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Electrolysis (Sono-Hydro-Gen) for hydrogen extraction by Wind system with storage

Presented by :

M. AMIRA LAGHOUATI

Supervised by :

Pr. MOUALDIA Abdelhafidh

Dr. BOULKHRACHEF Salah

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Dedications

To my dear parents, to my dear brother Mohamed and sisters Aya and Walaa, to those dear to my heart and dear friends, to my teachers and doctors. It has been a difficult year in which I went through a stage of no return, but praise be to God, here I am now standing before you today. Yes, the dream has come true, and the future is even more beautiful.

To my father and mother

Aya and Walaa

Mohamed

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Sometimes it falls on a generation to be great.You can be that great generation.

- Nelson Mandela

ملخص

تلعب أنظمة المحلل الكهربائي (سونوهيدروجين) دورًا حاسمًا في إنتاج الهيدروجين من الماء باستخدام طاقة الرياح، مما يوفر نهجًا مستدامًا لتوليد الطاقة. تستخدم هذه الأنظمة عملية التحليل الكهربائي التي تتضمن تمرير تيار كهربائي عبر الماء لفصله إلى هيدروجين وأكسجين. و لتعزيز معدلات إنتاج الهيدروجين يمكننا أن ندمج تكنولوجيا الموجات فوق الصوتية في عملية التحليل الكهربائي . علاوة على ذلك، فإن اقتران أنظمة التحليل الكهربائي هذه بطاقة الرياح يسمح بمصدر طاقة نظيف ومتجدد لإنتاج الهيدروجين. تعد أنظمة التخزين أيضًا مكونات أساسية، مما يضمن إمكانية تخزين الهيدروجين الزائد المنتج بكفاءة لاستخدامه لاحقًا، وبالتالي المساهمة في الاستدامة الشاملة للنظام.

الكلمات المفتاحية: المحلل الكهربائي، الهيدروجين، طاقة الرياح، أنظمة التخزين، الموجات فوق الصوتية.

Abstract

Sonohydrogen electrolyser systems play a crucial role in producing hydrogen from water using wind energy, providing a sustainable approach to power generation. These systems use the electrolysis process, which involves passing an electrical current through water to separate it into hydrogen and oxygen. To enhance hydrogen production rates, we can incorporate ultrasonic technology into the electrolysis process. Furthermore, coupling these electrolysis systems with wind power allows for a clean, renewable energy source for hydrogen production. Storage systems are also essential components, ensuring that excess hydrogen produced can be efficiently stored for later use, thus contributing to the overall sustainability of the system.

Keywords: Electrolyzer, Hydrogen, wind energy, Storage systems, ultrasound.

Résumé

Les systèmes d'électrolyse sonohydrogène jouent un rôle crucial dans la production d'hydrogène à partir de l'eau à l'aide de l'énergie éolienne, offrant ainsi une approche durable de la production d'électricité. Ces systèmes utilisent le processus d'électrolyse, qui consiste à faire passer un courant électrique dans l'eau pour la séparer en hydrogène et oxygène. Pour améliorer les taux de production d'hydrogène, nous pouvons intégrer la technologie ultrasonique dans le processus d'électrolyse. De plus, le couplage de ces systèmes d'électrolyse à l'énergie éolienne permet d'obtenir une source d'énergie propre et renouvelable pour la production d'hydrogène. Les systèmes de stockage sont également des composants essentiels, garantissant que l'excès d'hydrogène produit peut être stocké efficacement pour une utilisation ultérieure, contribuant ainsi à la durabilité globale du système.

Mots-clés : Electrolyseur, Hydrogène, énergie éolienne, Systèmes de stockage, ultrasons.

Contents

List of Figures i

List of Tables iv

General Introduction 1

1 Generality systems 3

1.1 Introduction . . . 3
1.2 Hydrogen . . . 5
1.2.1 History . . . 5
1.2.2 Definition . . . 6
1.2.3 Different Colors of Hydrogen . . . 6
1.3 Green Hydrogen . . . 8
1.3.1 Definition . . . 8
1.3.2 Hydrogen Production . . . 9
1.3.3 Properties of Hydrogen . . . 10
1.3.4 Hydrogen Storage . . . 10
1.3.5 Application of Hydrogen . . . 15
1.3.6 Advantages and Disadvantages of Hydrogen . . . 16
1.4 Electrolyzer . . . 17
1.4.1 Water Electrolysis Technologies . . . 17
1.4.2 Types of Electrolyzer . . . 18
1.5 Wind Energy . . . 23
1.5.1 Theory . . . 23
1.5.2 Energy From Wind . . . 24
1.5.3 Coupling with the Electrolyzer . . . 26
1.6 Conclusion . . . 27

2 Modeling systems 28

2.1 Introduction . . . 28

2.2 Modeling the wind conversion chain . . . 28
2.3 Synchronous Generator . . . 31
2.3.1 Synchronous Machine Theory . . . 31
2.3.2 Permanent Magnet Synchronous Generator . . . 32
2.3.3 MSAP model in the Park benchmark . . . 35
2.4 The Filter . . . 37
2.5 Power converter . . . 38
2.5.1 Diode rectifier . . . 38
2.6 Electrolyzer . . . 39
2.6.1 Alkaline Electrolyzer . . . 39
2.6.2 Boundary Conditions for the Alkaline Electrolyser . . . 41
2.7 Hydrogen Model Tank . . . 42
2.8 Conclusion . . . 42

3 Storage System **44**
3.1 Introduction . . . 44
3.2 Energy Storage . . . 44
3.3 Classification of Storage Systems . . . 45
3.3.1 Batteries (Accumulators) . . . 45
3.3.2 Equivalent Circuit of a Voltage Source . . . 45
3.3.3 Characteristics of an accumulator cell . . . 47
3.3.4 Types of battery . . . 48
3.3.5 Fuel Cell . . . 50
3.3.6 Coupling with System . . . 55
3.4 Conclusion . . . 57

4 Realization System **59**
4.1 Introduction . . . 59
4.1.1 Experimental Apparatus . . . 59
4.2 Experiment Protocol for Electrolyzer Sonohydrogen Production with Silver Electrodes . . . 65
4.2.1 Objective . . . 65
4.2.2 Equipment and Materials . . . 65
4.2.3 Experimental Setup . . . 66
4.2.4 Procedure . . . 66
4.2.5 Safety Precautions . . . 67
4.2.6 Data Analysis . . . 67

4.2.7 Hydrogen Production Methods 67
4.3 Conclusion 71

5 Simulations and Result of System **72**
5.1 Introduction 72
5.1.1 simulations of the system 73
5.1.2 Simulation Setup 73
5.2 Results and Analysis 78
5.2.1 Wind System Results 78
5.2.2 Electrolysis Results 81
5.2.3 Storage Results 82
5.3 Conclusion 87

General Conclusion **88**
5.4 Future work 89

Bibliography **90**

A Project Guide **A**

B Business Model Canvas **F**

C Fuel Cell Characteristic **G**

List of Figures

Fig. 1.1 Hydrogen extraction by wind system with storage 4
Fig. 1.2 Hydrogen color shades and their Technology, cost, and CO2 emissions . 6
Fig. 1.3 Major hydrogen production methods and applications 9
Fig. 1.4 Illustration of Liquid and compressed hydrogen storage tanks 13
Fig. 1.5 The timeline for developing low-temperature water electrolysis technology. Inset images reproduced with permission. 17
Fig. 1.6 Schematic illustration of alkaline water electrolysis working principle. . . 18
Fig. 1.7 Schematic view of PEM water electrolysis working principle. 20
Fig. 1.8 Schematic view of AEM water electrolysis working principle. 22
Fig. 1.9 Anion Exchange Membrane Electrolyzer 22
Fig. 1.10 The increase of average rotor diameter and capacity 24
Fig. 1.11 Wind turbine 25
Fig. 1.12 Electricity Generation Trends - IRENA 25
Fig. 1.13 Wind hydrogen system production 27

Fig. 2.1 The wind conversion chain 29
Fig. 2.2 Wind turbine dynamic model 29
Fig. 2.3 Some configurations of magnet placement 32
Fig. 2.4 a- machine asynchrone, b- machine à aimant permanent 33
Fig. 2.5 Representative diagram of the MSAP to be modeled 34
Fig. 2.6 Three-phase-two-phase transformation 35
Fig. 2.7 Block diagram (Matlab/Simulink) of the rectifier and filter 38
Fig. 2.8 Electric diagram of rectifier an uncontrolled three-phase 39

Fig. 3.1 Equivalent circuit of a battery. 46
Fig. 3.2 Source voltage as a function of source current for a battery. 46
Fig. 3.3 Schematic of a lithium-ion battery during discharge. Electrons from the oxidation reaction at the graphite anode travel through an external circuit and are consumed by a reduction reaction at the transition metal oxide cathode 48

Fig. 3.4 Voltage and capacity for various anode and cathode materials, both commercial and under research . . . 49
Fig. 3.5 Alkaline Fuel Cell . . . 51
Fig. 3.6 Constituents of a Fuel cell stack . . . 52
Fig. 3.7 Representation of Alkaline Fuel Cell (AFC) . . . 54
Fig. 3.8 Working Principle representation of Alkaline Fuel Cell (AFC) . . . 55

Fig. 4.1 Experimental diagram . . . 60
Fig. 4.2 voltage generator(alternative to a wind turbine)With Electrolyzer . . . 61
Fig. 4.3 Ultrasonic Generator . . . 63
Fig. 4.4 Gas Sensor and Arduino Card . . . 64
Fig. 4.5 Fuel Cell . . . 65
Fig. 4.6 A summary of sound wave industrial applications. . . . 69

Fig. 5.1 Schema of the General system . . . 73
Fig. 5.2 Block representation of Wind and Electrolysis system model in MATLAB/Simulink . . . 74
Fig. 5.3 Block representation of Electrolysis system model in MATLAB/Simulink 74
Fig. 5.4 Block representation of Battery system model in MATLAB/Simulink . 75
Fig. 5.5 Block representation of Battery management systems model in MATLAB/Simulink . . . 75
Fig. 5.6 Block representation of model in MATLAB/Simulink . . . 76
Fig. 5.7 Block representation of 2.4 kW – 48 Vdc AFC system . . . 77
Fig. 5.8 Block representation of Fuel cell stack . . . 77
Fig. 5.9 Block representation of Boost Converter . . . 78
Fig. 5.10 Wind Profile . . . 79
Fig. 5.11 Wind Power . . . 79
Fig. 5.12 Rotor Speed . . . 80
Fig. 5.13 Electromagnetic Torique . . . 80
Fig. 5.14 Hydrogen flow rate . . . 81
Fig. 5.15 MATLAB/Simulink model of the hydrogen storage system . . . 81
Fig. 5.16 Pressure of compressed hydrogen tank . . . 82
Fig. 5.17 Battery Power . . . 82
Fig. 5.18 Capacity of battery . . . 83
Fig. 5.19 Voltage . . . 83
Fig. 5.20 Discharge curve . . . 84
Fig. 5.21 Voltage of Fuel cell . . . 84

Fig. 5.22 Current of Fuel cell 85
Fig. 5.23 Voltage of Hacheur Boost 85
Fig. 5.24 Current of Hacheur Boost 86
Fig. 5.25 Discharge curve 86

Fig. C.1 . . . . . G

List of Tables

Tab. 1.1 Overview of specific and volumetric energy density 10
Tab. 1.2 General specifications of Alkaline electrolysis 19
Tab. 1.3 Characteristics of the PEM water electrolyzer 21

Tab. 2.1 Electrolyzer experimental data 41

Tab. 3.1 Summary of Different Types of Fuel Cells 53
Tab. 3.2 Summary of major fuel constituents' impact on AFC 55

Tab. 4.1 Comparison of Hydrogen Production Methods 67
Tab. 4.2 A conceptual illustration of different hydrogen production methods . . 70

Tab. B.1 Business Model Canvas for (Sono_Hydro_Gen) Project . . . . . F

List of Abbreviations and Acronyms

A	Ampere
AC	Alternating Current
AEM	Anion Exchange Membrane
AFC	Alkaline Fuel Cell
BC	Buck Converter
BMC	Boundary Element Method
CHP	Combined Heat and Power
CO2	Carbon Dioxide
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
FC	Fuel Cell
H2	Hydrogen
IRENA	International Renewable Energy Agency
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt-hour

lpm Liters Per Minute

MATLAB Matrix Laboratory (software for numerical computing)

MCFC Molten Carbonate Fuel Cell

MJ Megajoule

MPPT Maximum Power Point Tracking

m3 Cubic Meter

MW Megawatt

O2 Oxygen

PAFC Phosphoric Acid Fuel Cell

PEM Proton Exchange Membrane

RE Renewable Energy

Simulink A MATLAB-based graphical programming environment for modeling, simulating, and analyzing multidomain dynamical systems

SOC State of Charge

SOFC Solid Oxide Fuel Cell

V Voltage

Vdc Volts Direct Current

W Watt

Wh Watt-hour

BMS Battery management system

SMR	Steam Methane Reforming
POX	Partial Oxidation
ATR	Autothermal Reforming
CO2	Carbon Dioxide
NASA	National Aeronautics and Space Administration
HYOP	Hydrogen Year of Production
FCEVs	Fuel cell electric vehicles
LOHC	Liquid Organic Hydrogen Carriers
AEW	Alkaline Water Electrolyzer
KOH	Potassium Hydroxide
HER	The hydrogen evolution reaction
OER	The oxygen evolution reaction
MEA	Membrane electrode assembly
Cp	The power coefficient
Pm	Mechanical power
Pv	Wind power available
λ	Specific speed
ρ	Air density
R	Rotor radius
V	Wind speed
S	The area swept by the wind turbine blades

General Introduction

The quest for sustainable energy sources has led to innovative approaches in hydrogen production, with electrolysis emerging as a promising method. Electrolyzers play a crucial role in this process, utilizing electrical energy from renewable sources like wind to split water into hydrogen and oxygen.

In recent years, the integration of ultrasound technology into electrolyzers has garnered attention for its potential to enhance hydrogen production efficiency. This combination, known as electrolyzer sonohydrogen production, offers several advantages over traditional electrolysis methods.

The utilization of a wind system for electricity generation adds another layer of sustainability to this process. By harnessing wind power, the system can operate with minimal environmental impact, providing a clean and renewable source of energy for hydrogen extraction.

Moreover, the incorporation of energy storage solutions further enhances the versatility and reliability of the system. Energy storage allows for the capture and utilization of excess energy generated by the wind system, ensuring continuous operation even when wind conditions are variable.

Overall, electrolyzer sonohydrogen production offers a compelling solution for sustainable hydrogen extraction. By leveraging the power of wind energy and ultrasound technology, this approach holds the potential to revolutionize the field of hydrogen production, paving the way for a greener and more sustainable future.For this, our document is divided as follows:

In Chapter I, we will briefly present an extensive discussion on hydrogen, including its historical background, definition, types, sources, and forms. The chapter introduces green hydrogen, covering its definition, production methods, properties, storage techniques, and applications. Additionally, it examines the advantages and disadvantages of hydrogen as an energy carrier. Electrolysis is explored, focusing on water electrolysis technologies such as alkaline, proton exchange membrane, and anion exchange membrane electrolyzers. Finally, the chapter explores wind energy, its theoretical foundations, energy extraction

from wind, and its integration with electrolyzers for hydrogen production, highlighting potential synergies.

In the Chapter 2 explores modeling and simulation systems, focusing on wind energy conversion, synchronous generators like PMSGs, power converters including diode rectifiers and voltage inverters, and electrolyzers, particularly alkaline electrolyzers and their boundary conditions.

In the Chapter 3 introduces storage systems, covering energy storage methods and the classification of storage systems. It discusses batteries (accumulators), the control of Battery Management Systems (BMS), fuel cells, their integration with the system, and concludes with a summary.

In the Chapter 4 discusses the realization system, including the experimental apparatus and protocol for electrolyzer sonohydrogen production with silver electrodes. It covers the objective, equipment, experimental setup, procedure, safety precautions, data analysis, potential ultrasound application, and concludes with a summary.

In Chapter 5, we delve into the outcomes of our system. We begin by introducing the section, highlighting its focus on presenting the results and analysis. Next, we detail the simulation setup, which includes configurations for the wind system, electrolysis, and storage system. This setup provides the foundation for our analysis and helps us understand how the system performed under different conditions. Finally, we present the results of the simulations and analyze their implications. This analysis is crucial for drawing conclusions about the system's performance and its potential for real-world applications.

To complete this modest work, a general conclusion as well as a perspective will be presented.

Chapter 1

Generality systems

1.1 Introduction

Energy storage systems are considered the key factor to improve the reliability and stability of renewable-energy-based electricity [1]. For intermittent renewable energy sources, such as solar and wind, energy storage not only provides a way to match generation and load profiles but also serves as an auxiliary source to deliver power when renewable sources are unavailable.

