy, requiring storage or hybrid systems.
- High initial investment costs.
- Need for technical expertise in operation and maintenance [2]

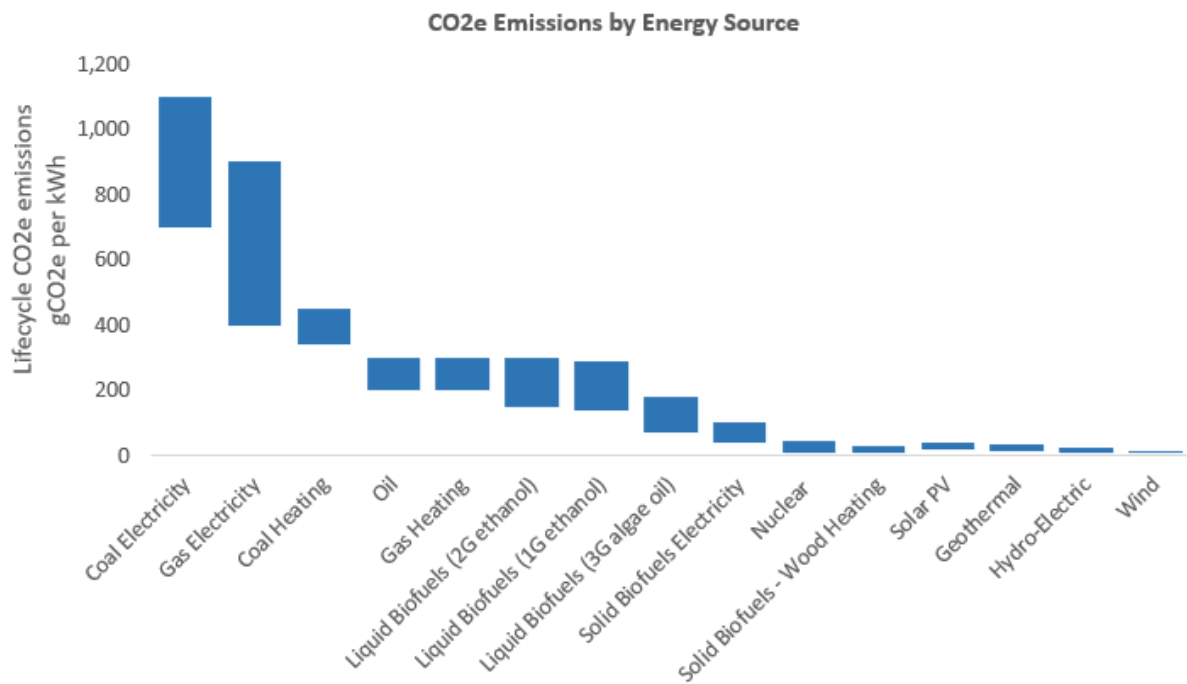


Figure I.3: Comparison of Renewable Energy vs. Fossil Fuel Emissions [10]

I.2.4 Renewable Energy Integration and Energy Transition

I.2.4.1 Current Status

- Isolated grids in southern Algeria rely mainly on diesel generators and gas turbines [9].
- Renewable penetration is growing, with pilot solar PV and hybrid systems implemented in southern regions [11].

I.2.4.2 Energy Transition Strategy

- Gradual replacement of fossil fuel dependency by hybrid systems (solar + hydrogen) [9].
- Incentives for renewable energy investments and public-private partnerships [12].
- Integration into both local isolated grids and the national network [2].

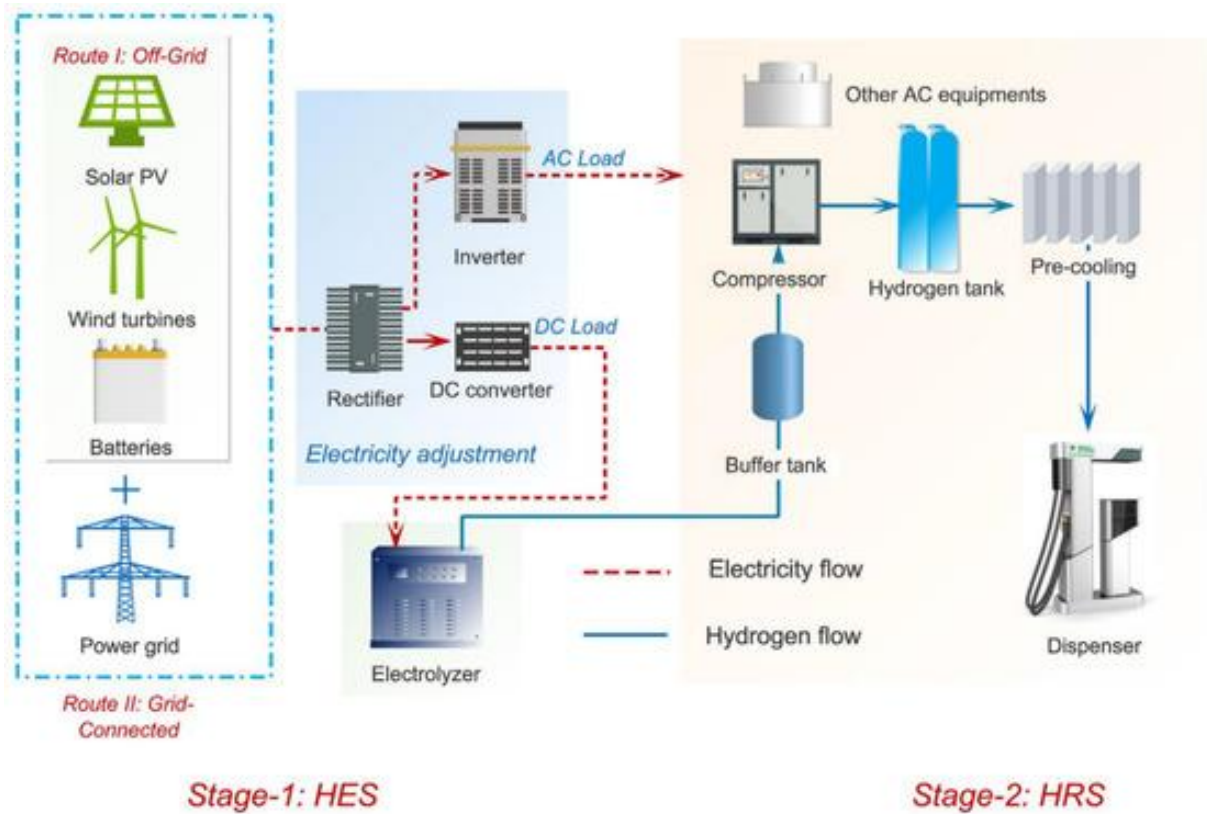


Figure I.4: Solar-Hydrogen Hybrid Energy System for Desert Grids [9]

I.2.5 Investment and Future Prospects

I.2.5.1 International Perspective

- Global investments in renewable infrastructure are increasing to reduce dependence on fossil fuels [14].
- Grid integration and storage solutions are essential for stable electricity supply [13].

I.2.5.2 National Perspective (Algeria)

- Algeria plans to expand solar PV capacity significantly in the next decade [11].
- Government policies encourage investment in renewable energy and energy transition projects [12].
- Hybrid solar-hydrogen plants are considered the most promising pathway for energy security and sustainable development [9].

Conclusion:

Chapter I has explored Algeria's main energy sources, highlighting the importance of fossil fuels and their environmental constraints, alongside the opportunities offered by renewable energy. Renewable sources, particularly solar and wind, provide a sustainable alternative to diversify the energy mix and support long-term development.

A balanced approach, combining existing fossil resources with renewable energy deployment, is essential to ensure energy security, environmental protection, and sustainable growth for Algeria.

Chapter II:

Hydrogen

Introduction:

Hydrogen is emerging as a central energy carrier for a sustainable and low-carbon future. Its combustion produces only water, with no greenhouse gas emissions, making it a clean alternative to conventional fossil fuels. Hydrogen can be produced through multiple methods, including water electrolysis, biomass conversion, and fossil fuel reforming, and it can be stored and transported for a wide range of applications such as electricity generation, industrial processes, and transportation.

In Algeria, the country's abundant renewable resources, especially solar and wind energy, create favorable conditions for producing green hydrogen. Utilizing these resources can reduce fossil fuel dependence, enhance energy security, and support sustainable development goals.

This chapter will explore the physical and chemical properties of hydrogen, production methods, storage technologies, and applications, as well as the challenges and prospects of integrating hydrogen into modern energy systems [15].

II.1 Physical and Chemical Properties of Hydrogen

Hydrogen is the simplest and lightest chemical element, consisting of a single proton and electron. In its molecular form (H_2), it is the most abundant element in the universe and plays a central role in energy systems, chemical processes, and industrial applications. Its unique physical and chemical characteristics make it an ideal candidate as a clean energy carrier, capable of storing and releasing large amounts of energy while producing zero greenhouse gas emissions during use.

Hydrogen's energy density per unit mass is significantly higher than conventional fuels. While its volumetric energy density is low at ambient conditions, this challenge can be addressed through compression, liquefaction, or storage in chemical compounds. Hydrogen's versatility allows its use in electricity generation, industrial reduction processes, fuel cells, and transportation, making it an integral component of future low-carbon energy systems. [16]

II.1.1 Physical Properties

Hydrogen is a colorless, odorless, tasteless, and non-toxic gas under standard conditions. It has the lowest density of all gases (0.08988 g/L at 0°C and 1 atm), which makes it extremely lightweight but also necessitates special storage and transport solutions. Hydrogen exists as a diatomic molecule (H_2) and is highly diffusive due to its small molecular size. Its melting point

is -259.14°C , and its boiling point is -252.87°C , meaning it is in gaseous form at room temperature but requires cryogenic cooling for liquid storage. [17]

Table II.1: Physical Properties of Hydrogen [16]

Property	Value	Unit
Molecular formula	H ₂	—
Molecular weight	2.016	g/mol
Boiling point	-252.87	$^{\circ}\text{C}$
Melting point	-259.14	$^{\circ}\text{C}$
Density (gas)	0.08988	g/L
Density (liquid)	70.85	kg/m ³
Solubility in water	1.6	mg/L
Lower heating value (LHV)	120	MJ/kg
Higher heating value (HHV)	142	MJ/kg

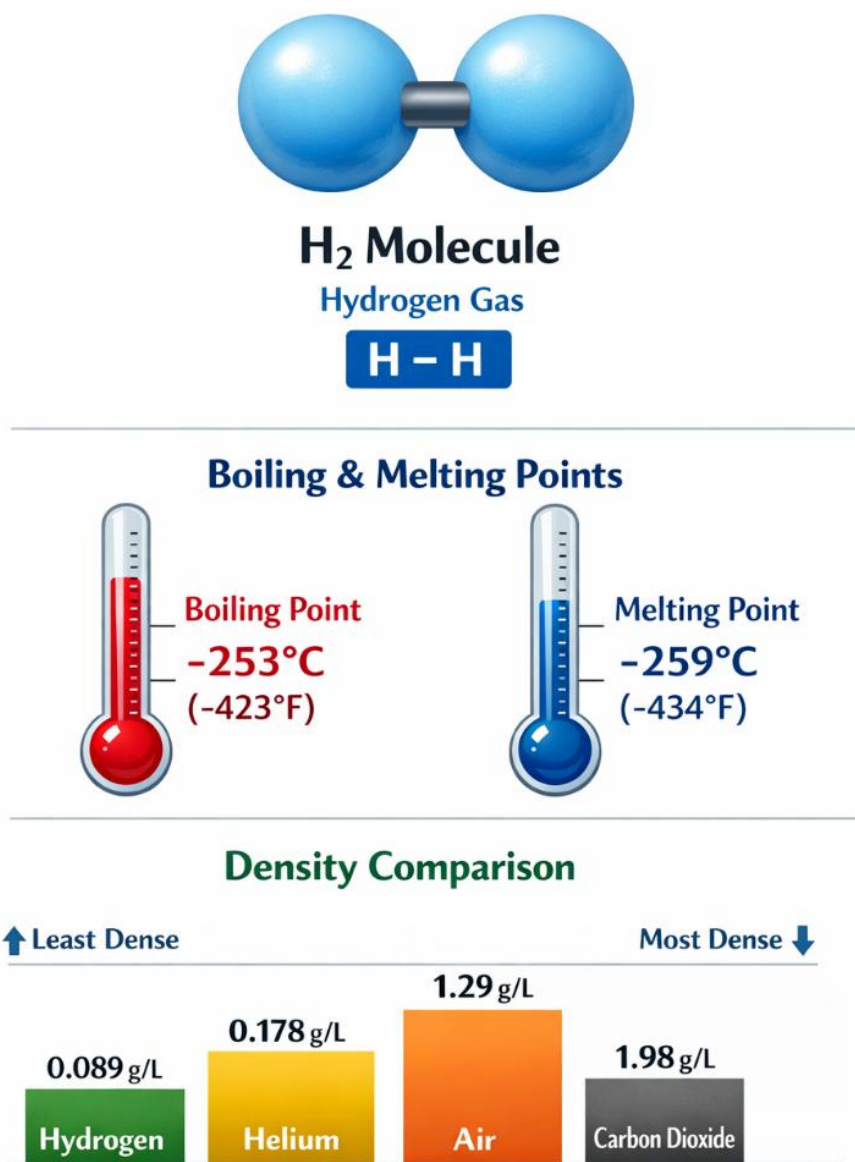


Figure II.1 :Hydrogen Physical Properties Overview [17]

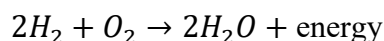
Hydrogen's high gravimetric energy density makes it attractive for energy storage and transportation applications. Its low volumetric energy density, however, poses challenges for storage and distribution, requiring high-pressure tanks, liquefied hydrogen systems, or material-based storage in hydrides.

II.1.2 Chemical Properties

Hydrogen is a highly reactive element that participates in a wide range of chemical reactions, which is key to its versatility in energy and industrial applications. Its main chemical properties include:

II.1.2.1 Combustion

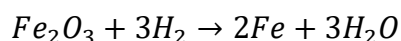
Hydrogen combusts readily with oxygen, producing only water vapor:



This reaction releases large amounts of energy (approx. 142 MJ/kg for HHV) without producing carbon dioxide, sulfur oxides, or nitrogen oxides, making it environmentally clean and suitable for low-carbon energy applications. [16]

II.1.2.2 Reducing Agent

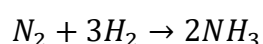
Hydrogen can act as a reducing agent in metallurgical and chemical processes. For example, it reduces iron oxide to produce metallic iron:



This property is exploited in green steel production, where hydrogen replaces carbon-based reductants to minimize CO₂ emissions.

II.1.2.3 Reactivity with Halogens and Other Compounds

Hydrogen reacts with halogens, forming hydrogen halides (e.g., HCl, HBr) used in industrial chemical processes. It can also react with nitrogen under high temperature and pressure to form ammonia (Haber–Bosch process), which is crucial for fertilizer production:



II.1.2.4 Storage Reactions

Hydrogen can form metal hydrides (e.g., MgH₂, NaH), which allow safe, compact storage for later energy use. Hydrogen can also be absorbed in carbon-based materials or chemical carriers for transport and fuel cell applications. [16]

Table II.2: Key Chemical Reactions of Hydrogen [16]

Reaction Type	Example	Product
Combustion	$2\text{H}_2 + \text{O}_2$	$2\text{H}_2\text{O}$
Reduction	$\text{Fe}_2\text{O}_3 + 3\text{H}_2$	$2\text{Fe} + 3\text{H}_2\text{O}$
Ammonia Synthesis	$\text{N}_2 + 3\text{H}_2$	2NH_3
Halogen Reaction	$\text{H}_2 + \text{Cl}_2$	2HCl
Metal Hydride Formation	$\text{Mg} + \text{H}_2$	MgH_2

Hydrogen's high reactivity also introduces safety considerations, as it is extremely flammable and forms explosive mixtures with air over a wide concentration range (4–75% H_2 in air). These characteristics must be considered in its storage, transport, and industrial application.

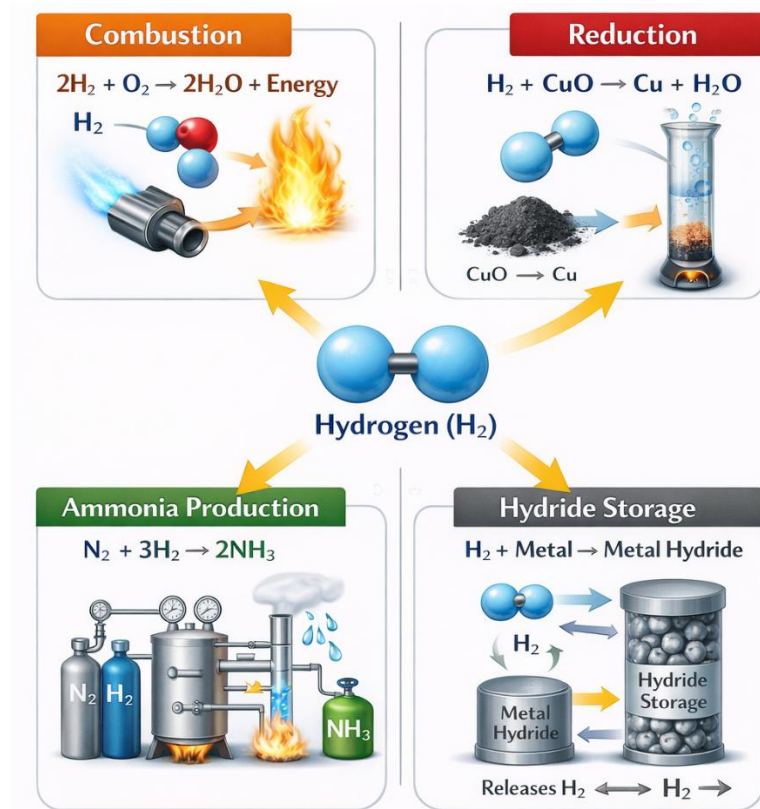


Figure II.2: Hydrogen Reactivity and Applications [17]

II.2 Hydrogen Production Methods

Hydrogen can be produced through a variety of methods, each with distinct technological, economic, and environmental characteristics. The selection of a production method depends on factors such as hydrogen purity, production scale, feedstock availability, energy efficiency, and environmental impact. Currently, the main hydrogen production techniques include water electrolysis, steam methane reforming, biomass conversion, and emerging thermochemical or photolytic methods.