Due to its sustainable production, hydrogen energy storage can be considered the most promising energy storage technology [2]. Like electricity, hydrogen can be produced from renewable or non-renewable sources and can have a wide range of environmental impacts. Among those classified as renewable, water electrolysis is considered the best mechanism for hydrogen production due to its high sustainability with low or no harmful emissions [3], [4].

Using DC current, a water molecule can be broken into hydrogen and oxygen. This process occurs inside an electrolyzer which consists of two electrodes and an electrolyte. Depending on the characteristics of the electrolyte, three different types of electrolyzers exist: alkaline, proton exchange membrane (PEM), and solid oxide (SOE) [2].

Due to its high maturity and economical costs, alkaline electrolysis is the most commonly used technology to produce hydrogen using water [5]. Even though the technology is already advanced, many challenges still exist, primarily in efficiencies, overall system design, and range of operation. Simulation is essentially important to further analyze these issues.

Hydrogen energy is a clean fuel and only generates water when used in fuel cells. It can be used as a fuel/energy source thanks to its high energy content per weight. Hydrogen energy does not exist by itself and must be extracted from the compounds that compose

it, especially from water, coal, methane sources, and biomass [6]. Many renewable energy resources can be used to generate green hydrogen, such as solar, wind, biomass, and geothermal. In fact, green hydrogen generation by wind-produced electricity through the electrolysis process is receiving more attention thanks to its simplest approach, lowest greenhouse gas emissions among all hydrogen generation resources, and cheapest as wind-produced electricity has the lowest cost per kilowatt-hour compared to other renewable energy sources [7].

A feasibility study was conducted on using six renewable energy sources, including wind energy, to produce hydrogen [8]. The results showed that the most performing source for hydrogen production is wind. Another study was also conducted by [9] to study the efficiency of using surplus energy generated from solar photovoltaic energy and wind energy to generate green hydrogen. It has been found that green hydrogen is generated by excess energy. A technical and economic analysis study was conducted by [10] to estimate the hydrogen generation and cost rate of a hybrid system of solar and wind energy with ocean heat for power generation and hydrogen production. It is found that wind speed and solar collector area are the main factors affecting the overall cost and energy performance. Emissions from vehicles and industries are the main sources of air pollution. Thus, using clean energy to fuel vehicles can reduce greenhouse gas emissions and improve air quality. The current chapter aims to estimate green hydrogen generation. This chapter also highlights the importance of using green hydrogen to fuel vehicles.

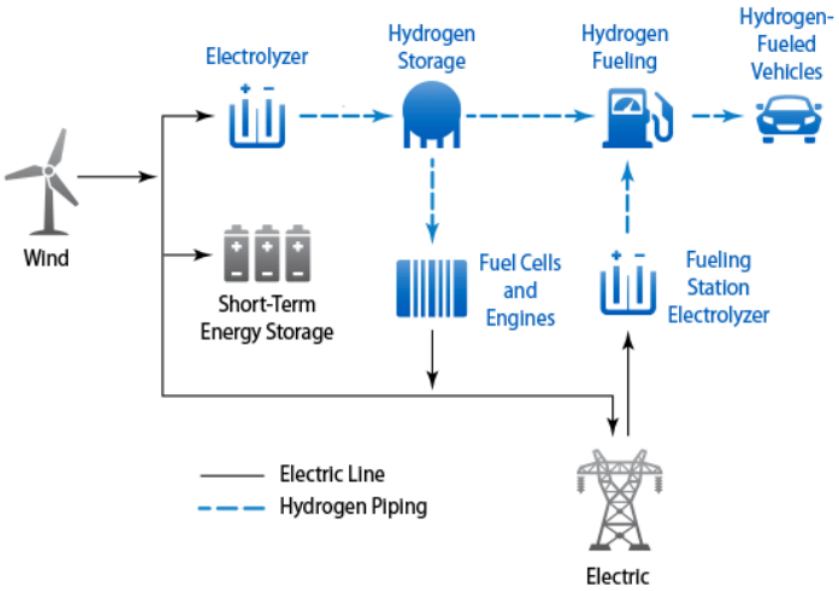


Figure 1.1: Hydrogen extraction by wind system with storage

1.2 Hydrogen

1.2.1 History

The most prevalent element in the universe, hydrogen, has gained attention as a potential solution to the world's energy and environmental problems. Hydrogen technology has made great strides throughout history, transitioning from a purely scientific curiosity to an important actor in the quest for a sustainable energy future. When Swiss alchemist Paracelsus first spoke of hydrogen gas in the early 16th century, the history of hydrogen as a source of energy began. However, it wasn't until the latter half of the 18th century that hydrogen's potential started to be recognized, owing to the groundbreaking work of English scientist Henry Cavendish, who separated and identified hydrogen as a unique element.

By the 20th century, hydrogen technology had made considerable strides. Sir William Grove developed the fuel cell concept in the early 1800s, laying the foundation for using hydrogen in electricity production. Later innovations in the mid-20th century advanced hydrogen technology significantly, such as the creation of the Proton Exchange Membrane (PEM) fuel cell by researchers at General Electric and the National Aeronautics and Space Administration (NASA). The space industry adopted fuel cells as a clean and reliable energy source for spacecraft, demonstrating the practicality of hydrogen-based energy systems.

Recently, there has been a resurgence of interest in hydrogen technology due to the urgent need to address climate change and transition to a low-carbon economy. Its potential to decarbonize various industries, including transportation, manufacturing, and electricity generation, has been acknowledged by governments, businesses, and researchers worldwide. The concept of "green hydrogen," produced through electrolysis powered by renewable energy sources, has gained popularity as a clean and sustainable alternative to traditional fossil fuels. Significant improvements have been made in fuel cell efficiency, robustness, and cost reduction over the course of hydrogen technology development. Additionally, advanced electrolyzer technologies have been developed for efficient hydrogen production.

By understanding the historical context and ongoing progress of hydrogen technology, we can appreciate the current state of the sector and the immense potential it offers for a sustainable energy future.

1.2.2 Definition

The hydrogen atom is composed of one proton and one electron, making it the lightest element in the universe, and having unique properties like high energy density (120 MJ/kg) and lower volumetric energy density (8 MJ/L). However, it is not readily available directly on the earth; it is available in chemically combined forms of water, fossil fuels, and biomass. Hence, the main challenge is to separate hydrogen from the naturally occurring compounds efficiently and economically.

1.2.3 Different Colors of Hydrogen

Producing hydrogen can be done in a number of ways. These processes utilize different sources of hydrogen, with various technologies, costs, and environmental impacts attached. The hydrogen is color-coded to easily distinguish between the differing methods [11]. Hydrogen is classified into different color shades, i.e., blue, gray, brown, black, and green, respectively, based on their hydrogen production technology, energy source, and environmental impact [11, 12], as shown in Figure 1.2.

Hydrogen Color	Technology	Source	Products	Cost ($ kg/H_2)	CO_2 emissions
Brown Hydrogen	Gasification	Brown coal (Lignite)	$H_2 + CO_2$	1.2–2.1	High
Black Hydrogen	Gasification	Black coal (Bituminous)	$H_2 + CO_2$	1.2–2.1	High
Grey Hydrogen	Reforming	Natural gas	$H_2 + CO_2$ (Released)	1–2.1	Medium
Blue Hydrogen	Reforming + carbon capture	Natural gas	$H_2 + CO_2$ (Captured 85-95%)	1.5–2.9	Low
Green Hydrogen	Electrolysis	Water	$H_2 + O_2$	3.6–5.8	Minimal

Figure 1.2: Hydrogen color shades and their Technology, cost, and CO2 emissions

1.2.3.1 Brown Hydrogen

Brown hydrogen is extracted from coal. This process of producing hydrogen is called coal gasification. Coal is heated up before a controlled stream of oxygen is added. This produces a mixture of hydrogen, carbon monoxide, and carbon dioxide. Water reacts with the carbon monoxide, resulting in more hydrogen and carbon dioxide being produced. Separation of the gases allows for pure hydrogen to be extracted on demand [11]. Nineteen tonnes of CO_2 is released into the atmosphere for every tonne of hydrogen produced, making this a highly pollutive process. Largely due to China's abundance of coal, brown hydrogen makes up 23% of worldwide production. At the same time, brown hydrogen

is amongst the cheapest methods to produce hydrogen. The costs of producing brown hydrogen are as low as 1.3 euro per kilogram of hydrogen [11, 12].

1.2.3.2 Grey Hydrogen

Grey hydrogen refers to hydrogen that has been produced from natural gas. In 2019, grey hydrogen made up 76% of total worldwide hydrogen production [5]. Grey hydrogen production is divided between three main methods. One of the methods is production by Steam Methane Reforming, SMR, where water acts as both the oxidizing agent as well as the source in which hydrogen is being extracted from. The second method for production is by Partial Oxidation, POX, where oxygen is extracted from the air to be used as an oxidizer. Lastly, there is Autothermal Reforming, ATR, a combination of the two aforementioned methods. SMR is the dominant method of producing hydrogen from natural gas, although some plants utilize ATR [1]. An average of 10 tonnes of CO_2 is released for every tonne of hydrogen produced. As grey hydrogen makes up the majority of worldwide production, the hydrogen industry as a whole is a sizeable emitter of climate gases. The cost of producing grey hydrogen, excluding carbon tax, is 1.5(euro/kg) [1, 5]. More than two-thirds of the cost is due to the cost of natural gas [1, 5].

1.2.3.3 Blue Hydrogen

Blue hydrogen is seen as a stepping stone between hydrogen production based on fossil fuels and green hydrogen. Blue hydrogen is produced by extracting the hydrogen from fossil fuels, before capturing the released gases. Carbon Capture and Storage (CCS) technology captures the carbon that would otherwise have been released. This carbon is then stored underground, or used in industry [1]. As discussed, the vast majority of hydrogen is produced from fossil sources, most notably natural gas. In the process of decreasing the world's dependency on fossil fuels, blue hydrogen may be a part of the solution. Production of blue hydrogen allows for a continued extraction of natural gas, but with the benefit of a significant reduction in accompanying climate gas emissions. Up to 90% of the related emissions can be removed when CCS is applied to brown and gray hydrogen production [1]. Hydrogen production presents an attractive opportunity for utilizing CCS technologies. Including CCS in the production chain increases production costs; however, these increases are relatively small. Especially brown hydrogen production allows for CCS integration with minor impact in terms of efficiency losses and cost increases [1].

Applying CCS to brown and grey hydrogen production increases the cost from 1.3 to 1.6 euro/kg, and 1.4 to 2 euro/kg, respectively. In a low-carbon economy, blue hydrogen will remain as the most cost-effective method in the near term [1, 5].

1.2.3.4 Green Hydrogen

Green hydrogen refers to hydrogen production fueled solely by renewable energy, mainly wind, solar, and hydro. This minimizes the emission of climate gases, thereby reducing its climate footprint. Currently, less than 100,000 tonnes of the 70 million tonnes of total dedicated hydrogen production stem from renewable sources [13,14]. Access to renewable energy is the largest limitation in green hydrogen production. Challenges in maintaining a steady supply and the increased cost accompanying renewable energy lead to an increase in the hydrogen production costs. The European Commission estimates green hydrogen to cost between 2.5 and 5.5 euro/kg [5]. This is expected to be reduced in the near future due to factors such as technological developments, economies of scale, and incentive programs. Estimated retail prices for liquid hydrogen range from 7.1 to 14 euro/kg. Prior to closing down, HYOP, a Norwegian hydrogen distributor, operated with a hydrogen price around 9 euro/kg [15–17].

1.3 Green Hydrogen

1.3.1 Definition

Green hydrogen is produced through the process of electrolysis, which involves the separation of water molecules into their constituent hydrogen and oxygen atoms using electricity [18]. When the electricity used in the process is generated from renewable sources, such as wind or solar power, the resulting hydrogen is known as green hydrogen. Unlike traditional hydrogen production, which is often derived from fossil fuels such as natural gas, green hydrogen offers a much cleaner and more sustainable alternative . Green hydrogen has a wide range of potential applications, ranging from transportation and power generation to industrial processes such as steel and cement production. In the transportation sector, green hydrogen can be used to power fuel cell vehicles, which have the potential to offer a zero-emissions alternative to traditional fossil fuel vehicles. In the power generation sector, green hydrogen can be used to generate electricity through fuel cells, which convert hydrogen into electricity without producing any harmful emissions . This has the potential to revolutionize the power industry, which is currently heavily reliant on fossil fuels. One of the key benefits of green hydrogen is its ability to reduce greenhouse gas emissions . When hydrogen is produced using renewable energy sources, it is a zero-emissions fuel, meaning that it does not produce any harmful pollutants when burned. This makes it an ideal alternative to traditional fossil fuels, which are a major contributor to greenhouse gas emissions and the resulting climate change. The use of

green hydrogen in transportation, power generation, and industrial processes could therefore significantly reduce the carbon footprint of these sectors and help to mitigate the effects of climate change. Another benefit of green hydrogen is its ability to enhance energy security . As a clean and renewable fuel, green hydrogen offers a more secure energy supply than traditional fossil fuels, which are subject to fluctuations in price and supply. The use of green hydrogen could therefore reduce our dependence on imported fossil fuels, enhance energy independence, and promote greater energy security [19].

1.3.2 Hydrogen Production

Hydrogen can be produced from various sources of raw materials, including renewable and non-renewable sources, totaling around 87 million tons/year [**?**]. However, as of 2020, most of the hydrogen (95%) was produced from non-renewable fossil fuels, especially steam reforming of natural gas, emitting 830 million tons/year of CO_2, while the rest of the hydrogen was produced from renewable resources, including water electrolysis [20]. The major hydrogen production methods and their applications are shown in Figure 1.3.

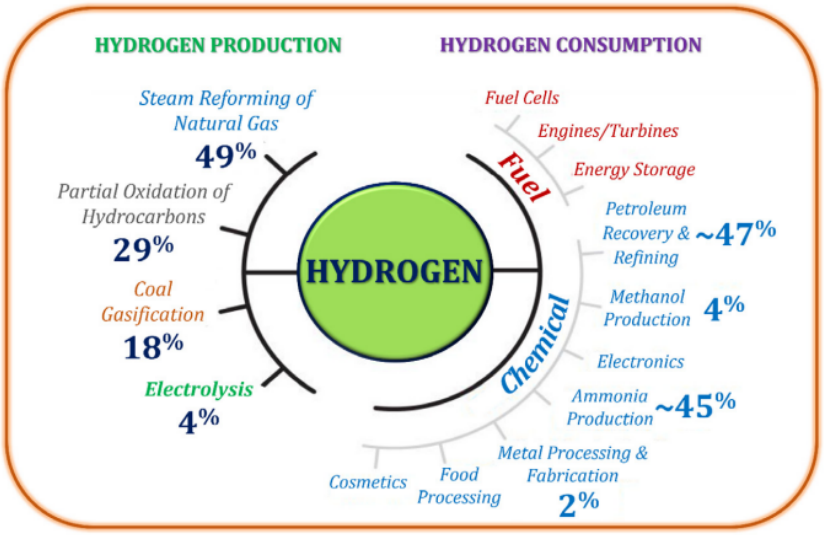


Figure 1.3: Major hydrogen production methods and applications [3]

Electrolysis is considered a promising and carbon-free technology for hydrogen generation from renewable resources. In this technology, a direct current supplied by a power source is used to split the water into hydrogen and oxygen in a unit known as an electrolyzer. Water electrolysis for hydrogen generation is an excellent solution to mitigate the intermittency of renewable energy. The hydrogen generation by water electrolysis powered by renewable resources has an efficiency of 80%-90% [7]. The amount of renewable

hydrogen produced by wind energy is shown in the following equation:

$$h = \frac{\eta_{el} E_{out}}{ec_{el}} \tag{1.1}$$

where:

h is the amount of hydrogen generated.

E_{out} is the wind electricity input to the electrolysis.

η_{el} is the electrolysis efficiency and it ranges between 80% and 90%.

ec_{el} is the electrolysis energy consumption.

1.3.3 Properties of Hydrogen

In addition to being a potential emission-free energy carrier, hydrogen also possesses several other favourable properties, with the main one being its high energy density. Compared to other fuels such as gasoline and diesel, hydrogen is able to deliver nearly three times the energy content per kg, 33 KWh/kg versus 13 KWh/kg for gasoline [21]. On a volumetric basis however, the situation shifts. Hydrogen is a gas with very low volumetric energy density at standard temperature and pressure (STP), and must be processed in order to increase its volumetric density. There are several ways of doing this, with the two most common methods being by liquefaction or compression. The processing increases the volumetric density, but comes at a significant cost. From Table1.1, the importance of hydrogen processing becomes obvious. The difference in volumetric density of hydrogen at atmospheric pressure (1 bar), to compressed (700 bar) and liquid is substantial, and increases the density by a factor of 593 and 790 respectively [22].