II.2.1 Water Electrolysis

Water electrolysis is the process of splitting water molecules (H_2O) into hydrogen and oxygen using electricity. When powered by renewable electricity, it produces green hydrogen, which is entirely carbon-free. Water electrolysis is particularly suited for integration with solar, wind, and hydropower energy systems.

II.2.1.1 Alkaline Water Electrolysis (AWE)

Alkaline electrolysis is the most mature and widely used technology, utilizing a liquid electrolyte such as potassium hydroxide (KOH) or sodium hydroxide (NaOH). Its advantages include low operating costs, robustness, and proven industrial-scale application. However, it has slow dynamic response, a large footprint, and limited compatibility with intermittent renewable energy sources [20].

II.2.1.2 Proton Exchange Membrane (PEM) Electrolysis

PEM electrolysis uses a solid polymer membrane as the electrolyte, enabling higher current densities, compact design, and faster response to fluctuations in electricity supply. This makes PEM electrolysis ideal for coupling with variable renewable sources like solar and wind. The main drawbacks are high capital costs and the need for precious metal catalysts (e.g., platinum, iridium) [20].

II.2.1.3 Solid Oxide Electrolysis (SOEL)

SOEL operates at high temperatures (700–1000°C) using a ceramic electrolyte. It can achieve higher efficiencies than AWE or PEM, particularly when industrial waste heat is available, as it reduces the electrical energy required for water splitting. Challenges include materials durability at high temperatures and high initial investment costs [20].

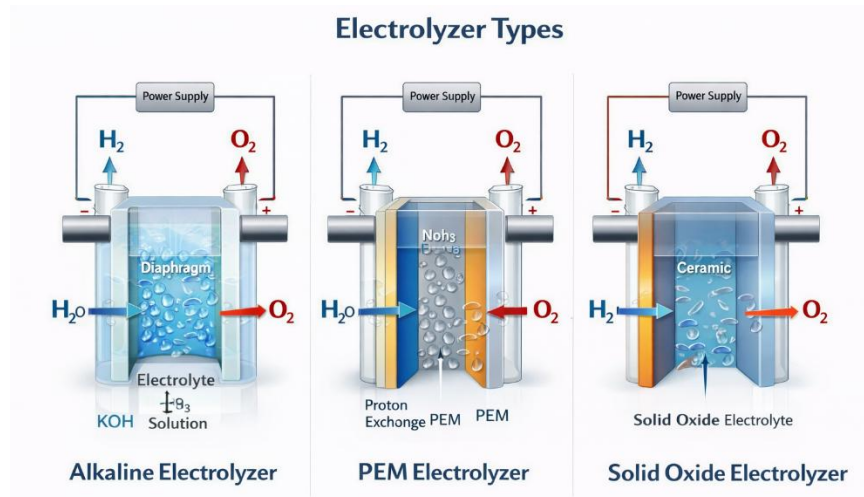


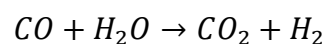
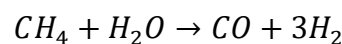
Figure II.3: Water Electrolysis Technologies – AWE, PEM, and SOEL [20]

Table II.3: Comparison of Water Electrolysis Technologies [20]

Technology	Electrolyte	Efficiency	Advantages	Limitations
Alkaline (AWE)	KOH/NaOH	60–70%	Mature, low-cost	Large footprint, slow response
PEM	Solid polymer	65–75%	Compact, responsive	High cost, catalyst sensitivity
SOEL	Ceramic	70–80%	High efficiency, heat integration	High temperature, material durability

II.2.2 Steam Methane Reforming (SMR)

Steam methane reforming is the most widely used commercial hydrogen production method, accounting for approximately 70–80% of global hydrogen production. It involves reacting natural gas (mainly methane) with high-temperature steam to produce hydrogen and carbon dioxide:



SMR is highly efficient and cost-effective but produces significant CO₂ emissions, making it a carbon-intensive method unless combined with carbon capture and storage (CCS). SMR is commonly used in industrial hydrogen production, such as ammonia synthesis, petroleum refining, and methanol production [21].

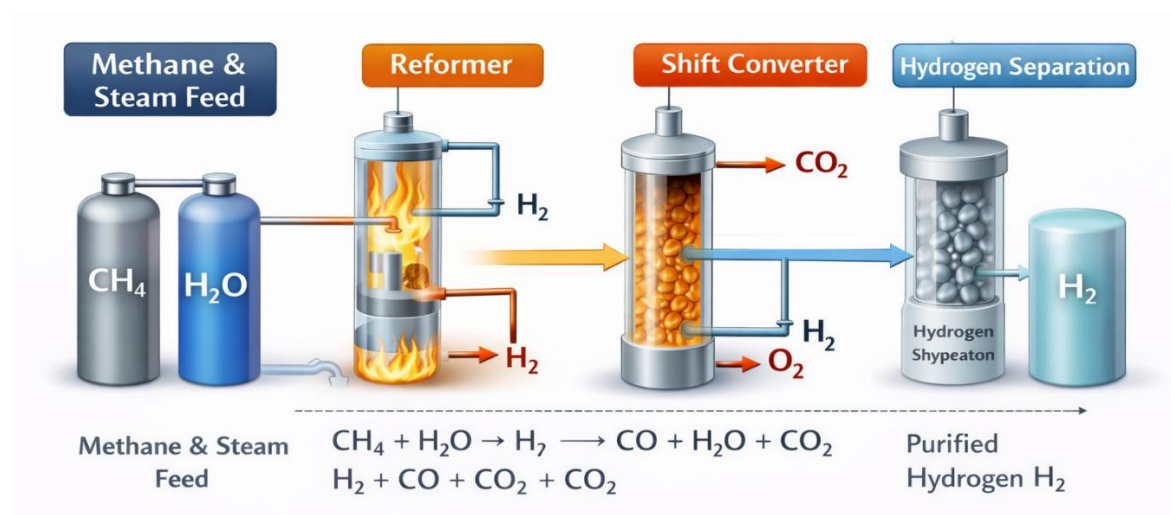


Figure II.4: Steam Methane Reforming Process [21]

II.2.3 Biomass-Based Hydrogen Production

Hydrogen can be generated from **biomass feedstocks** through processes such as **gasification**, **pyrolysis**, and **fermentation**. Biomass hydrogen offers a **renewable and potentially carbon-neutral** pathway. Key methods include:

- **Gasification:** Biomass is converted into a syngas mixture of H_2 , CO , and CO_2 under high temperature with limited oxygen.
- **Pyrolysis:** Thermal decomposition of biomass produces hydrogen-rich gases and bio-oils.
- **Biological fermentation:** Microorganisms produce hydrogen under anaerobic conditions.

Biomass hydrogen is attractive in regions with abundant agricultural residues, offering both energy and waste management benefits, but the technology is less mature than SMR or electrolysis [22].

Table II.4: Biomass Hydrogen Production Methods [22]

Method	Feedstock	Efficiency	Advantages	Limitations
Gasification	Wood, straw, agricultural waste	40–50%	Renewable, flexible feedstock	Complex gas cleaning
Pyrolysis	Wood chips, pellets	30–45%	Co-produces bio-oil	High temperature needed
Fermentation	Organic waste, sugars	20–30%	Low temperature, simple	Low yield, slow

II.2.4 Emerging Methods: Photolysis and Thermochemical Cycles

- **Photolysis:** Uses sunlight to split water directly through photocatalytic or photoelectrochemical reactions. Promising for decentralized green hydrogen but currently limited by low efficiency and cost of photocatalysts [22].
- **Thermochemical cycles:** Use high-temperature heat (from solar concentrators or nuclear reactors) to split water through multi-step chemical reactions. Offers high efficiency at large scale but requires advanced materials and infrastructure [22].