Table 1.1: Overview of specific and volumetric energy density

Technology	**KWh/kg**	**MWh/m³**
Li-ion battery	0.19	0.56
Hydrogen, 1 bar	33	0.0027
Hydrogen, 700 bar	33	1.6
Gasoline	13	9
Diesel	13	10

[23]

1.3.4 Hydrogen Storage

The energy density of hydrogen must be increased in order for it to be of any practical use. To increase the density, work must be applied to either compress the gas, reduce the

temperature below the critical point, or by chemically bonding hydrogen with another material [22]. The storage process is in many cases considered to be the bottleneck for the hydrogen production industry . There are various hydrogen storage technologies available in today's market, where the two leading technologies are compressed and liquid hydrogen. Other methods of storage include ammonia (NH_3), liquid organic carriers, and metal hydrides. Storage in metal hydrides will not be included, as the technology needs further research and development in order to be considered a viable option. The common denominator for every method of hydrogen storage is a substantial expenditure of energy in the storage process. This is of concern in terms of the overall efficiency of hydrogen as an energy carrier as well as a potential economic barrier .

1.3.4.1 Compressed Hydrogen

The most common and widely used method for storing hydrogen today is by compression. This is typically done with standard, piston-type mechanical compressors . By using several compressors in a step-wise manner, it is possible to get the compression as close to ideal and isothermal as possible to achieve higher efficiency, thus reducing the amount of work required for compression. The pressure of compressed hydrogen at ambient temperature ranges between 35-70 bar, where 70 bar is considered to be the top performing technology for compressed gaseous hydrogen, or CGH2 . At these levels of pressure, the CGH2 is able to meet the market requirements in terms of energy density [24]. CGH2 is the most mature technology for storing hydrogen and has the advantage of a simple treatment process, high applicability, and low cost. However, the biggest weakness of CGH2 is its low volumetric density, which makes CGH2 less popular in practice [25]. When dealing with pressurized hydrogen, the abilities and design of the storage vessels are highly important. There are several ways of storing CGH2. For large grid-based production sites, using old salt mines and underground caverns offers a cheap and reliable solution. Another option is to use cylindrical storage units. These storage tanks can be modified in terms of volume, weight, and strength (ability to withstand high pressure) to meet market/manufacturer demands. There are four different types of pressure vessels available in today's market. Each one is made up of different materials which determine the individual vessel's characteristics . The storage vessels range from low-cost, metallic tanks to expensive, fully composite, carbon fiber, polymer vessels [24]. The compression of hydrogen requires work, and it is useful to compare this work to the specific energy content of hydrogen, which is 33 kWh/kg. In this context, around 10% of the total energy available in the hydrogen is spent on compression, which is an irreversible loss . The compression increases the density by a factor of around 200. In addition to the energy lost by

compression, another concerning aspect is the so-called hydrogen embrittlement, which is a phenomenon where hydrogen dissolves in the metal of the storage unit and causes deterioration in the form of corrosion, cracks, and a reduced load-bearing capability in the units [26].

1.3.4.2 Liquid Hydrogen

The other storage method considered to be well-matured and commercially available is storage by liquefaction. To obtain hydrogen in its liquid form (LH2), cooling is required. Liquefaction usually occurs at the critical temperature of 20K (-253 degrees Celsius) at 1 atm pressure. Operating at such low temperatures is energy-consuming. The liquefaction process has an energy requirement of around 10-15 kWh/kg, which is equivalent to about 40% of the energy content stored in the produced hydrogen . This is a substantial amount compared to that of the CGH2 at around 10%. The main advantage of liquid hydrogen is the high energy density, about 1.6 times higher than the CGH2 [27]. Liquefaction is done through a multi-stage process that uses a series of refrigerants (often nitrogen) and several compression/expansion loops to convert the gaseous hydrogen to a liquid phase . The simplest liquefaction process is the Linde cycle, also known as the Joule-Thompson cycle. In this process, the gas is compressed at ambient pressure, then cooled in a heat exchanger, before it is passed through a throttle valve where an isenthalpic expansion results in the production of some liquid. The liquid is removed, before the process repeats until the conversion is complete . The storage of liquid hydrogen at temperatures around 20K is challenging and is highly demanding in terms of the technology and materials used for the storage vessels. Due to the large temperature difference between the LH2 and the ambient outside temperature, there is unavoidable thermal heat transfer occurring in the form of convection, conduction, and radiation. To minimize the losses, highly efficient, double-walled metallic containers covered with multiple layers of vacuum insulation are used in the storage vessels . The heat transfer into the storage unit will inevitably cause the liquid hydrogen to heat up and evaporate in what is known as the "boil-off," contributing to losses of between 0.3% and 3% per day as a result of hydrogen evaporation [25]. The advantage of liquefaction vs compression can be seen in Figure1.4 , where the density differences become clear in terms of storage volume required. As a rule of thumb, compressed hydrogen requires a storage area four times larger than liquid hydrogen [28].



Figure 1.4: Illustration of Liquid and compressed hydrogen storage tanks [29]

1.3.4.3 Liquid Organic Hydrogen Carrier

Another promising technology for storing hydrogen is by utilizing a liquid organic carrier (LOHC). The idea is to load and unload the organic compound with hydrogen in a chemically binding and cyclic procedure. The loading process, also known as hydrogenation, takes place at the hydrogen production site. This exothermic process is normally done at elevated pressures and temperatures, usually between 10-50 bar and 373 to 523K, depending on the compound that is being utilized. The endothermic unloading of hydrogen, the dehydrogenation, is typically done at ambient pressures and elevated temperatures, typically in the range of 5 to 10 bar and 423 to 673K . The fact that this is a cyclic process means that once the liquid carrier has been dehydrogenized, it can be recycled and returned to the spot of hydrogenation for reuse without having been consumed itself . There are several options in terms of the LOHC, and some of the most promising carriers are toluene, N-ethylcarbazole, dibenzyltoluene, as well as several other compounds. The carriers possess many similar traits to the ones found in well-known fossil fuel energy sources, such as diesel and gasoline. Some of these include a high energy density, the ability to be easily stored under ambient conditions without any substantial leakage or boil-off losses . Normally, these LOHCs have a capacity of storing 4-7 wt% of hydrogen . The fact that the LOHCs have several physical and chemical similarities with fossil fuels such as diesel means that the already existing infrastructure can be utilized when distributing and handling the LOHC, leading to a potentially less expensive and simpler

introduction of the technology. The main challenge for the LOHC is in the extraction of the stored hydrogen; the dehydrogenation. This endothermic process needs to be connected to an external heat source in order for the unloading to occur. Additionally, it is a rather slow process, taking up to 4 hours before the hydrogen can be extracted if the initial conditions are ambient [30].

1.3.4.4 Ammonia

Using ammonia (NH_3) as a liquid carrier for hydrogen storage is another interesting solution. Ammonia is in gaseous state at ambient pressure and temperature, but can be liquefied at 10 bar and room temperature, or by cooling to 240 K (-33°C) at atmospheric pressure (1 bar). This process is far less energy demanding than liquefying pure hydrogen [31], which needs to be cooled down to 20 K as previously mentioned. Ammonia is hydrogen-dense with about 17 wt% of hydrogen. This makes it an excellent hydrogen carrier, and in its liquid form, it is even more energy-dense than liquid hydrogen itself, with a volumetric hydrogen density about 45% higher than its counterpart. There are several methods of utilizing green hydrogen as a supplement to ammonia production. The most famous and widely used method is based on the Haber-Bosch principle. Gaseous H_2 is combined with pure nitrogen (N_2), which is extracted from the surrounding air (which naturally contains around 78% N_2), in a cryogenic process to form ammonia . For the reaction to occur, a temperature above 673 K (400°C) and pressures exceeding 200 bar are required. Such extreme operational conditions lead to the high costs of converting H_2 to ammonia . Many new and promising technologies for the production of ammonia are on the rise, and amongst these are the electroreduction of N_2 to NH_3. The electroreduction utilizes many of the same principles that are found in water electrolysis, such as water splitting at the anode into O_2, protons, and electrons. The protons flow through an ion-conducting membrane to the cathode. At the cathode is where the electroreduction process differs from that of the electrolytic cell. N_2 is fed to the cathodic department before being split by the use of a catalyst. The nitrogen then reacts with the proton and electron to form gaseous ammonia. The efficiencies can reach levels up to 70%, depending on the electrolyte of choice. There is, however, a dilemma in terms of efficiency vs. time consumption during production, which has proven to be the main challenge for this technology . How to efficiently make use of the end product, liquid ammonia, is another challenge. Today, most of the ammonia production is used for fertilization. There is also the possibility to burn ammonia directly for energy, or extract the stored hydrogen by "cracking" (at elevated temperatures of above 400°C) the ammonia, much similar to the dehydrogenation of LOHC. The only by-product from the combustion of ammonia is the

non-polluting N_2. The use of ammonia as a direct fuel has been gathering much attention in the past few years, particularly in the long-distance shipping industry [31].

1.3.5 Application of Hydrogen

As an energy carrier, hydrogen has a wide range of possible end-use applications that can be categorized as stationary, mobile, backup, or specificity. Some of the most promising include the following:

1.3.5.1 Enable Renewable Energy Integration

Using hydrogen for grid balancing is an interesting concept that revolves around a power-to-hydrogen conversion. By producing large amounts of hydrogen at times when the energy supplied from renewable sources surpasses the demand, it is possible to store energy that would otherwise be lost. The stored hydrogen can later be used to provide backup during energy deficits, thus offering the ability to adjust the energy output from renewable energy sources to accommodate demand. This can also help provide long-term seasonal flexibility in the energy sector .
Additionally, by shipping green hydrogen over longer distances, it allows for a global distribution of the stored renewable energy. This will become increasingly important with a growing share of renewable energy sources. Some countries do not have the ability to generate energy with wind or solar alone, and are dependent on imports to supply their needs. Others may not have the required resources needed to fund expensive renewable projects and will therefore need external supply. Furthermore, it can help bridge the gap between off-grid based energy production and the point of utilization by transportation of hydrogen, rather than electricity. This allows for a more flexible distribution network, without the need for grid connection .

1.3.5.2 Industry

It is expected that the first step of integrating green hydrogen will be in large industrial sectors, where hydrogen produced by fossil fuels has already been used for decades (refineries and ammonia production). Ammonia is used mainly as a fertilizer or for production of other chemicals, whereas refineries utilize hydrogen for the production of fuel from heavy oil . By replacing the fossil-fuel-based hydrogen with green hydrogen in these sectors, emissions of around 830 million tonnes of carbon dioxide per year would be avoided, equivalent to the CO2 emissions of the United Kingdom and Indonesia combined [32].

1.3.5.3 Transport

Fuel cell electric vehicles (FCEV) are expected to have an important role to play when it comes to decarbonizing the transportation sector, which today accounts for around 24% of the global CO2 emissions [33]. FCEVs offer many of the same abilities as conventional vehicles, such as the internal combustion engine vehicles (ICE). One of them is the ability to drive for longer distances without having to refuel—up to 500 km, as well as a short refueling time of only 3-5 minutes. The battery electric vehicle (BEV) is another interesting source of comparison to the FCEV.
Because of the high specific energy density of hydrogen compared to the Li-ion batteries, the FCEV can be considered as complementary to the BEVs as a low-carbon mobility option. FCEVs have the ability to reach high utility segments such as long-range and high-utilization vehicles like buses, trucks, trains, and ferries, which are areas where today's batteries are struggling to reach. The application of hydrogen, or hydrogen-based synthetic fuels, is also being heavily researched for use in shipping and aviation. Both are in the developing and demonstration stages but are showing promising signs of rapid development .

1.3.6 Advantages and Disadvantages of Hydrogen

1.3.6.1 Advantages

1. It does not emit greenhouse gases during its production or use, unlike fossil fuels.
2. It can be produced from renewable energy sources, through water electrolysis using solar or wind energy.
3. It can be used flexibly in a variety of applications including energy transmission, generation, and storage.
4. It can be used in vehicles powered by hydrogen, such as trains, ships, and planes, eliminating emissions of atmospheric pollutants in transport.
5. It can be used in fuel cells to generate electricity and be stored for future use.
6. It can be used as a raw material for the chemical, petrochemical, pharmaceutical, cement, and steel industries, replacing fossil fuels and reducing greenhouse gas emissions.

1.3.6.2 Disadvantages

1. It still has a high production cost when compared with other energy sources, mainly due to the low technological maturity involved in its production.

2. For its use as a substitute for fossil fuels, such as gasoline or diesel, the automobile industry would need to adapt to using hydrogen, in addition to having other options, such as the electric car, which could be used as an alternative.

3. The low density of hydrogen, whether in the liquid or gaseous state, also results in a low energy density. This indicates that hydrogen, in its pure form, is not a good means of transporting energy.

1.4 Electrolyzer

1.4.1 Water Electrolysis Technologies

Water electrolysis concerns the splitting of water molecules into oxygen and hydrogen. It can be divided into four different categories based on their electrolytes, ionic agents, operating conditions, and working principles. Some of the benefits of water electrolysis include high cell efficiency and a better rate of hydrogen production. The main technologies currently on the market are alkaline water electrolyzers and proton exchange membrane water electrolyzers. In particular, these technologies operate at low temperatures, making these devices suitable for pairing with intermittent wind or solar power sources, as they can operate with constant loads and can be turned on and off quite easily [34].

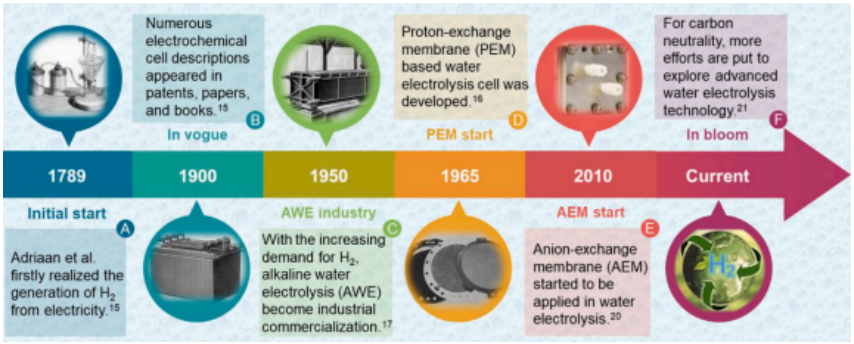


Figure 1.5: The timeline for developing low-temperature water electrolysis technology. Inset images reproduced with permission.

1.4.2 Types of Electrolyzer

1.4.2.1 Alkaline Water Electrolyzer

Currently, the most basic industrial process for producing nearly pure hydrogen is water electrolysis. Water electrolysis is based on the movement of electrons assisted by an external circuit.
Alkaline water electrolyzer (AWE) is a well-established method which works with a KOH-rich electrolyte without the expensive platinum catalyst. [34]

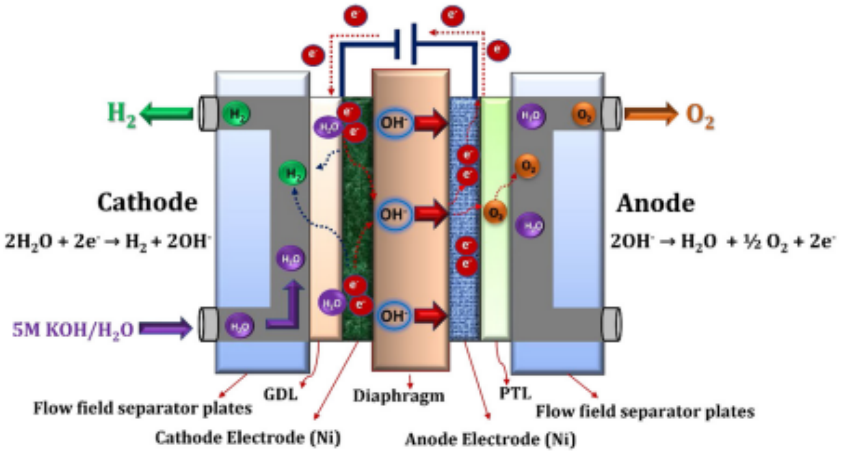


Figure 1.6: Schematic illustration of alkaline water electrolysis working principle.

Anion Exchange Membrane Water Electrolyzer (AEM-WE) is a type of AWE that works with a solid polymer membrane instead of a liquid electrolyte (KOH), having the same chemical processes as shown below: [34]

$$\text{Anode:} \quad 4OH^- \rightarrow O_2 + 2H_2O + 4e^- \tag{1.2}$$

$$\text{Cathode:} \quad 4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \tag{1.3}$$

$$\text{Overall:} \quad 2H_2O \rightarrow 2H_2 + O_2 \tag{1.4}$$

In the case of AWE, two molecules of the alkaline solution, usually KOH or NaOH, are reduced to one hydrogen molecule on the cathode chamber and two hydroxyl ions are produced. H2 produces precipitate from the surface of the cathode to recombine as a gas while the hydroxyl ions are transported under the action of an electrical circuit between the anode and cathode through the porous diaphragm to the anode where they are discharged into half oxygen molecule and one molecule of water. O2 recombines on the electrode surface and escapes as hydrogen. Alkaline electrolysis operates at lower

temperatures, such as 30-80°C, and with an electrolyte concentration of 20 - 30%.
In addition, asbestos diaphragms and nickel materials as electrodes are used. The diaphragm is located in the center of the cell and separates the two chambers and the gas produced by the respective electrodes, avoiding any mixing. The disadvantages of alkaline electrolysis are the limited current density below 400 mA/cm^2, the low operating pressure, and the low energy efficiency. [34]
The general specifications about this technology are reported in Table 1.2: General specifications of Alkaline electrolysis.

Table 1.2: General specifications of Alkaline electrolysis

Specification	Alkaline	Unit
Technology maturity	State of art	-
Cell temperature	60-80	°C
Cell pressure	<30	bar
Current density	0.2-0.4	A/cm^2
Cell voltage	1.8-2.4	V
Power density	Up to 1.0	kW/cm^2
Voltage efficiency	62-82	%
Specific energy consumption	4.5-7	kWh/Nm^3
Hydrogen production	<760	Nm^3/hr
Stack lifetime	<90,000	hr
System lifetime	20-30	yr
Hydrogen purity	>99.8	%
Cold start-up time	15	min

1.4.2.2 Proton Exchange Membrane Water Electrolyzer

The first method of water electrolysis using a proton exchange membrane (PEM) was idealized by Grubb in the early 1950s and developed by General Electric Co. in 1966 to overcome the disadvantages of alkaline water electrolysis . PEM water electrolyzer (PEM-WE) uses a solid polysulfonated membrane such as Nafion®, Fumapem®, as the electrolyte . These proton exchange membranes have numerous benefits such as lower gas permeability, high proton conductivity, lower thickness, and high-pressure operation. Furthermore, PEM water electrolysis has great advantages such as compact design, high current density, high efficiency,fast response, small area, and lower temperature operation. It also generates high-purity hydrogen as well as oxygen as a by-product. All these positive features have made PEM technology dominant in the market.

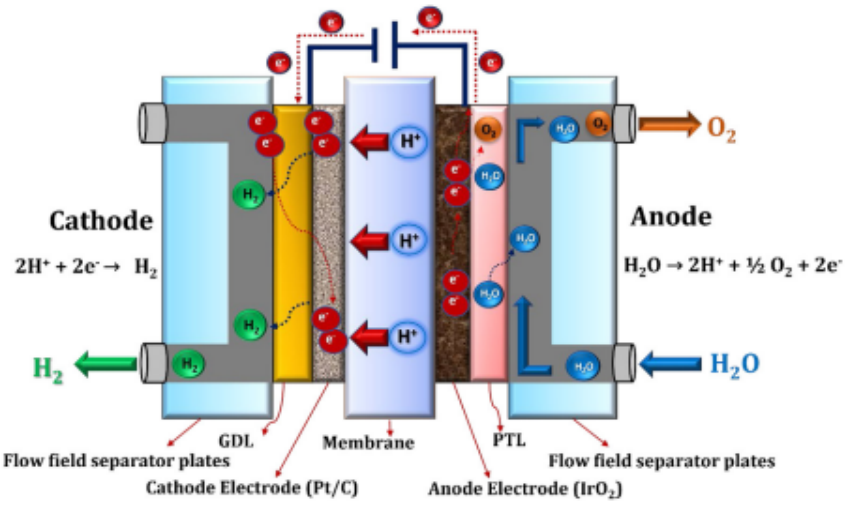


Figure 1.7: Schematic view of PEM water electrolysis working principle.

Electrolytic catalysts, such as platinum and palladium, are exceptionally reactive noble metals used to generate hydrogen (HER) at the cathode, while iridium oxide and ruthenium oxide generate oxygen (OER) at the cathode. PEM technology uses an electrocatalyst from rare elements found mainly in South Africa and Russia, the main consequence of which are the high associated costs and their unpredictable fluctuations. [34] In addition, PEM-WE is based on fluorine-based polymers that have a high environmental impact due to fluorocarbon emissions [34] . The working principle of the PEM-WE, as shown in Figure 1.7, consists of two electrodes, one solid electrolyte (membrane), circulating deionized water and a power supply The membrane transports ionic charges and separates the electrolysis products to prevent recombination into water. The electrolysis process also requires electrical energy through a potential difference between the electrodes. During electrolysis, the following half-cell reactions take place for the anode and cathode in formulas1.5,1.6 respectively.

$$Anode : H_2O(l) = \frac{1}{2}O_2(g) + 2H_2(g) + 2e^- \tag{1.5}$$

$$Cathode : 2H^+(aq) + 2e^- = H_2(g) \tag{1.6}$$

$$Overall : 2H_2O = \frac{1}{2}O_2(g) + H_2(g) \tag{1.7}$$

All the characteristics of the PEM water electrolyzer are reported in the following table:

Table 1.3: Characteristics of the PEM water electrolyzer

Specification	PEM	Unit
Technology maturity	Demonstration	-
Cell temperature	50-80	°C
Cell pressure	<30	bar
Current density	0.6-2	A/cm^2
Cell voltage	1.8-2.2	V
Power density	Up to 4.4	kW/cm^2
Voltage efficiency	67-82	%
Specific energy consumption	4.5-7	kWh/Nm^3
Hydrogen production	<30	Nm^3/hr
Stack lifetime	<20,000	hr
System lifetime	<15	yr
Hydrogen purity	99.99	%
Cold start-up time	<15	min

1.4.2.3 Anion Exchange Membrane Electrolyzer

Anion exchange membrane water electrolyzer (AEM-WE) could be a technology able to combine the advantages of alkaline water electrolyzers and proton exchange membrane water electrolyzers [34]. The essential difference between these two methods is that the electrode separator used in AWE technology has no intrinsic ionic conductivity that is provided by KOH which fills the pores of the separator. In AEM-WE, a polymeric membrane is non-porous and inherently anionic conductive. Most of the AEM-WE studies are currently restarting to dilute the KOH electrolyte carrier to achieve high efficiency [34]. Moreover, AEM-WE is more efficient than AWE and is capable of operating in high pH environments without platinum group metals or critical raw materials and without alkaline electrolytes [34].

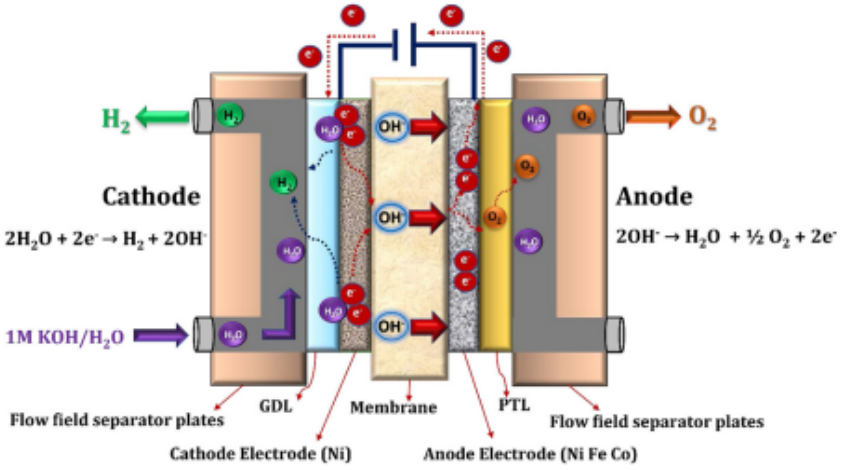


Figure 1.8: Schematic view of AEM water electrolysis working principle.

Summarizing the advantages of this new technology over AWE and PEM electrolyzers, it can be seen that the current density used is higher due to its lower ohmic resistance and thus a smaller volumetric footprint; the device enables the electrochemical pressurized hydrogen process, which facilitates its subsequent storage, distribution, and ultimate use; non-porous membrane increases the safety of the whole device. Besides, AEM-WE shows a reduced reliance on critical raw materials and the smallest footprint over the product lifecycle. The AEM-WE cells operate by using a hydrocarbon anion exchange membrane and two electrodes. To enhance the conductivity, a low-concentration alkaline solution or distilled water can be employed as the electrolyte in the AEM-WE, as an alternative to the concentrated KOH solution.

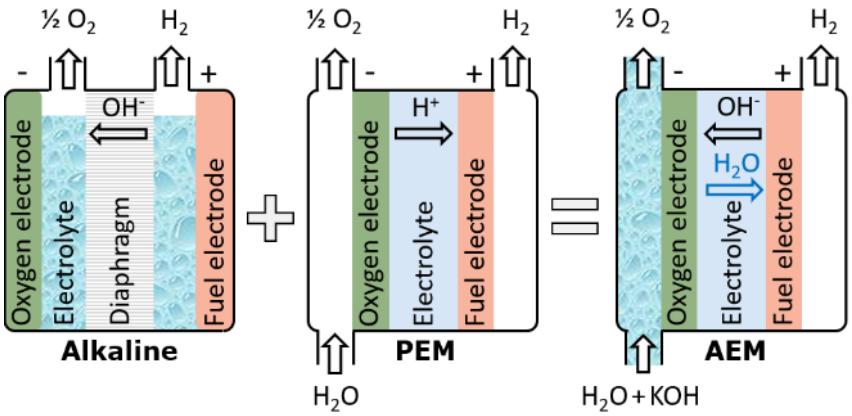


Figure 1.9: Anion Exchange Membrane Electrolyzer

An external power supply is connected to both sides providing a direct current supply. The overall reaction is made by two half-cell reactions that occur in the anode and

the cathode: the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER). The AEM-WE cell operates by circulating water through the cathode side, where it undergoes reduction to form hydrogen and hydroxyl ions by accepting two electrons. The hydroxyl ions then move through the anion exchange membrane to the anode section due to the positive attraction of the anode, while the electrons travel to the anode through the external circuit. In the anode chamber, the hydroxyl ions combine to form water and oxygen by giving up electrons. Oxygen is produced as bubbles and released from the anode surface. Both the cathode and anode reactions require a catalytic activity for the formation and release of the respective gases from the electrode surfaces.

Components of AEM-WE:

- **Membrane electrode assembly (MEA):** This consists of a solid electrolyte (AEM) that facilitates both the OER and HER reactions by improving their kinetics, as well as anode and cathode catalyst layers and an ionomer that help establish connections between the membrane and the reaction sites in the catalyst layer.
- **Gas diffusion layer:** This layer is present at both the cathode and anode sides and conducts electricity, water, heat, and gas. The surface of the layer at the anode side is hydrophilic to facilitate water uptake, while the cathode side is hydrophobic to enable water removal.
- **Bipolar plates:** These plates separate each cell in the electrolyzer stack and are equipped with channels for the circulation of water. [35]

Overall, the obtained results suggest the potential of the PA-$SiNH_2$ membrane in an anion exchange membrane water electrolyzer system. [36]

1.5 Wind Energy

1.5.1 Theory

This section of the thesis will present all relevant information related to the thesis. The necessary theoretical background will be established, laying the foundation for understanding the challenges and opportunities related to large-scale green hydrogen production.

1.5.2 Energy From Wind

Wind power is defined as the extraction of mechanical or electrical energy from wind. A growing population, accompanied with an increasing energy demand, poses supply challenges in the energy sector. Wind power is part of the solution in supplying green energy for use in households as well as in the industry. This section will put forward the developments in wind energy technology and economics, establishing its feasibility and role related to green hydrogen production.

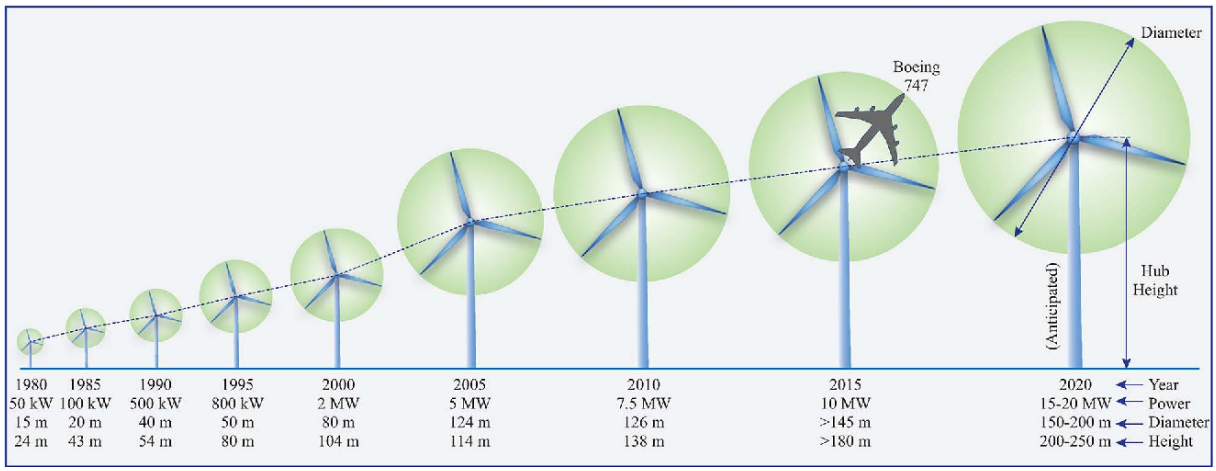


Figure 1.10: The increase of average rotor diameter and capacity

1.5.2.1 Technological Developments

Technological advances have drastically improved onshore wind turbines over the last decades. The turbines which are being deployed today are larger and more efficient than previous models. Innovations and growing competition among producers are pushing prices down. The developments in the physical size of the turbines contribute to decreasing costs. illustrates the average sizes and capacities of onshore wind turbines over the last ten years. As illustrated, both the average nameplate capacity and rotor diameter of onshore wind turbines are increasing. In combination with decreasing installation costs, and a more mature supply chain, these innovations are causing wind energy to be able to compete with traditional energy sources such as coal and nuclear energy. Wind power is a stochastic energy source whose output is unpredictable and changes over time. Wind power depends on wind speed, which can change rapidly. This sets it apart from traditional energy sources such as coal, natural gas, and nuclear power for more stable and controllable performance.

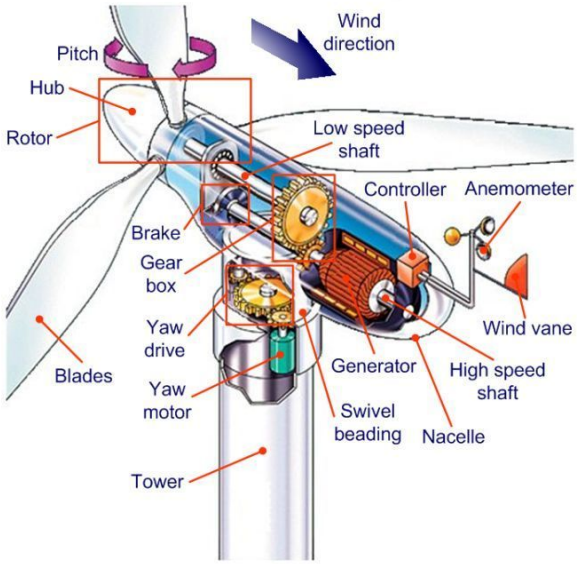


Figure 1.11: Wind turbine

Nevertheless, wind energy has grown rapidly since 2000, driven by research and development, policy support, and falling costs. According to IRENA data,as reported in 1.12.