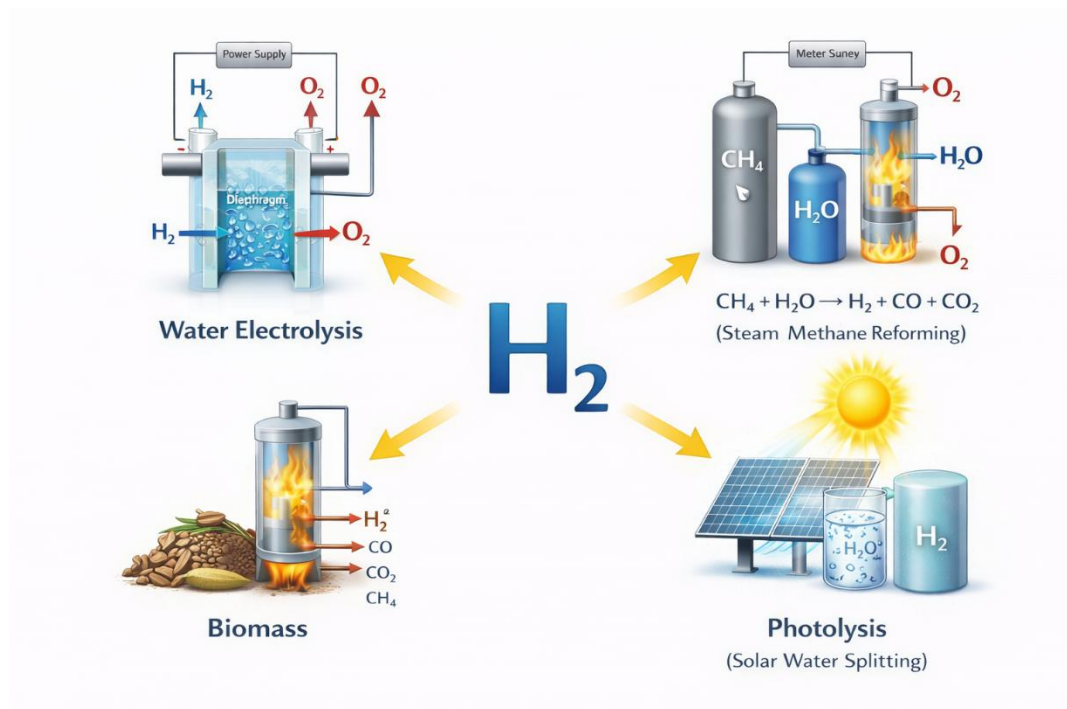


Figure II.5: Overview of Hydrogen Production Pathways [20]

II.3 Hydrogen Storage Technologies

Hydrogen storage is one of the most critical components of the hydrogen energy value chain. Due to hydrogen's low volumetric energy density and small molecular size, effective storage is essential to ensure safe, efficient, and economically viable transport and usage. Storage technologies are generally classified into physical storage (compressed gas, liquid hydrogen), material-based storage (metal hydrides, chemical hydrides, carbon-based materials), and emerging methods (liquid organic hydrogen carriers and advanced materials). Selecting the appropriate storage method depends on application scale, safety requirements, energy density, cost, and operational conditions [15].

II.3.1 Physical Storage Methods

Physical storage relies on hydrogen's gaseous or liquid form to store energy directly.

II.3.1.1 Compressed Gas Storage

Hydrogen gas is typically compressed to 350–700 bar in reinforced tanks. Compressed hydrogen is widely used in fuel cell vehicles, portable hydrogen systems, and industrial supply.

- **Advantages:** Mature technology, relatively low cost, simple infrastructure.
- **Limitations:** Low volumetric density, high compression energy, tank weight, and leakage risk.
- **Applications:** Transportation, industrial hydrogen delivery, backup power [18].

Table II.5: Compressed Hydrogen Storage Parameters [18]

Parameter	Value
Pressure	350–700 bar
Tank Material	Carbon fiber reinforced polymer
Volumetric Energy Density	1.3–1.4 kWh/L
Gravimetric Energy Density	5–6 wt%

II.3.1.2 Liquefied Hydrogen (LH₂)

Hydrogen can also be stored as a cryogenic liquid at -253°C , which increases volumetric density.

- **Advantages:** Higher energy density than compressed gas, suitable for large-scale storage and long-distance transport.
- **Limitations:** High energy consumption for liquefaction ($\sim 30\%$ of energy content), boil-off losses, and complex insulation requirements.
- **Applications:** Industrial supply, space programs, energy storage for large facilities [18].



Figure II.6: Physical Hydrogen Storage Comparison [18]

II.3.2 Material-Based Storage Methods

Material-based storage involves **absorbing or binding hydrogen in solids or liquids**, which allows higher volumetric density and improved safety.

II.3.2.1 Metal Hydrides

Hydrogen reacts with metals to form metal hydrides (e.g., MgH_2 , LaNi_5H_6 , TiFeH_2).

- **Advantages:** High volumetric density, low-pressure storage, reversible hydrogen absorption/desorption.
- **Limitations:** Heavy weight (low gravimetric density), slow kinetics, heat management needed for hydrogen release.
- **Applications:** Stationary hydrogen storage, backup power, renewable energy systems [19].

Table II.6: Common Metal Hydrides for Hydrogen Storage [19]

Metal Hydride	H ₂ Capacity (wt%)	Absorption/Desorption Temp
MgH ₂	7.6	300–400°C
LaNi ₅ H ₆	1.4	20–60°C
TiFeH ₂	1.9	80–120°C

II.3.2.2 Chemical Hydrogen Storage

Hydrogen can also be stored chemically in liquid organic carriers or chemical hydrides (e.g., ammonia, sodium borohydride).

- **Advantages:** Ambient temperature and pressure storage, high volumetric density, transportable as liquids.
- **Limitations:** Hydrogen release requires energy and catalysts; regeneration can be complex.
- **Applications:** Long-distance transport, industrial hydrogen storage, energy carriers [20].

II.3.3 Emerging Storage Technologies

II.3.3.1 Carbon-Based Materials

Hydrogen can adsorb onto nanoporous carbons, graphene, or carbon nanotubes.

- **Advantages:** Reversible storage at moderate pressures, lightweight, high surface area.
- **Limitations:** Low gravimetric capacity at ambient conditions, still under research.
- **Applications:** Portable hydrogen storage, fuel cell vehicles, research prototypes [19].

II.3.3.2 Liquid Organic Hydrogen Carriers (LOHCs)

Hydrogen is chemically bound to organic liquids (e.g., N-ethylcarbazole, toluene).

- **Advantages:** Storage under ambient conditions, compatible with existing liquid fuel infrastructure.
- **Limitations:** Energy required for hydrogen release, need for catalysts.
- **Applications:** Long-distance transport, integration with renewable hydrogen production [20].

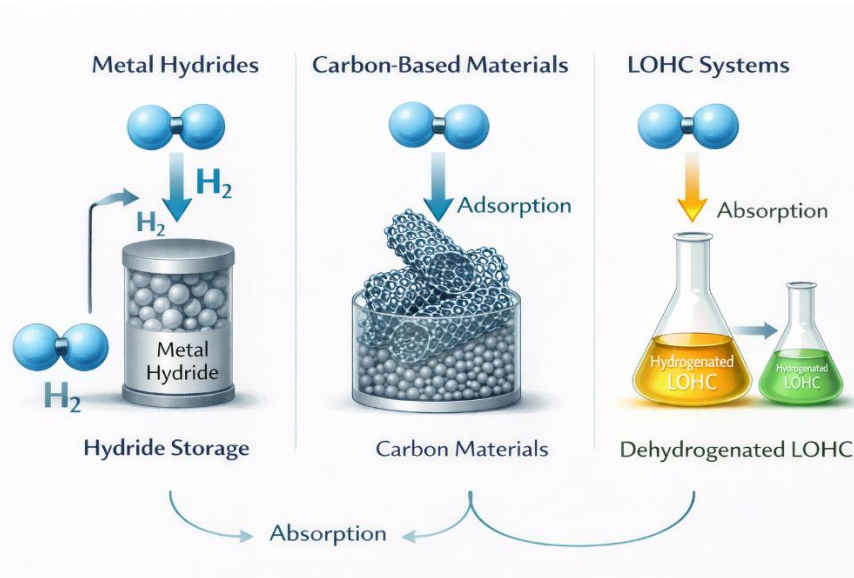


Figure II.7: Material-Based and LOHC Hydrogen Storage [20]

II.3.4 Selection Criteria for Hydrogen Storage

When selecting a storage method, engineers and researchers consider:

- Gravimetric and volumetric energy density
- Safety and stability
- Cost and material availability
- Integration with hydrogen production and utilization
- Environmental impact and lifecycle emissions

Table II.7 :Comparative Overview of Hydrogen Storage Methods [20]

Storage Method	Gravimetric Density	Volumetric Density	Pressure/Temperature	Advantages	Limitations
Compressed Gas	5–6 wt%	1.3–1.4 kWh/L	350–700 bar	Simple, mature	High pressure, low density
Liquefied H ₂	8 wt%	2.36 kWh/L	–253°C	High density, transportable	Cryogenic losses, high energy cost
Metal Hydrides	1–8 wt%	High	1–50 bar	Safe, compact	Heavy, slow kinetics
Chemical Hydrides	3–10 wt%	High	Ambient	Transportable	Energy required for release
LOHC	5–6 wt%	High	Ambient	Infrastructure compatible	Requires catalyst/energy

Hydrogen storage technologies are diverse, ranging from physical methods (compressed, liquefied) to material-based systems (metal hydrides, chemical carriers, carbon materials, LOHCs). Each method presents trade-offs between gravimetric and volumetric energy density, safety, cost, and operational conditions. The choice of storage technology depends on the application—transportation, stationary energy, or industrial use. Advances in materials science and engineering are expected to improve storage efficiency, reduce costs, and enable the widespread adoption of hydrogen as a sustainable energy carrier [20].