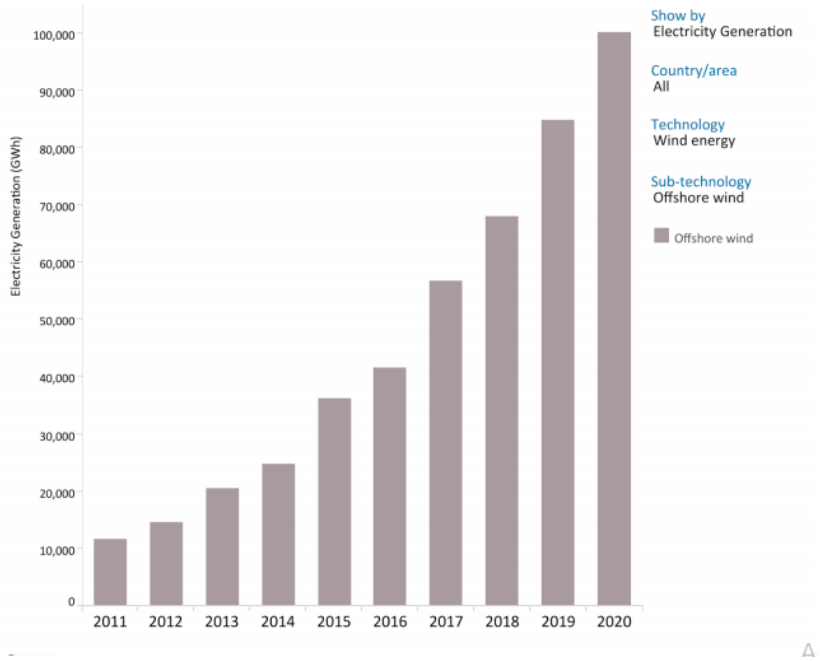


Figure 1.12: Electricity Generation Trends - IRENA [37]

The advantages of wind power:

- Very clean form of energy.
- Sustainable method of power generation.
- No complex maintenance necessary.
- Wind as a free resource.
- Reduced energy costs for whole countries.
- Wind power makes self-sufficiency possible.
- Creation of numerous jobs.

The disadvantages of wind power:

- Visual landscape impairment.
- Negative impact on wildlife.
- High noise level.
- Hidden costs.
- Unsteady wind.
- Difficulty in finding suitable areas.

1.5.3 Coupling with the Electrolyzer

For PEM, AEM, and alkaline cells, the only input energy required is electrical energy, which can be sourced from renewable resources such as wind power plants. Integrating wind power plants with electrolysis has several advantages, as the electrolysis process is the best option because it can produce hydrogen with high concentration, whereas the purity of hydrogen produced by fossil fuels is low. The optimal scenario for the electrolyzer would be to maintain rated power while tolerating power fluctuations between 0-100%. With improvements in technology, the minimum operation power of alkaline electrolyzers has been restricted to be from 5% to 10% of the total electric power, and its regulation speed has improved to milliseconds, making it more appropriate for large-scale wind-hydrogen coupling systems. A significant issue with using wind turbine-electrolyzer systems is the fluctuation in wind speed, which results in fluctuations in power output. This can lead to

the deterioration of the electrolyzer and reduced efficiency due to thermal management issues. To mitigate these problems, various control strategies have been suggested, such as using smaller electrolyzers that operate at their full load condition to produce more hydrogen or using smaller wind turbines in areas with lower wind speeds. Furthermore, since the nominal size of wind turbines is often higher than that of the electrolyzer, excess power may be produced and cannot be used by the electrolyzer. To optimize the system, the design should aim for the highest hydrogen production with the lowest amount of unused power.

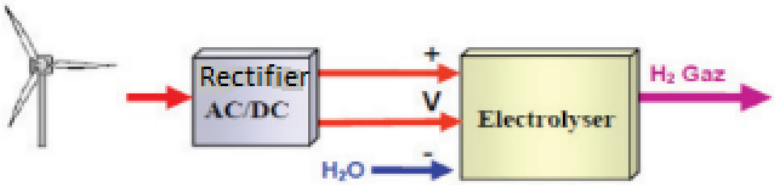


Figure 1.13: Wind hydrogen system production

1.6 Conclusion

In this chapter we propose the use of renewable energy as an alternative to fossil fuels, which are limited and contribute to pollution. On the other hand, renewable energy sources are endless and do not produce any pollution during their operation. However, renewable energy sources also have limitations that hinder their use. They are only available in certain locations and some, such as wind and solar, are intermittent and cannot provide a constant supply of energy. To overcome these problems, renewable energy sources can be modified by integrating them with hydrogen production systems. Hydrogen has many advantages over other energy carriers, including the fact that it does not produce pollutants and can be produced from a variety of raw materials, making it a limitless renewable resource. It also has the ability to store and transport, thus meeting the challenges associated with renewable energy sources. Green hydrogen is a promising and widely available source of renewable energy that requires large-scale investment. To learn more, we will discuss modeling , which will give us the opportunity to expand further.

Chapter 2

Modeling systems

2.1 Introduction

In this chapter, it is necessary to describe and represent practical systems mathematically, even if that is also the case difficult, in order to identify their characteristics so that appropriate control can be designed. The aim This section aims to explain green hydrogen extraction by wind systems and derive its mathematical models . These mathematical expressions developed in this chapter are the basics of control design,Modeling of the entire system. This chapter begins with explorations Modeling synchronous generators for correct representation of the system, then Modeling and mathematical representation of the Electrolyzer. Moreover, mathematical representation From the Electrolyzer.

2.2 Modeling the wind conversion chain

Wind is the reason for wind turbines. The kinetic energy contained in the wind is partly transformed into mechanical energy by the turbine, then into electrical energy by the generator it is therefore an important variable to model because the precision of the simulations will depend on the quality of its model. The geographical choice of a wind site is essential in an energy production project. The characteristics of the wind will determine the quantity of energy that can actually be extracted from the wind source. Much work on wind modeling has been carried out. One of the principles retained consists of generating the temporal pattern of the wind from white noise to which a transfer function to be determined is applied. The wind turbine is a three-dimensional element with complex shapes, in motion, and immersed in an air flow. However, and this is an important point, the model in question must describe the actual mechanical dynamics of the rotor blades, and not just the quasi-static behavior. A wind turbine rotor converts the energy of the

moving air mass and delivers mechanical power characterized by the rotational speed and mechanical torque.

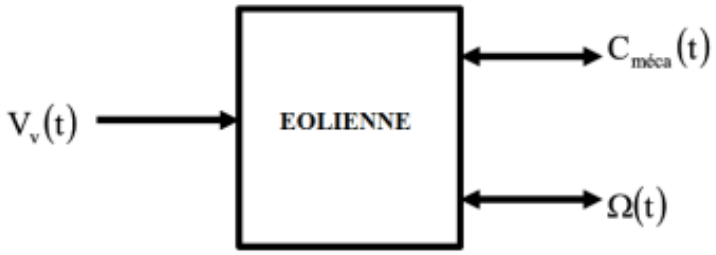


Figure 2.1: The wind conversion chain

Physical Modeling of the Wind Turbine

The wind turbine is a three-dimensional element with complex shapes, in motion, and immersed in an airflow. The model must accurately describe the mechanical dynamics of the blade, including its motion and interaction with the airflow. A wind blade converts the energy of the moving air mass into mechanical power, characterized by the rotation speed and the mechanical torque.

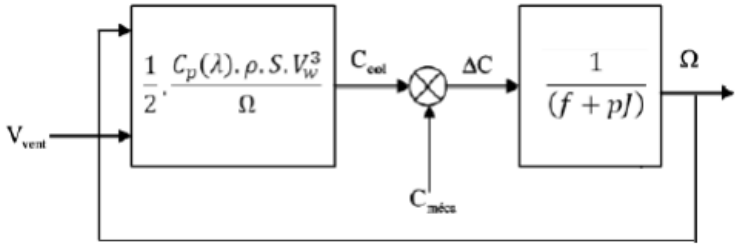


Figure 2.2: Wind turbine dynamic model

The mechanical power P_m available on the shaft of a wind generator is expressed as follows:

$$P_m = \frac{P_m}{P_v} \cdot P_v = C_p(\lambda) \cdot P_v = \frac{1}{2} \cdot C_p(\lambda) \cdot \rho\pi R^2 V_v^3 \tag{2.1}$$

The power extracted by a wind turbine is given by the following relationship:

$$P_{eol} = \frac{1}{2} \cdot C_p(\lambda) \cdot \rho S V_W^3 \tag{2.2}$$

Where

C_p is the power coefficient, which is a function of the specific speed λ. λ is the specific

speed, representing the ratio between the linear speed at the tip of a blade and the wind speed, given by $\lambda = \frac{\Omega}{w}$.

ρ is the wind density in [Kg/m^3].

S is the area swept by the wind turbine blades [m^2].

Ω is the angular mechanical speed of the wind turbine rotor [rad/s].

V_w is the wind speed [m/s].

R is the radius of a turbine blade [m]. Several numerical approximations have been developed in the literature to determine an expression for the C_p coefficient. Among these approximations, we cite those published in the following references :

1. First expression:

$$C_p = \frac{1}{2}(\gamma - 0.022\beta - 5.6)e^{-0.17\gamma} \tag{2.3}$$

Where: γ is the peripheral speed ratio. β represents the blade angle of attack in degrees.

2. Second expression:

$$C_p = 0.73\left(\frac{151}{\lambda'} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{-\frac{18.5}{\gamma}} \tag{2.4}$$

3. Third expression:

$$C_p = 0.5176\left(\frac{116}{\lambda'} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda'}} + 0.0068\lambda \tag{2.5}$$

With

$$\frac{1}{\lambda'} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{2.6}$$

The latter expression is part of the SIMULINK library and will be used to validate the model of our wind system. Several curves are represented on this figure depending on the angle of attack β, but for economic reasons, we are only interested in the one corresponding to $\beta = 0$.

The expression of the torque corresponding to the previously mentioned power is given by:

$$C_{eol} = \frac{P_{eol}}{\Omega} = \frac{1}{2} \cdot \frac{C_p(\lambda) \cdot \rho S V_W^3}{\Omega} \tag{2.7}$$

The mechanical torque seen by the synchronous machine is different from the wind turbine torque because it is necessary to take into account the inertia J of the wind turbine and the viscous friction f specific to the wind turbine structure. This can be expressed mathematically by the following equation:

$$T_{\text{mech}} = T_{\text{wt}} \cdot \frac{1}{\eta_{\text{gen}}} \cdot \frac{1}{\eta_{\text{trans}}} + J \cdot \frac{d\omega_{\text{wt}}}{dt} + f \cdot \omega_{\text{wt}} \tag{2.8}$$

2.3 Synchronous Generator

The specific energy density of hydrogen is huge when it is compressed and transported at higher pressure and lower temperature. Therefore, to minimize the high delivery cost, the hydrogen production is preferred to be decentralized by being connected to the distribution or transmission network of the power system . Such networks can be modeled as synchronous generators, as both of them have relatively similar operational characteristics. Therefore, the mathematical expression of the synchronous generator is derived here to represent the system network that supply electric power to the electrolyzer.

2.3.1 Synchronous Machine Theory

Synchronous generators form the principal source of electrical energy in power systems . Every synchronous machine consists of two essential elements. The first part is the armature which is the stationary part that has three windings to carry three-phase induced voltage. And the second part is the rotor which is the rotating section that consists of a field winding which carries direct current to produce a magnetic field to induce alternating voltage in the armature windings and short-circuited damper windings that stabilize the electrical operation of the machine and provide start-up torque for the generator . The schematic of the cross-section of a three-phase synchronous machine with one pair of field poles is shown in Figure2.3. The rectangles with dots and x's indicate the three-phase windings a, b, and c. The current flow is assumed to be into the "x" and out of the "dot" located in the opposite side. The axes are determined based on the voltage polarity of the coils which are assumed to be plus to minus from the "x" to the "dot" . An arbitrary δ is an angle between the axis of phase a and the q-axis.

When the rotor of the synchronous machine is moved by a prime-mover (e.g., a wind-turbine)and an excitation voltage is applied on the rotor-windings, a direct current is flowing in the field winding of the rotor which causes the creation of rotating magnetic field in the air-gap. Then, this magnetic field crosses the armature windings which enables a voltage induction in the stator. When a load is connected to the stator, a three-phase current flows in the armature that produces another magnetic field in the air-gap which rotates at synchronous speed. The superposition of these two fields (created by rotor and stator windings) determines the machine's behavior in each operating point for a known armature current frequency f in Hz and pole pairs p of the machine, the synchronous speed n in rev/min can be determined as

$$n = \frac{60f}{p} \tag{2.9}$$

The electromagnetic torque on the rotor acts in a direction to bring the magnetic fields into alignment. If the rotor field leads the armature field, the torque acts in opposition to the rotation with the machine acting as a generator. On the other hand, if the rotor field lags the stator field, the torque acts in the direction of rotation with the machine acting as a motor. In other words, for generator action, the rotor field leads the armature field by the forward torque of a prime mover; for motor action, the rotor field lags behind the armature field due to the retarding torque of shaft load .

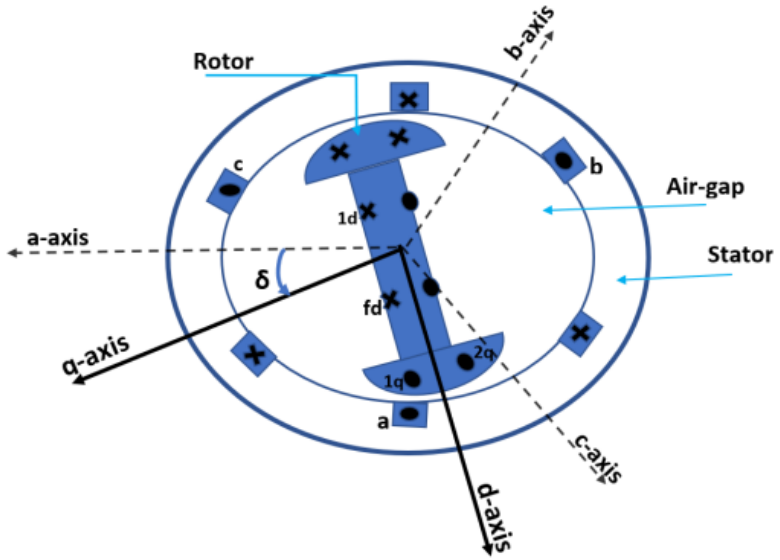


Figure 2.3: Some configurations of magnet placement

2.3.2 Permanent Magnet Synchronous Generator

The alternator used in our study is a permanent magnet synchronous generator with 6 pairs of surface-mounted poles on the rotor. This type of generator, with a large number of poles, makes variable speed systems more attractive. This kind of machine allows for maximum energy extraction while reducing mechanical constraints by eliminating the need for a speed multiplier, which improves system reliability and reduces maintenance costs. In contrast to the doubly-fed asynchronous machine, which requires a mechanical speed multiplier [38].

2.3.2.1 Modeling of the permanent magnet synchronous machine

The modeling of the PMSM consists of constructing a mathematical model of the machine, translating the electromagnetic and mechanical phenomena that govern its operation. This allows for a relevant study of the behavior of different variables in dynamic and static modes, and to exploit this model in simulations [38].

2.3.2.2 Simplifying Assumptions

In order to simplify the modeling of the synchronous machine, it is necessary to make the following simplifying assumptions:

- The stator is connected in star configuration, with the neutral point left open to eliminate the homopolar component of the currents.
- Magnetic circuit saturation is neglected, leading to the expression of magnetic fluxes as linear functions of phase currents.
- The distribution of the MMF (magnetomotive force) in the air gap is sinusoidal, hence neglecting space harmonics.
- Hysteresis and eddy current losses are neglected.
- Skin effect and temperature effects are neglected.

2.3.2.3 The Formulation of the Unified Model of Electric Machines

The most commonly used models for electric machines are based on the unified theory of electric machines. This theory is based on the Park transformation, which relates the stator and rotor electrical equations to a Cartesian coordinate system, d and q

In the classical reference frame, there are three axes (as, bs, cs) oriented along the axes of the three stator windings of the machine. Usually, the as axis is considered as the reference for further transformations. Since the stators of asynchronous and synchronous machines are similar, the stator reference frames for both types of machines are identical.

As for the rotors, there are always three axes (ar, br, cr) corresponding to the three rotor windings for the asynchronous machine (AM), but only one axis (F) corresponding to the direction of magnetization for the permanent magnet synchronous machine (PMSM). The angle θ_r represents the position of the rotor relative to the stator [38].

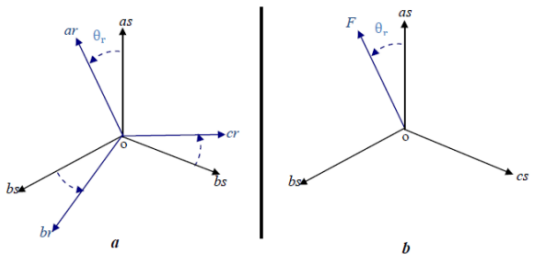


Figure 2.4: a- machine asynchrone, b- machine à aimant permanent

The MSAP model that will be developed in our work is based on the diagram in the next figure:

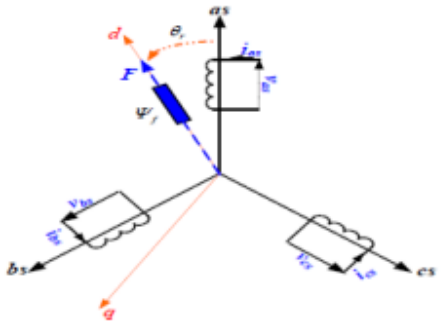


Figure 2.5: Representative diagram of the MSAP to be modeled

Electrical equations

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Psi_a \\ \Psi_b \\ \Psi_c \end{bmatrix} \tag{2.10}$$

- $[\mathbf{v_a}\ \mathbf{v_b}\ \mathbf{v_c}]$: Vecteur tension de phases statoriques.
- $[\mathbf{i_a}\ \mathbf{i_b}\ \mathbf{i_c}]$: Vecteur courant de phases statoriques.
- $[\mathbf{\Psi_a}\ \mathbf{\Psi_b}\ \mathbf{\Psi_c}]$: Vecteur des flux totaux traversant les bobines statoriques.
- R_S: la résistance des phases statoriques.