II.4 Applications of Hydrogen in Industry, Transport, and Energy Systems

Hydrogen’s versatility as an energy carrier allows its integration across multiple sectors: industrial processes, transportation, and energy systems. Its high energy density, clean combustion, and chemical reactivity make it suitable for decarbonizing sectors that are otherwise difficult to electrify, contributing to sustainable development and climate change mitigation [15].

II.4.1 Industrial Applications

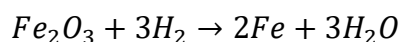
Hydrogen is widely used in chemical, metallurgical, and refining industries.

II.4.1.1 Chemical Industry

- **Ammonia Production:** Hydrogen is combined with nitrogen via the Haber–Bosch process to produce ammonia for fertilizers.
- **Methanol Synthesis:** Hydrogen reacts with CO or CO₂ to produce methanol, used as a fuel and chemical feedstock.
- **Hydrogenation Reactions:** Hydrogen is used in petrochemical processes to saturate hydrocarbons, producing cleaner fuels [17].

II.4.1.2 Metallurgical Processes

Hydrogen can replace carbon as a reducing agent in steel production, minimizing CO₂ emissions:



This “green steel” approach is increasingly considered in Europe and North Africa for sustainable metallurgy [19].

Table II.8: Industrial Hydrogen Applications [17]

Sector	Application	Hydrogen Role
Chemical	Ammonia	Feedstock
Chemical	Methanol	Feedstock
Petrochemical	Hydrocracking/Hydrogenation	Reaction medium
Metallurgy	Steel production	Reducing agent

II.4.2 Hydrogen in Transportation

Hydrogen can be used as a fuel for vehicles, either directly in internal combustion engines or in fuel cells:

II.4.2.1 Fuel Cell Vehicles (FCVs)

- Fuel cells convert hydrogen to electricity electrochemically, powering electric motors with zero tailpipe emissions.
- Advantages: High efficiency (40–60% vs. ~25% for combustion engines), fast refueling (~3–5 min).
- Applications: Cars, buses, trucks, trains [20].

II.4.2.2 Hydrogen Internal Combustion Engines

- Hydrogen can be combusted in modified engines.
- Advantages: Simpler technology, use of existing engine architecture.
- Limitations: Lower efficiency than fuel cells, NO_x emissions may occur.

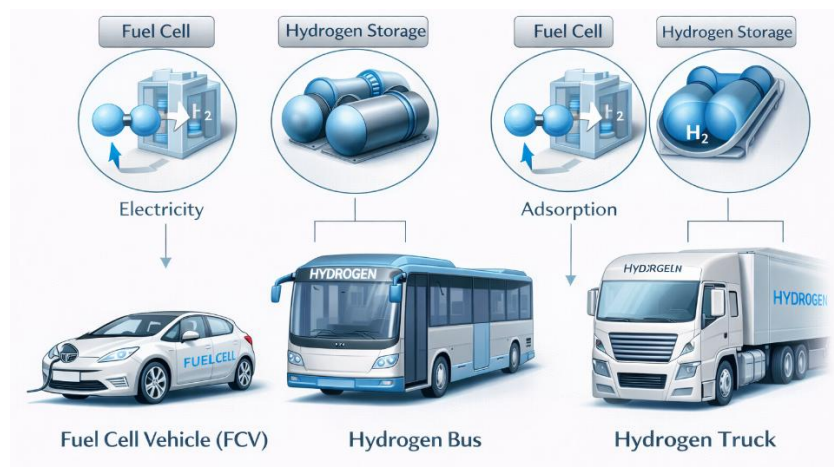


Figure II.8: Hydrogen Applications in Transportation [20]

II.4.3 Energy System Applications

Hydrogen provides flexibility and storage for electricity systems, particularly when coupled with renewable energy sources:

II.4.3.1 Grid Energy Storage

- Hydrogen can store excess renewable energy via power-to-gas systems, converting electricity to hydrogen during low demand and releasing it during peak demand through fuel cells or turbines.
- Advantages: Long-duration storage, grid stabilization.
- Applications: Microgrids, isolated grids in desert regions (e.g., southern Algeria) [20].

II.4.3.2 Combined Heat and Power (CHP) Systems

- Hydrogen fuel cells can generate both electricity and heat for industrial or residential use.
- Applications: Decentralized energy systems, industrial heat supply.

II.4.3.3 Hybrid Renewable-Hydrogen Systems

- Integration with solar and wind energy allows production of “green hydrogen,” which can then be stored or transported to other regions.
- Advantages: Reduces curtailment of renewables, increases renewable energy utilization, supports national energy security [20].

Table II.9: Hydrogen Applications in Energy Systems [20]

Application	Description	Benefits
Grid Storage	Excess renewable → H ₂ → Electricity	Long-duration, grid stability
CHP	Fuel cells provide heat + electricity	Efficient, reduces emissions
Renewable Integration	Solar/Wind → H ₂ storage	Flexible, carbon-free energy

Hydrogen is a versatile and clean energy carrier capable of decarbonizing sectors that are difficult to electrify. Its applications in industry, transport, and energy systems demonstrate its potential to support sustainable development and the energy transition. While challenges

remain in storage, infrastructure, and cost, technological advances in fuel cells, hybrid systems, and renewable hydrogen production are rapidly expanding its feasibility.

II.5 Challenges and Future Prospects

Despite its enormous potential as a clean energy carrier, the widespread adoption of hydrogen faces multiple technical, economic, and infrastructural challenges. Addressing these barriers is crucial for integrating hydrogen into industry, transport, and energy systems, particularly in regions like Algeria where renewable energy potential is high.

II.5.1 Technical Challenges

II.5.1.1 Hydrogen Production Costs

Green hydrogen produced via water electrolysis is currently more expensive than hydrogen from fossil fuels (grey hydrogen). High capital costs of electrolyzers, limited availability of renewable electricity in some regions, and efficiency losses contribute to elevated production costs. Economies of scale and technological advances in electrolysis efficiency are required to make green hydrogen competitive [22].

II.5.1.2 Storage and Transport

Hydrogen's low volumetric energy density and high diffusivity pose storage and transport challenges. Compressed gas storage requires heavy, high-pressure tanks, while liquefied hydrogen necessitates energy-intensive cryogenic cooling. Material-based storage (metal hydrides, chemical carriers) shows promise but is limited by cost, weight, and kinetics. Safe, efficient, and scalable storage solutions remain a critical barrier [19].

II.5.1.3 Infrastructure Limitations

Hydrogen requires dedicated pipelines, refueling stations, and transport networks. Existing natural gas pipelines are not always compatible with hydrogen due to embrittlement and leakage risks. Developing nationwide or regional infrastructure is capital-intensive and requires coordinated policy support [20].

II.5.2 Economic and Market Challenges

- **High Initial Investment:** Large-scale hydrogen production, storage, and distribution systems require significant capital investment.

- **Market Uncertainty:** Hydrogen markets are still emerging, with limited demand compared to fossil fuels.
- **Policy and Incentives:** Adoption depends on supportive regulatory frameworks, carbon pricing, and subsidies for green hydrogen production [19].

Table II.10: Summary of Key Hydrogen Challenges [20]

Category	Challenge	Impact
Technical	High production costs	Limits green hydrogen adoption
Technical	Storage & transport	Safety, efficiency, cost
Technical	Infrastructure	Pipeline compatibility, refueling networks
Economic	Capital investment	Financial feasibility
Economic	Market demand	Low initial uptake
Policy	Regulatory support	Incentives needed for scaling

II.5.3 Environmental and Safety Considerations

While hydrogen itself is clean, leakage of hydrogen can contribute to indirect greenhouse effects, and improper storage or handling can lead to explosions. Safety standards for production, transport, and usage must be rigorously enforced, including leak detection, ventilation, and emergency protocols.

Additionally, hydrogen production from non-renewable sources (grey hydrogen) still generates CO₂ emissions. Transitioning to green hydrogen using solar or wind electricity is essential to ensure environmental benefits [19].