Passage to Park marker

In order to simplify the dynamic model of the machine, we apply a change of reference. This mathematical transformation transforms the three stator coils phase-shifted by $2\pi/3$ into two equivalent fictitious coils phase-shifted by $\pi/2$ and located on the rotor (Figure2.6).

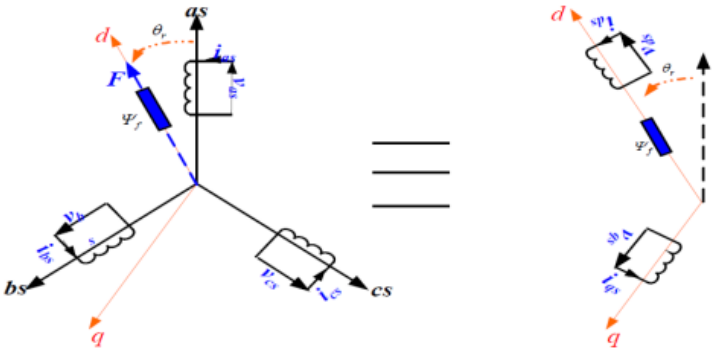


Figure 2.6: Three-phase-two-phase transformation

The Park transformation ($P(\theta)$) is defined by the following matrix:

$$P(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta - \frac{4\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) & 1 \end{bmatrix} \tag{2.11}$$

$P(\theta)$ defines the passage from the reference a, b, c to d, q, o.

$$P(\theta)^{-1} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{2.12}$$

$P(\theta)^{-1}$ defines the passage from the mark d, q, o to a, b, c.

We also define another transformation, the Concordia transformation, which defines other fictitious axes α and β such that the α axis is aligned with the a_s axis, which amounts to setting $\theta_r = 0$ in the Park transformation. The Concordia transformation is given by:

$$C = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \tag{2.13}$$

2.3.3 MSAP model in the Park benchmark

The simplified diagram of the GSAP in the Park benchmark is shown in Figure 2.6. The model of the MSAP is defined by the following different electrical, magnetic, and mechanical equations:

Electrical equations

The electrical equations of the MSAP motor convention are given by:

$$\begin{cases} V_{ds} = R_s i_{ds} + L_s \dfrac{di_{ds}}{dt} - \omega_r L_d i_q \\ V_{qs} = R_s i_{qs} + L_s \dfrac{di_{qs}}{dt} + \omega_r L_d i_d + \omega_r \Psi_f \end{cases} \tag{2.14}$$

In generating convention, we reverse the direction of the currents, and we will therefore have the electrical equations of the GSAP as follows:

$$\begin{cases} V_{ds} = -R_s i_{ds} + L_s \dfrac{di_{ds}}{dt} + \omega_r L_d i_q \\ V_{qs} = -R_s i_{qs} + L_s \dfrac{di_{qs}}{dt} - \omega_r L_d i_d + \omega_r \Psi_f \end{cases} \tag{2.15}$$

This sign convention will be kept throughout this modeling.

Magnetic equations

In the MSAP model, the magnetic equations relating voltages and currents to the flux linkages are given by:

$$\begin{cases} \Psi_{ds} = L_s \cdot i_{ds} + \Psi_f \\ \Psi_{qs} = L_s \cdot i_{qs} \end{cases} \tag{2.16}$$

In sinusoidally distributed synchronous machines, the direct axis (Ψ_{ds}) and quadrature axis (Ψ_{qs}) fluxes are linear functions of the direct axis (i_{ds}) and quadrature axis (i_{qs}) currents, respectively.

Expression of Electromagnetic Torque

The electromagnetic torque is expressed by the partial derivative of stored electromagnetic energy with respect to the geometric angle of rotor rotation :

$$C_{em} = \frac{dW_e}{d\theta_{geo}} = \frac{dW_e}{d\theta_r} p \tag{2.17}$$

where,

- W_e: Energy stored in the magnetic circuit.
- θ_{geo}: Angular displacement of the moving part relative to the fixed part (rotor relative to stator).

- p: Number of pole pairs.

The expression for the transmitted power is given by:

$$P(t) = \frac{3}{2}(v_{ds}i_{ds} + v_{qs}i_{qs}) \tag{2.18}$$

By replacing v_d and v_q with their expressions, we have:

$$P(t) = \frac{3}{2}\Big[- R_s(i_{ds}^2 + i_{qs}^2) - \left(i_{ds}\frac{d\psi_{ds}}{dt} + i_{qs}\frac{d\psi_{qs}}{dt}\right) + \frac{d\psi_f}{dt}(v_{ds}i_{qs} - v_{qs}i_{ds})\Big] \tag{2.19}$$

Where

$\frac{3}{2}R_s(i_{ds}^2 + i_{qs}^2)$ Represents the power dissipated by Joule effect

$\frac{3}{2}\left(i_{ds}\frac{d\psi_{ds}}{dt} + i_{qs}\frac{d\psi_{qs}}{dt}\right)$ The variation of energy stored in the stator windings

$\frac{3}{2}(\frac{d\psi_f}{dt}(v_{ds}i_{qs} - v_{qs}i_{ds}))$ The electromagnetic power

Knowing that $P = C_{em}\Omega$ and $\Omega = \frac{d\theta}{dt}$ (Ω = mechanical speed), we have:

$$C_m = \frac{3}{2}p(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \tag{2.20}$$

And after assigning the flux values, we have:

$$C_{em} = \frac{3}{2}p\left[(L_d - L_q)\cdot i_{ds}\cdot i_{qs} + i_{qs}\cdot\psi_f\right]$$

Where:

C_m : Motor torque.

Ω_f : Viscous friction torque.

f : Coefficient of viscous friction.

J : Moment of inertia of the machine.

2.4 The Filter

A filter (C_f) is inserted between the rectifier and the inverter to maintain a nearly constant voltage and a slightly rippled current. The capacitor C_f aims to eliminate sudden variations in the voltage U_d during switching intervals and to absorb the negative current

returned by the load through the recovery diodes of the inverter. The filter is illustrated in Figure2.7.

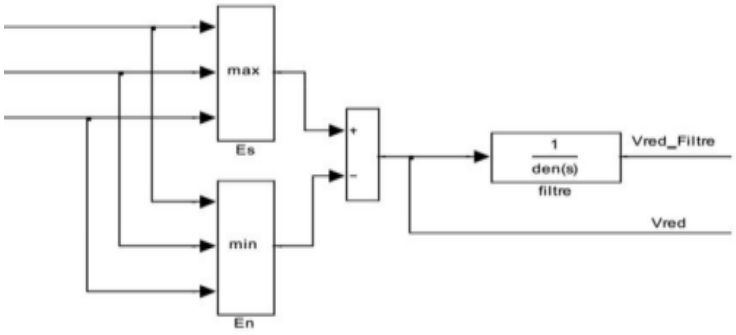


Figure 2.7: Block diagram (Matlab/Simulink) of the rectifier and filter

2.5 Power converter

The main load considered in this thesis is the hydrogen producer electrolyzer which needs DC power. Therefore, a power conversion system is implemented to connect the electrolyzer with the AC grid. The electrical system that converts AC voltage to DC voltage is called a rectifier. Usually, the electrolyzer is connected to the rectifier via a DC-DC converter for proper operation and secure lifespan. Most electrolyzers operate at a low voltage compared to the output of the rectifier or DC bus. Therefore, the DC-DC converter, especially the buck converter, steps down the voltage to the operating range of the electrolyzer. Another reason is the DC-DC converters can be configured in different ways to increase the input current for a constant input voltage so that to enhance the hydrogen production. In addition, the lifespan of electrolyzers can be improved by decreasing the ripple effect using a high switching frequency of the DC-DC converter. Thus, both the rectifier and DC-DC power converters are described and modeled in this section.

2.5.1 Diode rectifier

2.5.1.1 Definition

The rectifier is a static converter that converts. It is powered by an alternating voltage source and allows continuous power supply to the receiver connected to its output. Rectifiers are used whenever continuous sources are needed, knowing that electrical energy is available in alternating current. Rectifiers have a wide range of applications, but

unfortunately, their major drawback is the generation of non-sinusoidal currents rich in harmonics sent to the grid.

2.5.1.2 Rectifier Structure:

The structure under study is the three-phase bridge rectifier with a ripple factor of six, as illustrated in Figure 2.8. The bridge rectifier is powered by a three-phase source. The line-to-line voltages of a balanced three-phase signal are:

$$\begin{aligned} V_a &= V_m \sin(\omega t) \\ V_b &= V_m \sin(\omega t - 120^\circ) \\ V_c &= V_m \sin(\omega t + 120^\circ) \end{aligned} \tag{2.21}$$

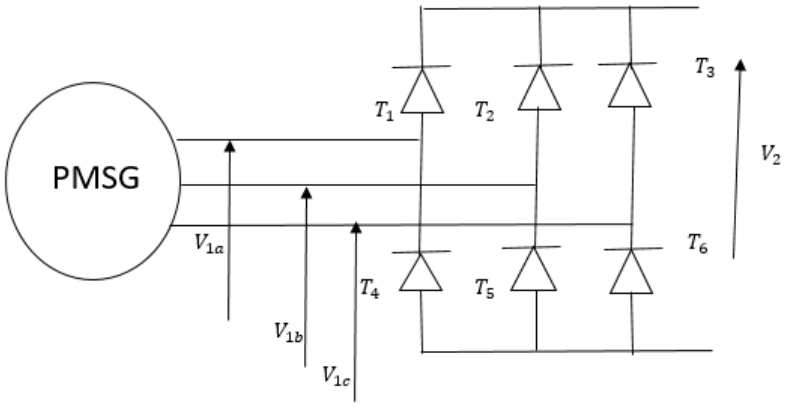


Figure 2.8: Electric diagram of rectifier an uncontrolled three-phase

2.6 Electrolyzer

2.6.1 Alkaline Electrolyzer

Water can only be split into hydrogen and oxygen when a minimum electrical voltage is applied. Ideally, the cell voltage is equal to this minimum voltage, called reversible voltage, but due to irreversibility, the cell voltage is always higher. The extra voltage present in the cell is called overvoltage and is composed of ohmic, activation, and diffusion overvoltages. Ohmic overvoltage is the overvoltage due to the overall resistance of all components of the electrical circuit, while the activation overvoltage is the overvoltage related to extra energy required to start the oxygen and hydrogen formation process in the electrodes . Diffusion overvoltage only takes precedence at high current densities when the reaction changes from

electronic transfer to matter transfer. An empirical model involving ohmic and activation overvoltages proposed in [39] is expressed by 2.22. The model has six different parameters to characterize the logarithmic response of an electrolyzer cell voltage in terms of current and temperature.

$$V = V_{\text{rev}} + \frac{r_1 + r_2 T}{A} I + S \log\left(\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right)\frac{I}{A} + 1\right) \tag{2.22}$$

where:

- T is the temperature of the cell,
- A is the area of the electrodes,
- r_1 and r_2 are the ohmic overvoltage parameters,
- t_1, t_2, t_3, and S are the activation overvoltage parameters.

V_{rev} is the reversible voltage of the cell and is temperature and pressure dependent, with a value of 1.229 V at standard conditions (1 bar, 25°C). For low temperature ranges of up to 100°C, voltage variation is small and can be considered constant [39]. The production rate of hydrogen can be related to the input current using Faraday's law. An empirical expression for the hydrogen production efficiency is called Faraday efficiency. This relationship is summarized in 2.23.

$$\dot{n}_{H_2} = \left(\frac{\left(\frac{I}{A}\right)^2}{f_1 + \left(\frac{I}{A}\right)^2 f_2}\right)\frac{I}{zF} \tag{2.23}$$

where:

- f_1 and f_2 are parameters related to Faraday efficiency,
- z is the number of electrons transferred in the reaction (2 electrons for water electrolysis),
- F is Faraday's constant,
- n is the molar flow rate per second.

f_1 and f_2 are usually considered constant for the overall model. However, they vary with temperature [39]. The assumption of a linear relation with temperature in [39] depends on the temperature range of operation. In this research, a linear expression only applies for f_1 whereas for f_2 a limit value must be set to guarantee a range value between

0 and 1. Using the experimental data shown in Table 2.1, a linear empirical expression is obtained for f_1 as shown in 2.24 and a quadratic for f_2 as shown in 2.25. Note that an extra point was added to f_2 at 0°C to guarantee a limit value of 1.

$$f_1 = 2.5T + 50 \tag{2.24}$$

$$f_2 = 1 - 6.25 \times 10^{-6}T \tag{2.25}$$

A unit conversion is needed for the flow rate in2.23to obtain a rate in kilograms rather than moles. This will facilitate comparisons in the result section. Using the volume of an ideal gas at standard conditions, the volumetric flow rate and the mass flow rate are given by 2.26.

$$\dot{V} = \dot{n}_{v_std} \longrightarrow \dot{M} = \dot{V}c \tag{2.26}$$

where $v_{\text{std}} = 0.0224136\ \text{m}^3/\text{mol}$ and $c = 0.08988\ \text{kg/m}^3$.

Table 2.1: Electrolyzer experimental data

	Temperature (°C)	f_1	f_2
[39]	0	100	1.00
	40	150	0.99
	80	250	0.96

2.6.2 Boundary Conditions for the Alkaline Electrolyser

Due to the presence of a logarithmic function in 2.22, a careful consideration is needed to avoid negative values that can produce unrealistic results. This is obvious at low levels of current where the model parameters cannot follow the electrolyser response properly.
Similarly, when input current is zero in 2.22, the electrolyser cell is equal to the reversible voltage and can potentially act as a voltage source feeding current to other elements of the electrical circuit. To avoid this situation, the mathematical element is disconnected from the circuit to block any current flow and to force the voltage to follow the external circuit.
Finally, production rate given by 2.23 only depends on the input current regardless of the voltage input. This is not accurate since water can only be divided into hydrogen and oxygen when the cell voltage is enough to provide the required activation energy.

$$V = \begin{cases} V_{\text{rev}} + \frac{r_1+r_2T}{A} I + s \log\left(\left(\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right)\frac{I}{A} + 1\right), I > -A\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right)^{-1}\right) \\ V_{\text{rev}} + \frac{r_1+r_2T}{A} I, \quad I \leq -A\left(t_1 + \frac{t_2}{T} + \frac{t_3}{T^2}\right)^{-1} \\ V_{\text{outside}}, \quad I = 0 \end{cases} \tag{2.27}$$

$$\dot{n}_{\text{H}_2} = \begin{cases} \left(\frac{(I/A)^2}{f_1+(I/A)^2} f_2\right)\frac{1}{2F}, & V > V_{\text{rev}} \\ 0, & V \leq V_{\text{rev}} \end{cases} \tag{2.28}$$

2.7 Hydrogen Model Tank

Compressed gas or liquid hydrogen can be stored in tanks using different techniques, including physical hydrogen storage. To store hydrogen gas produced by the electrolyzer,a static model of the tank is created in MATLAB/Simulink and can be expressed by Equation 2.29.

$$P - P_{\text{bi}} = Z \cdot \frac{N_{\text{H}_2} R T_{\text{b}}}{M_{\text{H}_2} V_{\text{b}}} \tag{2.29}$$

where P is the pressure of the tank measured in Pascals, P_{bi} is the initial pressure of the storage tank in Pascals, R is the universal gas constant in J/kmol·K, T_{b} is the operating temperature in K, V_{b} is the volume of the tank in m^3, T is the temperature, and CF is the compressibility factor as a function of pressure, as shown in Equation 2.30 .

$$Z = \frac{P V_{\text{m}}}{RT} \tag{2.30}$$

where P and V_{m} are the pressure and molar volume, respectively. This model equation determines the tank pressure using the ratio of hydrogen flow rate to the tank. Equation 2.30 is implemented in MATLAB/Simulink to store the hydrogen and deliver it to the fuel cell.

2.8 Conclusion

In this chapter, we discussed modeling the wind energy conversion chain starting with the synchronous generator. We covered the theory of synchronous machines and specifically looked at the permanent magnet synchronous generator (PMSG). The PMSG is crucial

in converting mechanical energy from wind turbines into electrical energy.