II.5.4 Future Prospects

The future of hydrogen is promising, with key drivers including:

1. **Technological Improvements:** Advances in electrolyzers, fuel cells, and storage materials will improve efficiency and reduce costs.
2. **Integration with Renewable Energy:** Hydrogen enables seasonal energy storage, grid balancing, and utilization of excess renewable electricity.

3. **Sector Coupling:** Hydrogen can decarbonize hard-to-electrify sectors, such as heavy industry, shipping, and aviation.
4. **Policy Support and Investments:** Strategic national policies, carbon pricing, and incentives for green hydrogen projects will accelerate adoption.

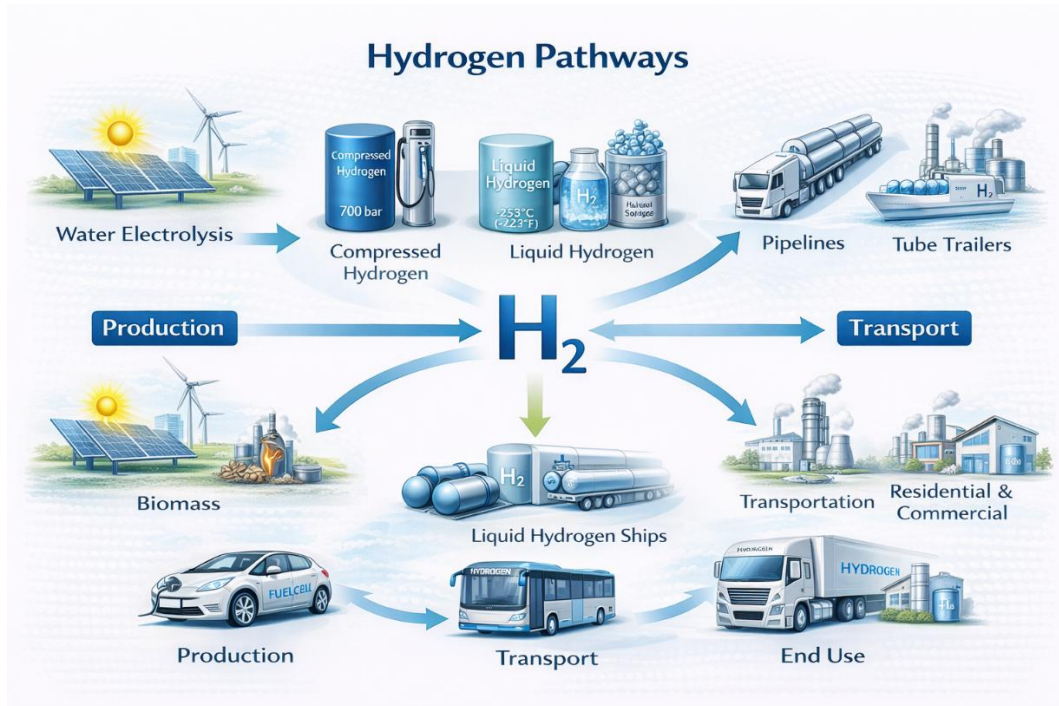


Figure II.9: Future Prospects of Hydrogen in Energy Systems [20]

In Algeria, exploiting solar and wind energy for green hydrogen production presents a significant opportunity to achieve energy independence, reduce fossil fuel reliance, and contribute to global climate goals. Hybrid systems combining hydrogen with renewable energy can provide flexible solutions for both local and national energy grids, particularly in isolated regions like the Sahara [22].

Hydrogen offers enormous potential as a clean energy vector for industrial, transportation, and energy system applications. However, technical, economic, infrastructural, and safety challenges must be addressed to enable widespread adoption. Research and development in electrolyzers, storage materials, and fuel cell technologies, coupled with supportive policies and investments, are crucial to transition from pilot projects to large-scale, cost-competitive hydrogen deployment. Green hydrogen, produced from renewable energy sources, will play a central role in decarbonizing hard-to-electrify sectors and achieving a sustainable energy future.

Conclusion :

Chapter II highlighted hydrogen's potential as a clean and versatile energy carrier. It covered its physical and chemical properties, production methods, storage technologies, and applications in industry, transport, and energy systems. The chapter also discussed technical, economic, and infrastructural challenges and emphasized that advances in technology, renewable energy integration, and supportive policies are key for the widespread adoption of hydrogen.

Chapter III:

Experimental Study

Introduction:

Hydrogen production through water electrolysis is considered one of the promising solutions for addressing the energy crisis and reducing environmental pollution, caused by fossil fuel sources.

The objective of this work, in the first stage, is to investigate the effect of electrolyte type on hydrogen production efficiency during water electrolysis, in order to determine the most effective electrolyte. In the second stage, the effect of varying the concentration of the selected electrolyte on hydrogen production efficiency was studied, under the same operating conditions.

III.1 Measuring instruments and equipment

III.1.1 The water electrolyzer :

The water electrolyzer is the main device used in this experiment. It is employed to decompose water (H_2O) into hydrogen gas (H_2) and oxygen gas (O_2) using a direct electric current. In this work, a simple laboratory electrolysis setup (see figure.1) was used, consisting of an electrolytic cell, two electrodes, and a direct current power supply connected through conducting wires.

Regarding the electrodes, brass alloy electrodes (CuZn40Pb2) were used.

This process is based on the passage of an electric current through an aqueous solution containing an electrolyte. The electrolyte dissolves in water, producing free ions responsible for the transport of electric charge within the solution, which allows the current to flow between the electrodes. When an electrical voltage is applied, the ions move within the solution: negative ions migrate toward the anode, while positive ions migrate toward the cathode. Hydrogen gas is produced at the cathode, whereas oxygen gas is generated at the anode.

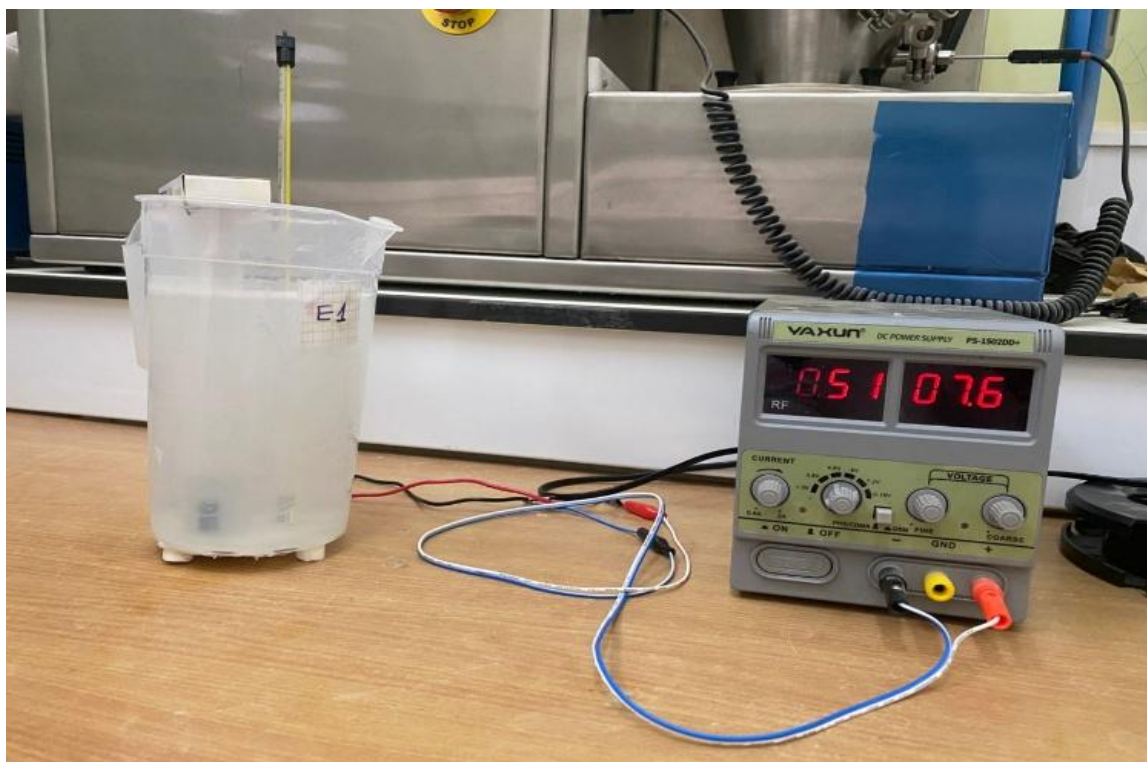


Figure III.1: The electrolyzer used

III.1.2 DC power supply:

The DC power supply, shown in Figure III.2, is an electrical device used to provide the electrolysis cell with direct current and adjustable voltage. In this experiment, it represents the main source of electrical energy required to split water molecules into hydrogen and oxygen.