Next, we examined the power transformer section, focusing on the diode rectifier and its structure. The rectifier is necessary to convert the AC voltage generated by the PMSG to DC voltage.

Additionally, we briefly touched on the electrolyzer, a key component in the hydrogen production process. The electrolyzer uses electricity to split water into hydrogen and oxygen, allowing the hydrogen to be stored and used as a clean energy source.

Overall, modeling these components is crucial for understanding and improving the efficiency of a wind energy conversion system, especially in integrating renewable energy sources such as wind energy with the water electrolyzer. However, storage also plays an important role, which we will discuss in the next chapter.

Chapter 3

Storage System

3.1 Introduction

Due to the intermittent nature of wind energy, it is integrated into electrical electronics that create implicit variance and uncertainty. The effect of wind energy integration on system stability reliability depends on the level of the password. Of reliability, net load nuances compared to the load current difference. It also penetrates the wind required to purchase spare parts, including a specific item only variations worth experiencing in wind turbine production and loading due to random energy interruptions and winds . It can also contain grid voltage due to wind energy increase or decrease in electricity. In addition, thus meeting the growing need for storage to manage uncertainty in generating power, increasing the vitality of the system to generate power, reducing energy consumption costs. Moreover, it contains electrical energy possibility of enabling power supply. These problems are the same when the vaccine is connected to the wind farm, hydrogen is then produced, and a storage system has become necessary. Currently, a large amount is stored.

3.2 Energy Storage

Energy storage involves preserving a quantity of energy for use later. By extension, the expression also designates the storage of matter containing energy. Energy storage is at the heart of current challenges, whether it involves optimizing resources energy or to promote access to them. It allows you to adjust “production” and “consumption” energy by limiting losses. Energy stored when its availability is greater than needs, can be returned at a time when demand is greater. Faced with intermittency or fluctuation in the production of certain energies, for example renewables, this operation allows also to respond to constant demand.

Storage methods depend on the type of energy. Fossil energy sources (coal, gas, oil), in the form of reservoirs in their natural state, naturally fill the stock function. Once extracted, they can easily be isolated, hosted and transported from a technical point of view. Storage turns out to be more complex for energies intermittent: their production is relayed by energy vectors such as electricity, heat or hydrogen, requiring specific storage systems.

But energy is a quantity that is strongly linked to time. Its storage is therefore relatively complex. This storage can be done in a large number of forms. We therefore made the choice, initially, to group them into five large families of storage: mechanical, thermal, chemical, electrochemical and electrical.

3.3 Classification of Storage Systems

3.3.1 Batteries (Accumulators)

The terms "battery" or "accumulator" refer to "small reservoirs" that can store energy in chemical form to release it later. It is a mixture called "electrolyte" that allows the accumulation or release of this energy. The most commonly used electrolytes currently are:

- For lead-acid batteries: Lead/Acid mixture;
- For nickel batteries, which are the most common today: Ni-MH: Nickel-Metal Hydride and Ni-Cd: Nickel-Cadmium;
- For a lighter and more efficient generation: lithium-ion and lithium polymer.

It is called a battery when the accumulator is composed of several elements. The term accumulator is more general and is used for both a single element or a battery.

3.3.2 Equivalent Circuit of a Voltage Source

All voltage generators can be represented by an equivalent circuit consisting of an ideal voltage source in series with a resistance.

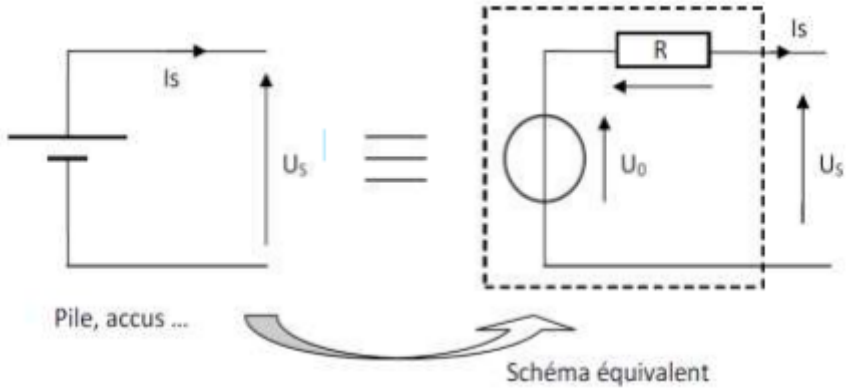


Figure 3.1: Equivalent circuit of a battery.

- U_0: is called the electromotive force (EMF) or open-circuit voltage. It is defined when the source does not supply any current ($I_s = 0$).
- R: is the internal resistance of the source.

An ideal voltage source has zero internal resistance. Therefore, the output current is not limited, and the output voltage remains constant regardless of the output current value.

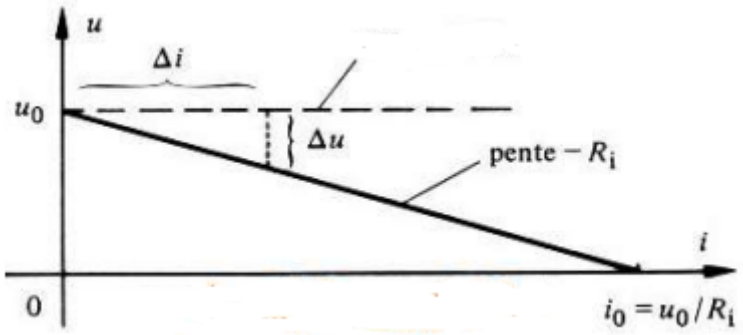


Figure 3.2: Source voltage as a function of source current for a battery.

According to Kirchhoff's voltage law:

$$u = u_0 - R \cdot i$$

If $i = 0$, then $u = u_0$ (open-circuit voltage).
And the internal resistance R is given by:

$$R = \frac{\Delta u}{\Delta i}$$

3.3.3 Characteristics of an accumulator cell

- Technology: It is the nature of the electrolyte contained in the accumulator.
- Element voltage: It is the potential difference between the two poles (+) and (-). For a nickel accumulator, it evolves from about 1.35 V when the element is fully charged to about 1 Volt when the element is fully discharged. For calculations, the nominal voltage is considered "fixed" at 1.2 Volts.
- Stored energy: Energy in Wh (or in joules) = Capacity x Voltage. $1\text{Wh} = 1\text{V} \times 1\text{A} \times 1\text{h} = 1\text{Ah} \times 1\text{V}$
- Physical volume of the element: Proportional to the capacity for a given technology. The elements are generally cylindrical. For compatibility reasons, there are standard sizes or formats corresponding to some of the R03, R6, R14, and R20 battery formats.
- Specific energy: It is interesting to have an idea of the order of magnitude of specific energy. This energy is traditionally expressed in Joules/Kg or Wh/Kg.
- Theoretical specific energy: is the maximum theoretical energy deliverable by a lead-acid accumulator.
- Energy density: is the actual specific energy provided by an accumulator when the connectors are added.
- DOD: Depth of Discharge is the depth of discharge of the accumulator.
- SOC: State of Charge is the state of charge of an accumulator.
- Overcharge coefficient: is the overcharge coefficient in voltage of the accumulator.
- Energy efficiency: is the efficiency between the useful energy for charging the accumulator and the energy recovered during discharge.

The capacity of the element or Nominal Capacity: It is the amount of electricity it is capable of delivering when charged. This capacity is expressed in Ampere-Hours (symbol: Ah) or for small accumulators in Millie ampere-hours (mAh). The voltage of the accumulator generally varies with capacity. That is why the characteristic (voltage-discharge time) is plotted.

3.3.4 Types of battery

3.3.4.1 The lithium ion battery

Lithium-ion battery is one of the main energy storage components at present. In order to ensure the safe and reliable operation of the whole battery energy storage system.

3.3.4.2 Battery management system (BMS)

Battery management system (BMS)is needed to estimate and predict the state of charge (SOC) and state of health (SOH) of lithium-ion battery. In order to accurately estimate the state of lithium-ion battery, it is necessary to establish an accurate battery model .

3.3.4.3 Working principle

The working principle of rechargeable, or secondary, lithium ion batteries is identical to other secondary battery systems. When the battery is discharged, the chemical energy stored in the active materials of the electrodes is converted through a reduction-oxidation (redox) reaction into electrical energy, resulting in a flow of electrons from the negative to the positive electrode through an external circuit. The battery can be recharged by applying external electric energy, which is stored as chemical energy in the active materials of the electrodes.

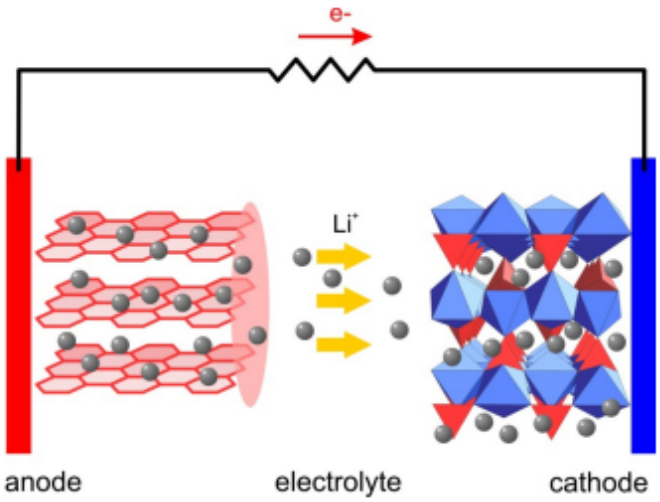


Figure 3.3: Schematic of a lithium-ion battery during discharge. Electrons from the oxidation reaction at the graphite anode travel through an external circuit and are consumed by a reduction reaction at the transition metal oxide cathode

The electrochemical cell consists of two electrodes, separated by an electrolyte, as shown in 3.3. According to the standard definition, the electrode where the oxidation re-

action takes place is defined as the anode, and the electrode hosting the reduction reaction is defined as the cathode. When the cell is discharged, the oxidation reaction on the anode (negative electrode) supplies electrons, which are transferred via an external circuit and consumed by the reduction reaction on the cathode (positive electrode). Consequently, the electrodes act as anode or cathode depending on whether the cell is being charged or discharged. A more useful designation is to take the cathode as the electrode with the highest potential with respect to the other, as shown in 3.3. This potential difference between the two electrodes causes lithium ions to move spontaneously from the anode to the cathode through the electrolyte when the battery is discharged. The electrolyte enables internal charge transfer between the electrodes through high ionic and low electric conductivity, which prevents direct electron exchange and short circuiting of the cell. The charge balance is maintained by the flow of cations and anions in the electrolyte towards the oppositely charged electrodes during charge and discharge. Further, as an additional safety measure, most cells employ a polymeric separator, acting as a physical barrier to keep the electrodes from coming into direct contact. The battery is charged by applying a voltage higher than the electrochemical potential between the electrodes. This results in a reversal of the electron, cation, and anion flow. For practical applications, several individual cells are combined in series and parallel to achieve a desired voltage and capacity, respectively.

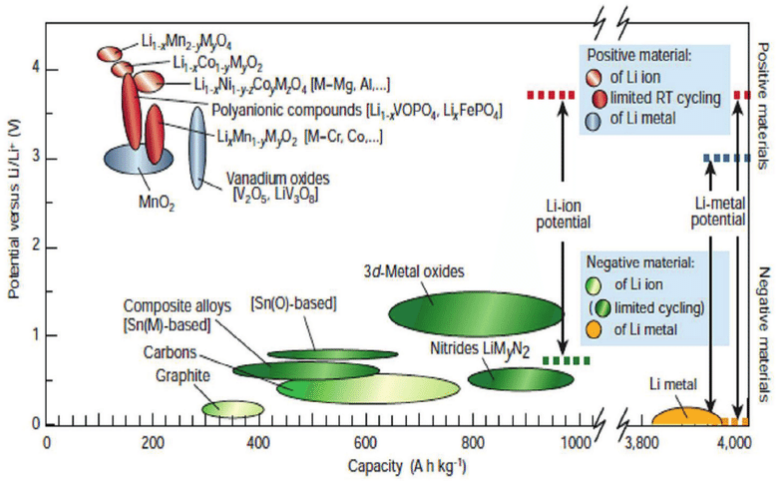


Figure 3.4: Voltage and capacity for various anode and cathode materials, both commercial and under research .

3.3.4.4 Electrode reactions

Today's lithium-ion battery electrodes are based on intercalation compounds. These compounds are characterized by the ability to reversibly insert and deinsert Li^+-ions

in a host structure. Intercalation compounds are usually layered structures, the most common materials being graphite on the anode side and lithium transition metal oxides on the cathode side. In most cases, the intercalation and deintercalation do not change the structure of the material significantly, but a slight volume change is usually involved.

The charge reaction for the anode and cathode proceeds according to Equations3.1, respectively:

$$\begin{aligned} x\mathrm{Li}^+ + y\mathrm{C} + xe^- &\rightarrow \mathrm{Li}_x\mathrm{C}_y \\ \mathrm{LiMO}_2 &\rightarrow \mathrm{Li}_{1-x}\mathrm{MO}_2 + x\mathrm{Li} + xe^- \end{aligned} \tag{3.1}$$

The total reaction is then:

$$\mathrm{LiMO}_2 + y\mathrm{C} \rightarrow \mathrm{Li}_{1-x}\mathrm{MO}_2 + \mathrm{Li}_x\mathrm{C}_y \tag{3.2}$$

where M denotes a transition metal, commonly Co, Mn, or Ni. The factor x varies from material to material, but due to structural restrictions, it is usually limited to a number between 0.5 and 1. For every x Li^+-ions intercalated, y carbon atoms are needed. y has the smallest value of six for x = 1, i.e., LiC_6. By reversing the direction of Equations3.1 and 3.2 , the discharge reaction is obtained.

3.3.5 Fuel Cell

Fuel cells are significant enabling technologies for the state's energy portfolio and have the potential to reshape the world's power generation, offering cleaner and more efficient alternatives to the combustion of gasoline and other fossil fuels. They have the capability to replace internal combustion engines in vehicles and provide power in stationary as well as portable applications due to their fuel flexibility, cleanliness, and energy efficiency . Fuel cells are primarily classified by the type of electrolyte they use, which determines the electrochemical reactions, catalysts, operating temperature range, fuel requirements, and other components. These characteristics, in turn, influence the applications for which these cells are most suitable . Each type of fuel cell has unique and important features for specific applications; however, the Alkaline Fuel Cell (AFC) stands out with some unique advantages over other types of fuel cells. AFCs operate using compressed hydrogen and oxygen and typically utilize a solution of potassium hydroxide (KOH) in water as their electrolyte.

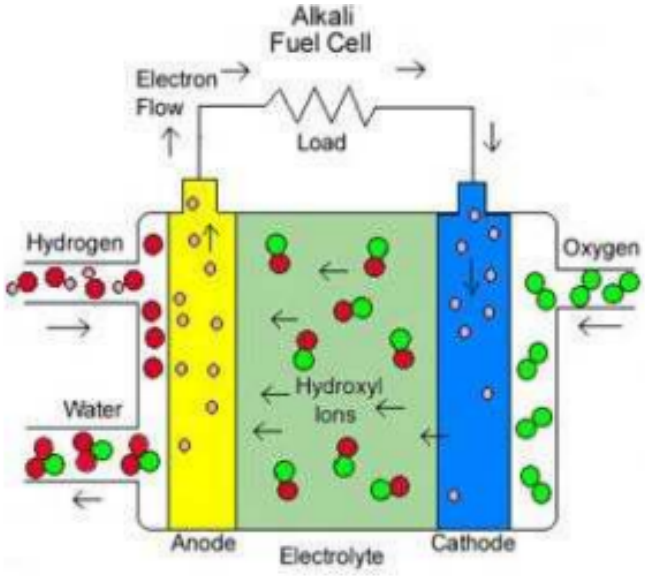


Figure 3.5: Alkaline Fuel Cell
[3]

In AFCs, an aqueous potassium hydroxide solution soaked in a porous matrix or alkaline polymer membrane is used as the electrolyte. The stack size of AFCs ranges from 1 kW to 100 kW. The electrical efficiency (Lower Heating Value, LHV) of AFCs is about 60%. AFCs have been utilized in various applications such as military, space, backup power, and transportation. AFCs offer several advantages including (i) a wider range of stable materials allowing for lower cost components; (ii) operation at low temperatures; and (iii) quick start-up . The term "flow rate" refers to the quantity of a gas or liquid moving through a pipe or channel within a given period (usually a minute or hour). Therefore, fuel flow rate refers to the quantity of fuel moving through a pipe or channel within a given time period. The definition of air flow rate is similar, except it uses air instead of fuel. Similarly, the term "supply pressure" refers to the pressure supplied to the high-pressure or inlet side of a regulator. Thus, fuel supply pressure refers to the pressure supplied to the inlet side of a regulator for fuel. The definition of air supply pressure is similar, except it uses air instead of fuel. The objective of this paper is to investigate the output behavior of a generic model parameterized to represent a type of fuel cell stack fed with hydrogen and air. A Simulink model is used as a test system to investigate the output behavior over time. This paper is organized as follows:
Section 2 presents a brief overview of fuel cells, their working principles, and types. A brief overview of alkaline fuel cells and their working principle is presented in Section 3. Simulation results and analysis are discussed in Section 4.
Finally, Section 5 concludes the work highlighting the major contributions.