Figure III.2: DC power supply

III.1.3 Thermometer:

The thermometer (figure.3) is an instrument used to measure temperature during the experiment. The thermometer used in our experiment is a glass thermometer. It is equipped with a graduated scale that allows the reading of the temperature of the solutions during the water electrolysis process.



Figure III.3: Thermometer

III.1.4 Graduated Cylinder:

The graduated cylinder (figure.4) is a calibrated glass instrument used during the experiment to collect and measure the volume of the hydrogen gas produced.



Figure III.4: Graduated Cylinder

III.2 Chemical materials:

III.2.1 Mineral water:

The water used in the experiment is mineral water, which is used as a solvent for the electrolytes

III.2.2 The electrolytes used in the experiment :

In this study, several electrolytes were used in order to compare their effect on hydrogen production efficiency during water electrolysis. The table below shows the electrolytes used in our experiments:

Table III.1: Used Electrolytes and Their Properties

Electrolyte	Molar mass (g/mol)	Appearance and color
KOH	56.106	White solid in the form of flakes.
NaOH	40	White solid in the form of granule , it dissolves easily in water.
CaO	56.08	White solid powder
NaCl	58.44	White crystalline solid (table salt)
Citric Acid	192.12	White crystalline powder, almost colorless and odorless, easily soluble in water.

III.3 Experiment (First Part) :

III.3.1 Introduction :

The first part aims to investigate the effect of electrolyte type on hydrogen production and to determine the most efficient electrolyte.

III.3.2 Experimental procedure :

Initially, the electrolyte solution was prepared in a beaker by adding 0.25 mol of the electrolyte (NaOH, KOH, NaCl, etc.), followed by a small amount of mineral water. The solution was

stirred to ensure complete dissolution of the electrolyte. The prepared solution was then transferred into a flask, and mineral water was added until a final volume of 1 L was reached.

After preparing the solution, the graduated cylinder used for gas collection was filled with the electrolyte solution. The remaining solution was then poured into the electrolysis cell container. Subsequently, the graduated cylinder filled with the solution was inverted and placed inside the electrolysis container, above the negative electrode (cathode). The electrical wires and the DC power supply were then connected, and the device was switched on.

The water electrolysis process then started and lasted for one hour. The same procedure was repeated for each electrolyte, while maintaining identical operating conditions.

III.4 Experiment (The second part) :

III.4.1 Introduction :

After identifying the best electrolyte in the first part, we proceed to the second part. The aim of the second part is to study the effect of the concentration of the best electrolyte on hydrogen production efficiency.

III.4.2 Experimental procedure :

Two solutions containing the same electrolyte were prepared using the same procedure described previously in the first part, but with two different concentrations:

- -0.5 mol/L
- -1 mol/L

The two experiments were carried out under the same operating conditions as previously applied in terms of:

- Water volume
- Experiment duration
- Type of electrodes

The volume of hydrogen gas produced in each experiment was then measured.

Note: In this experiment, only hydrogen gas was collected and measured. Oxygen gas was not collected because the main objective of the study was to compare the influence of electrolyte type and concentration on hydrogen production efficiency.

III.5 Experimental Measurements:

The measurements recorded during each experiment were as follows:

- Electrical voltage
- Electric current
- Hydrogen volume
- Temperature

III.6 Results and Discussion:

III.6.1 Results and Discussion (Part One) :

III.6.1.1 Results :

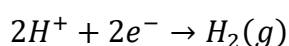
In this section, we present the experimental results obtained from the experiments carried out in the first part, followed by a discussion and analysis of these results.

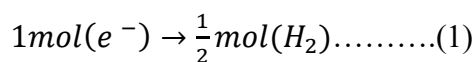
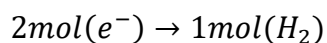
Table III.2: Experimental Results of the Effect of Electrolyte Type on Hydrogen Production Yield

Electrolyte	Current (A)	Voltage(v)	Experimental volume(ml)	Standard volume(ml)	Quantity of electricity	Hydrogen efficiency %
KOH	0.12	7.1	29	26.3	432	52.39
NaOH	0.12	7.1	28.2	25.49	432	50.77
CaO	0.12	7.1	26.7	24.13	432	48.06
NaCl	0.12	7.1	0	0	432	0
C6H8O7	0.12	7.1	0	0	432	0

III.6.1.2 Method for calculating efficiency :

III.6.1.2.1 Hydrogen formation reaction at the cathode :





III.6.1.2.2 Calculation of the electric charge required to release one mole of electrons :

$$Q_{cb} = N_A \times e^-$$

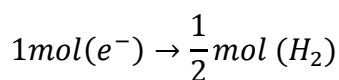
$$N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$$

$$e^- = 1.602 \times 10^{-19} \text{ cb}$$

$$Q_{cb} = 6.022 \times 10^{23} \times 1.602 \times 10^{-19}$$

$$Q_{cb} = 96368 \text{ c/mol}$$

$$\text{Equation} \dots \dots (1)$$



$$96368 \rightarrow 22.4/2(L)$$

$$96368 \rightarrow 11.2(L)$$

III.6.1.2.3 Experimental data for KOH electrolyte :

Electrolyte	KOH
Current (A)	0.12
Volume at experimental conditions(ml)	29
Temperature (c°)	28
Concentration (mol/l)	0.25
Time (s)	3600

III.6.1.2.4 Conversion of volume from experimental conditions to standard conditions :

Standard conditions:

Temperature: 0 °C (273.15 K)

Pressure: 1 atm

$$p_1 = p_2$$

$$\frac{nRT_1}{v_1} = \frac{nRT_2}{v_2} \Rightarrow \frac{273.15}{v_1} = \frac{(28 + 273.15)}{29}$$

$$v_1 = \frac{29 \times 273.15}{(28 + 273.15)}$$

$$v_1 = 26.3ml$$

Volume at experimental conditions : 26.3ml

III.6.1.2.5 Calculation of electric charge(Q) :

$$Q = I \times T$$

$$Q = 0.12 \times 3600$$

$$Q = 432cb$$

III.6.1.2.6 Theoretical volume calculation :

$$\begin{cases} 96368 \rightarrow 11200ml \\ 432cb \rightarrow x \end{cases}$$

$$x = \frac{11200 \times 432}{96368}$$

$$x = 50.25 ml$$

III.6.1.2.7 Efficiency calculation:

$$= \frac{\text{Volume at experimental conditions}}{\text{Theoretical volume}} \times 100$$

$$= \frac{26.3}{50.25} \times 100$$

$$= 52.39\%$$

The hydrogen production efficiency obtained using KOH electrolyte is 52.39 %.

The same calculation method was applied to determine the hydrogen production efficiency for the remaining electrolytes.

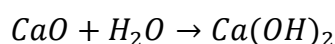
III.6.1.3 Discussion of Results:

The experimental results showed a clear variation in the volume of hydrogen gas produced depending on the type of electrolyte. This is mainly attributed to the difference in electrical conductivity of each solution. KOH electrolyte recorded the highest hydrogen yield compared to the other electrolytes, due to its high electrical conductivity and its complete dissociation in water, which increases the number of free ions and facilitates the passage of electric current through the solution. NaOH also showed good hydrogen production efficiency, as it is a strong electrolyte; however, it remains lower than that of KOH. Both electrolytes are fully soluble in water and dissociate into ions.



Both contain OH^{-} ions, but K^{+} ions exhibit higher mobility in solution compared to Na^{+} ions.

Regarding CaO, its efficiency was lower compared to NaOH and KOH, since it does not dissolve directly in water; instead, it is converted into $Ca(OH)_2$.



which reduces the number of available ions in the solution. However, hydrogen production was still significant.

For NaCl, the results showed that no hydrogen gas production was recorded when using this electrolyte; therefore, the efficiency was zero, despite applying the same electrolysis conditions. During the electrolysis of the NaCl solution, a green coloration of the solution was observed, which is explained by the formation of chlorine gas at the anode. This may account for the absence of hydrogen production.

Regarding citric acid, the results showed that no hydrogen gas production was recorded when using this electrolyte. This can be explained by the fact that citric acid is a weak electrolyte; meaning that it partially dissociates in water. This leads to a low number of ions in the solution, and consequently, low electrical conductivity. In addition, the concentration of citric acid can directly affect hydrogen production during electrolysis. Increasing the electrolyte concentration

leads to an increase in the number of free ions in the solution; therefore, electrical conductivity improves, and hydrogen production increases.

III.6.1.4 Conclusion n°1:

Based on the conducted experiments and the obtained results, it can be concluded that potassium hydroxide is the most suitable electrolyte for hydrogen production, owing to its properties that enhance hydrogen yield during the electrolysis process.

III.6.2 Results and Discussion (Part Two) :

III.6.2.1 Results :

In the second part, we present the experimental results (Table 3) related to the study of the effect of the optimal electrolyte concentration on hydrogen production.

Table III.3: Experimental Results of the Effect of Optimal Electrolyte Concentration on Hydrogen Production Yield

Electrolyte	Concentration (mol/l)	Current (A)	Voltage(v)	Experimental volume(ml)	Standard volume(ml)	Quantity of electricity	Hydrogen efficiency %
KOH	0.25	0.12	7.1	29	26.3	432	52.39
KOH	0.5	0.12	7.2	25.57	23.11	360	55.24
KOH	1	0.12	7.5	25.57	23.11	266.4	74.64

III.6.2.2 Discussion of Results :

The experimental results show that the concentration of the electrolyte (KOH) has a direct effect on hydrogen production yield. The results show that changing the concentration of KOH influenced the hydrogen production efficiency. However, the measured hydrogen volume did not increase regularly with concentration. The highest experimental volume was obtained at 0.25 mol/L, while the volumes measured at 0.5 mol/L and 1 mol/L were lower and almost identical. This means that the relationship between concentration and hydrogen production was not strictly linear under the conditions of this experiment.

The increase in calculated efficiency at higher concentrations is mainly related to the values of electric charge used in the calculation. Therefore, the comparison must be interpreted carefully. If the experiment duration and current were the same for all tests, the electric charge should also be the same. In that case, the efficiency values for 0.5 mol/L and 1 mol/L must be recalculated using the same value of Q .

In general, increasing the electrolyte concentration can improve the conductivity of the solution by increasing the number of ions. However, after a certain concentration, other factors such as gas bubble accumulation, electrode surface behavior, solution resistance, and measurement uncertainty may affect the volume of hydrogen collected.

III.6.2.3 Conclusion n°2:

The experimental results obtained demonstrate that the concentration of the electrolyte (KOH) is a fundamental parameter, as it directly influences hydrogen production yield. Accordingly, the selection of the optimal electrolyte concentration is essential to achieve maximum efficiency in hydrogen production.

Conclusion :

The experimental study showed that the type of electrolyte has a clear influence on hydrogen production during water electrolysis. Among the tested electrolytes, KOH gave the best result, followed by NaOH and CaO. This behavior can mainly be related to the high ionic conductivity of alkaline electrolytes, which improves the passage of electric current through the solution.

The results also showed that electrolyte concentration affects the electrolysis process. However, the relationship between concentration and hydrogen production was not perfectly linear in the obtained experimental data. For this reason, the comparison between concentrations must be made carefully, especially because the quantity of electricity used in the calculations was not the same for all tests.

Overall, KOH can be considered the most suitable electrolyte in this experiment. Still, more accurate measurements are needed to confirm the optimal concentration, especially by keeping the same current, time, temperature, and electrode conditions in all tests.

General Conclusion

General Conclusion:

The present work studied the influence of the electrolyte on the efficiency of hydrogen production by water electrolysis. The subject is important because hydrogen is considered a promising clean energy carrier, especially when it is produced using renewable electricity. Since pure water has low electrical conductivity, the use of an electrolyte is necessary to improve ion transport and allow the electrolysis process to take place more effectively.

The theoretical part first presented the main energy sources, including fossil fuels and renewable energies. Fossil fuels remain important in the global energy system, but their environmental impact and limited availability make the transition toward cleaner energy sources necessary. Renewable energy, especially solar energy, represents an important opportunity for countries such as Algeria, which has high solar potential. In this context, hydrogen can play an important role as a storage medium and as a clean fuel.

The second chapter focused on hydrogen, its physical and chemical properties, production methods, storage technologies, and applications. Among the different production methods, water electrolysis is one of the most suitable for green hydrogen production. It can be combined with renewable electricity and does not directly emit carbon dioxide during the production process. However, the performance of electrolysis depends on several parameters, including the type of electrolyte, electrolyte concentration, electric current, voltage, temperature, electrode material, and operating time.

The experimental study was carried out in two parts. In the first part, different electrolytes were tested under the same operating conditions in order to compare their effect on hydrogen production. The results showed that potassium hydroxide (KOH) gave the highest hydrogen production efficiency, followed by sodium hydroxide (NaOH) and calcium oxide (CaO). No hydrogen volume was recorded for sodium chloride and citric acid under the selected experimental conditions. This confirms that strong alkaline electrolytes are more suitable for this type of electrolysis because they provide better ionic conductivity.

In the second part, the effect of KOH concentration was studied. The results showed that electrolyte concentration has an influence on hydrogen production efficiency. However, the obtained values must be interpreted carefully because the quantity of electricity used in the calculations was not identical for all concentrations, although the experimental procedure states that the same duration and current were used. For a more accurate comparison, the same calculation basis should be applied to all experiments.

General Conclusion

Overall, the study confirms that the choice of electrolyte is a key factor in improving hydrogen production by water electrolysis. KOH was found to be the most effective electrolyte among those tested. The work also shows that concentration can affect the electrolysis process, but further experiments are needed to determine the optimal concentration more accurately.

For future work, it is recommended to repeat the experiments using more precise measuring equipment, collect both hydrogen and oxygen gases, and control temperature, pressure, and current more carefully. It would also be useful to test other electrode materials, such as stainless steel or nickel-based electrodes, and to study higher current values in order to better evaluate the real efficiency of the electrolysis system.

Bibliography

Bibliography:

- [1] Ziani Bey, S., & Zerouat, F. (2022). Prospects for Developing the Renewable Energy Sector in Algeria: A Prospective Study Using the MICMAC Structural Analysis Technique. Research Laboratory STRATEV, Abdelhamid Ben Badis University of Mostaganem, Algeria.
- [2] Raache, M. N. (2021). Utilisation des nano-fluides dans le procédé de la production de l'hydrogène. Université Kasdi Merbah Ouargla, Doctoral Thesis.
- [3] Lyons, W. C., & Plisga, G. J. (2011). Standard handbook of petroleum and natural gas engineering. Elsevier.
- [4] Pirani, S. (2018). Burning up: A global history of fossil fuel consumption. Pluto Press.
- [5] Smith, K. K. (2005). Powering our future: An energy sourcebook. iUniverse.
- [6] Michels, R., & Huc, A.-Y. (2013). La formation des ressources fossiles. In R. Mosseri & C. Jeandel (eds.), *L'énergie à découvert*. Paris: CNRS Éditions.
- [7] Hsu, C. S., & Robinson, P. R. (2017). Springer handbook of petroleum technology. Springer.
- [8] Berkowitz, N. (1997). Fossil hydrocarbons: Chemistry and technology. Academic Press.
- [9] Bederina, H. (2025). Renewable energies as energetic alternatives to achieve environmental security in Algeria. *Journal of Excellence for Economics and Management Research*, 9(01), 446–460.
- [10] Douah, B. (2018). Renewable energies in the service of sustainable development. *Review of Human Sciences*, 18(02), 144–159.
- [11] Idda, A., Bentouba, S., & Sellami, M. H. (2025). Energy Transition in Algeria's Desert: Current State and Future Perspectives. *Renewable and Sustainable Energy: An International Journal*, 1(1), 19–33.
- [12] Sheikh, N. (2021). The facts and prospects for the development of renewable energies in the Maghreb countries: Algeria, Tunisia, Morocco. *Maghreb Energy Review*.

Bibliography

- [13] Heywood, J. B. (2018). Internal combustion engine fundamentals (2nd ed.). McGraw-Hill Education.
- [14] Hamza, J. (2018). Mechanisms for financing and developing renewable energy projects to achieve sustainable development in Algeria. *Energy Policy Journal*.
- [15] Chebbah, Y., Kaouche, Y., & Frerhous, A. I. (2023). Hydrogen properties, production, and uses. *Energy Science and Technology Journal*, 5(2), 112–135.
- [16] Imad Eddine, A., & Chebbah, Y. (2022). Physical properties and thermodynamic characteristics of hydrogen for energy applications. *International Journal of Hydrogen Energy*, 47(45), 20050–20068.
- [17] Yahia, C., Kaouche, Y., & Frerhous, A. I. (2023). Hydrogen storage technology and its challenges: A review. *Renewable and Sustainable Energy Reviews*, 170, 112–128.
- [18] Dutta, A. (2014). A review on production, storage of hydrogen and its utilization as an energy resource. *Journal of Industrial and Engineering Chemistry*, 20(4), 1148–1156.
- [19] Yahia, C., Kaouche, Y., & Frerhous, A. I. (2022). Water electrolysis: From textbook knowledge to latest scientific strategies and industrial developments. *International Journal of Hydrogen Energy*, 47(68), 28750–28772.
- [20] Literature Review of Hydrogen Energy Systems and Renewable Energy Sources.pdf.
- [21] Amara, M., Benhassine, M., & Meziane, H. (2022). Green hydrogen production in Algeria: Potentials, challenges, and strategic energy perspectives. *International Journal of Hydrogen Energy*, 47(10), 6523–6535.
- [22] Dincer, I., & Acar, C. (2015). Review and evaluation of hydrogen production and storage methods for renewable energy system applications. *International Journal of Hydrogen Energy*, 40(34), 11094–11111.