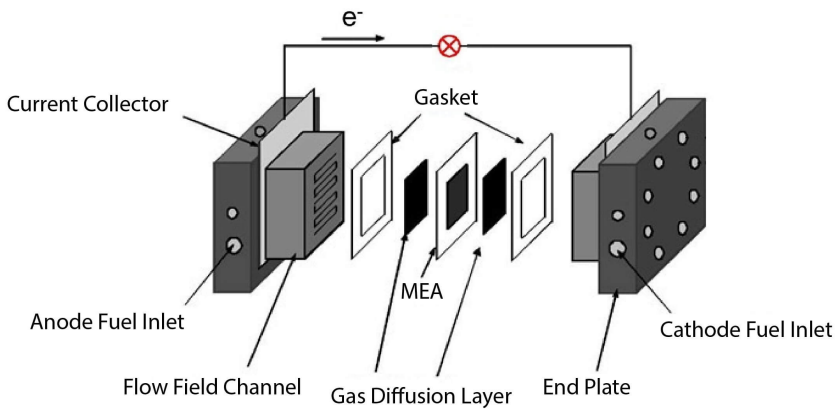


Figure 3.6: Constituents of a Fuel cell stack
[7]

3.3.5.1 Fuel Cell and Working Principle

A fuel cell uses the chemical energy of hydrogen to cleanly and efficiently produce electricity with water and heat as by-products. Fuel cells are unique in terms of the diversity of their potential applications; they have provided energy for structures as large as an efficacy power station and as small as a laptop computer.

Fuel cells were invented in 1840 but have been revived as a promising candidate for an alternative power source. A fuel cell is an electrochemical device that generates an electric current as a result of a chemical reaction between a fuel (often hydrogen) and an oxidant, with the only byproducts being heat and water. Since no combustion takes place, efficiencies of more than two times that of a traditional IC engine are possible. A fuel cell system consists of a stack of identical cells combined to achieve the desired power output, as shown below. Each independent cell assembly consists of an electrolyte membrane sandwiched between two catalyst-impregnated anode and cathode electrodes. This basic cell is further sandwiched between two bipolar plates used to deliver the reactants to the working fuel cell.

3.3.5.2 Types of Fuel Cells

Different fuel cells have been explored over time, characterized according to the electrolyte they use and the reactions they facilitate. The most common types of fuel cells and their applications in the industry are summarized below.

Table 3.1: Summary of Different Types of Fuel Cells

Fuel Cell Type	**Mobile Ion**	**Operating Temperature**	**Applications & Notes**
Proton Exchange Membrane Fuel Cell (PEMFC)	H^+	30 - 100 °C	Vehicles & mobile applications, and for small-scale CHP systems
Direct Methanol Fuel Cell (DMFC)	H^+	20 - 90 °C	Suitable for portable electronic devices, long-lasting operation
Phosphoric Acid Fuel Cell (PAFC)	H^+	∼220 °C	Large numbers of 200 kW CHP systems in use
Molten Carbonate Fuel Cell (MCFC)	CO_3^{2-}	∼650 °C	Suitable for medium to large-scale CHP systems, up to MW capacity
Solid Oxide Fuel Cell (SOFC)	O^{2-}	500 - 1000 °C	Suitable for all sizes of CHP systems, from 2 kW to multi-MW
Alkaline Fuel Cell (AFC)	OH^-	50 - 200 °C	Used in space missions such as Apollo and Shuttle

Fuel cells have various advantages over traditional combustion-based technologies and are currently used in passenger vehicles and many power plants. They emit no emissions at the point of performance, reducing air pollutants and greenhouse gases that can cause health issues.

3.3.5.3 Alkaline Fuel Cell and Working Principle

The Bacon fuel cell, also known as the Alkaline Fuel Cell (AFC), was invented by a British inventor. The Alkaline Fuel Cell (AFC) was one of the first fuel cell technologies developed and was the first type of fuel cell widely used in the U.S. space program to produce water

and electrical energy on-board spacecraft. AFCs use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as catalysts at the anode and cathode. AFCs typically operate at high temperatures, such as between 100 °C and 250 °C (212 °Fahrenheit and 482 °Fahrenheit). However, newer AFC designs operate at lower temperatures of roughly 23 °C to 70 °C (74 °Fahrenheit to 158 °Fahrenheit).

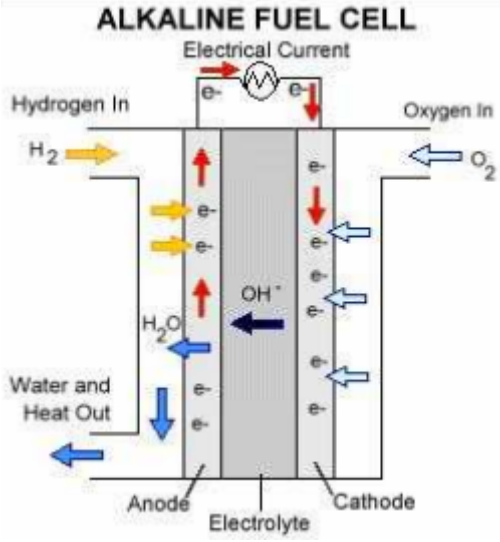


Figure 3.7: Representation of Alkaline Fuel Cell (AFC) [10]

In recent years, novel AFCs which use a polymer membrane as the electrolyte have been developed. These fuel cells are closely related to conventional PEM fuel cells, except that they use an alkaline membrane instead of an acid membrane. The high performance of AFCs is due to the rate at which electrochemical reactions take place in the cell. They have also demonstrated efficiencies above 60% in space applications. Cost is less of a factor for remote locations, such as in space or under the sea. However, to compete effectively in most mainstream commercial markets, these fuel cells will have to become more cost-effective. To be economically viable in large-scale utility applications, AFCs need to reach operating times exceeding 40,000 hours, something that has not yet been achieved due to material durability issues [3].

By utilizing alkaline electrolyte potassium hydroxide (KOH), AFCs generate electric power in a water-based solution. The existence of the hydroxyl ions traversing across the electrolyte allows a circuit to be made and electrical energy to be extracted. Figure 3.8 illustrates an alkaline fuel cell. At the anode section, 2 hydrogen gas molecules are combined with 4 hydroxyl ions with a negative charge to release 4 water molecules and 4 electrons. The redox reaction taking place is oxidation as in 3.3 [10]:

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \tag{3.3}$$

Electrons released in this reaction reach the cathode through the external circuit and react with water to generate (OH^-) ions. At the cathode section, an oxygen molecule and

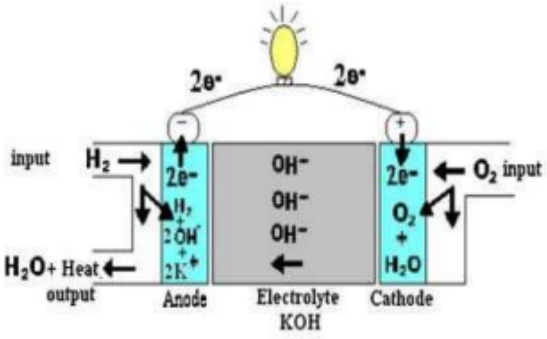


Figure 3.8: Working Principle representation of Alkaline Fuel Cell (AFC)

2 water molecules combine and absorb 4 electrons to form 4 negatively charged hydroxyl ions. The occurring redox reaction is reduction as shown below :
(Reduction)

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{3.4}$$

AFCs have been considered the most cost-efficient type of fuel cells since the electrolyte used is a standard chemical potassium hydroxide (KOH) [2]. There are some major fuel constituents which have an impact on AFC performance and are summarized in Table3.2.

Table 3.2: Summary of major fuel constituents' impact on AFC [40]

Gas Species	Impact on Alkaline Fuel Cell (AFC)
H_2	Fuel
CO	Poison
CH_4	Poison
CO_2	Poison
S (as H_2S, COS)	Poison

Next section represents the simulation results carried out on a Simulink model based on fuel cell manufacturer's data sheet.

3.3.6 Coupling with System

By connecting a lithium-ion battery to a fuel cell to extract hydrogen using a wind system, we can store excess wind energy in the form of hydrogen. This stored hydrogen can then

be used to generate electricity, providing us with a more stable and reliable power supply. A lithium-ion battery can store energy for short-term use, while hydrogen can be stored for longer periods, allowing for greater flexibility and efficiency in energy management.

3.3.6.1 working principle

The working principle of a system combining a lithium-ion battery with a fuel cell for hydrogen extraction using a wind system involves several key steps:

1. **Wind Energy Generation**: Wind turbines harness wind energy to generate electricity.
2. **Electrolysis for Hydrogen Extraction**:
   - Electricity generated by the wind turbines is used for electrolysis, which splits water (H_2O) into hydrogen (H_2) and oxygen (O_2).
   - The electrolyzer consists of an anode and a cathode separated by an electrolyte. When electricity is applied, water molecules at the anode are oxidized to produce oxygen and positively charged hydrogen ions (protons). The hydrogen ions then migrate through the electrolyte to the cathode.
   - At the cathode, the hydrogen ions combine with electrons from the external circuit and possibly water molecules to form hydrogen gas.
3. **Hydrogen Storage**: The produced hydrogen is stored, possibly in a high-pressure tank or through other storage methods, for later use.
4. **Lithium-Ion Battery Storage**:
   - Excess electricity generated by the wind system can be stored in a lithium-ion battery for later use.
   - The battery provides a buffer for fluctuations in wind energy production and demand.
5. **Fuel Cell Electricity Generation**:
   - When electricity demand exceeds the current wind and battery capacity, the stored hydrogen can be used in a fuel cell to generate electricity.
   - In the fuel cell, hydrogen is combined with oxygen from the air in an electrochemical reaction, producing electricity, water, and heat.

- The electricity generated by the fuel cell can be used to meet immediate demand or stored in the battery for later use.

6. **System Integration and Control**:

   - Sophisticated control systems manage the flow of energy between the wind system, electrolyzer, battery, and fuel cell to ensure optimal efficiency and performance.
   - The control system also ensures that the electrolyzer operates at the most efficient conditions and that the battery and fuel cell are used effectively to balance energy supply and demand.

This integrated system provides a renewable and sustainable approach to energy production and storage, utilizing wind energy to produce hydrogen for fuel cells and storing excess electricity in lithium-ion batteries .

3.4 Conclusion

The integration of storage systems, such as lithium-ion batteries and fuel cells, plays a crucial role in enhancing the reliability and stability of renewable energy sources, particularly in the context of wind energy. These storage systems help overcome the intermittent nature of wind energy by storing excess energy generated during high-wind periods and delivering it during low-wind periods or high demand.

Lithium-ion batteries are well-suited for short-term energy storage, offering a reliable and efficient solution for managing fluctuations in energy production and demand. They provide high energy density, long cycle life, and fast response times, making them ideal for smoothing out variations in renewable energy production.

On the other hand, fuel cells, such as the alkaline fuel cell (AFC), offer a unique advantage for long-term energy storage. They can efficiently convert stored hydrogen into electricity when needed, providing a reliable backup power source. AFCs are particularly advantageous due to their use of potassium hydroxide (KOH) as an electrolyte, making them cost-effective and suitable for various applications.

The integration of lithium-ion batteries and fuel cells into renewable energy systems, coupled with advanced control systems, enables efficient utilization of renewable energy sources such as wind energy. This integrated approach not only improves the reliability and stability of the electrical grid but also contributes to the transition towards a more sustainable and environmentally friendly energy system. Based on our discussions and

achievements, we have identified significant challenges in hydrogen production and storage, particularly the high cost of electrolyzers. To address this issue, we have proposed a novel solution that we will discuss in detail.

Chapter 4

Realization System

4.1 Introduction

The realization of an efficient and effective system for electrolyzer sonohydrogen production using silver electrodes marks a significant advancement towards sustainable hydrogen energy. This chapter presents the design and implementation of test models aimed at enhancing the performance of the electrolyzer sonohydrogen process with silver electrodes. By integrating ultrasound technology into electrolysis and utilizing silver electrodes, the system aims to improve hydrogen production rates and overall energy efficiency. The chapter begins by outlining the design considerations for the test models, including the selection of materials, electrode configurations, and ultrasound parameters specific to the use of silver electrodes. It then describes the experimental setup and methodology used to evaluate the performance of the system with silver electrodes. Through a series of experimental runs, the chapter explores various approaches to optimizing the system for maximum hydrogen production using silver electrodes. Furthermore, the chapter discusses the challenges encountered during the realization process with silver electrodes and proposes potential solutions to enhance the system's performance. By analyzing the results of the experimental runs, the chapter aims to provide insights into the feasibility and effectiveness of using electrolyzer sonohydrogen with silver electrodes as a clean and sustainable energy source.

4.1.1 Experimental Apparatus

A set of experimental models were designed and manufactured to study the parameters affecting hydrogen production through alkaline water electrolysis. Figure **??** shows the experimental apparatus for alkaline water electrolysis assisted by wind power. The electrolyzer is a single-cell system, consisting of two electrodes, a positive electrode and a

negative electrode, and an electrolyte solution, powered by an electric generator. The electrolyte solution can be either an aqueous solution or a polymer membrane for proton exchange or a ceramic membrane for oxygen ion transport. Electrical energy is required to produce electrolytic hydrogen from water. The experimental model consists of the following components: an voltage generator (alternative to a wind turbine) as a power source, an electric wire, a silver electrode electrolyzer, an ultrasonic generator, a computer, a sensor gaz, and an Arduino Card, fuel cell.

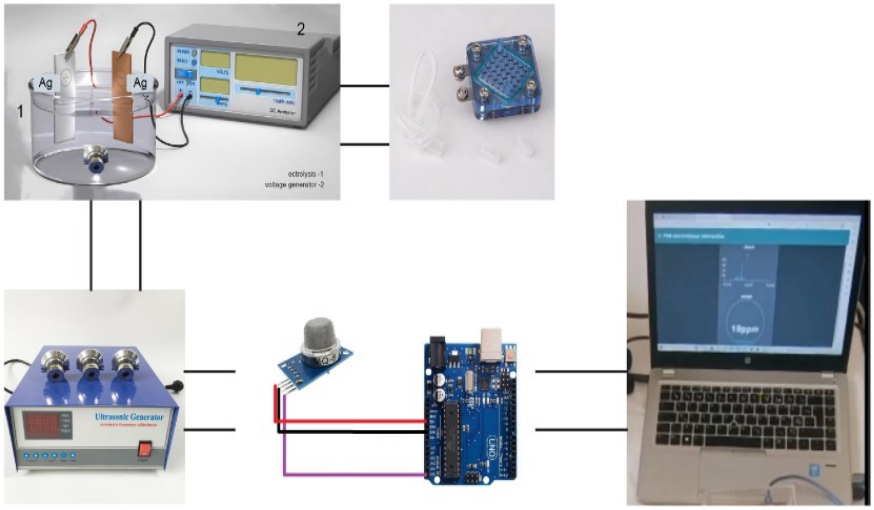


Figure 4.1: Experimental diagram

It looks like you've listed the components of the experimental model for studying hydrogen production through alkaline water electrolysis. Here's a breakdown of each component:

1.Voltage Generator: This serves as an alternative power source to a wind turbine. It generates the electrical energy needed for the electrolysis process.

2.Electric Wire: Used to connect the components and transmit electrical energy.

3.Silver Electrode Electrolyzer: The electrolyzer used for the electrolysis process, where water is split into hydrogen and oxygen using silver electrodes.

4.Ultrasonic Generator: Possibly used for enhancing the electrolysis process or for a specific aspect of the experiment.

5.Computer: Used for monitoring and controlling the experiment, as well as data

analysis.

6.Gas Sensor: Used to detect and measure the gases produced during electrolysis, such as hydrogen and oxygen.

7.Arduino Card: Likely used for data acquisition or controlling certain aspects of the experiment.

8.Fuel Cell: Possibly used for storing or utilizing the produced hydrogen.

This setup demonstrates a comprehensive approach to studying and optimizing hydrogen production through electrolysis.

4.1.1.1 Components

Voltage Generator(Alternative to a Wind Turbine) With Electrolyzer Using a voltage generator as an alternative to a wind turbine in a system with an electrolyzer to power the electrolysis process. Here's a general overview of how such a system would work:

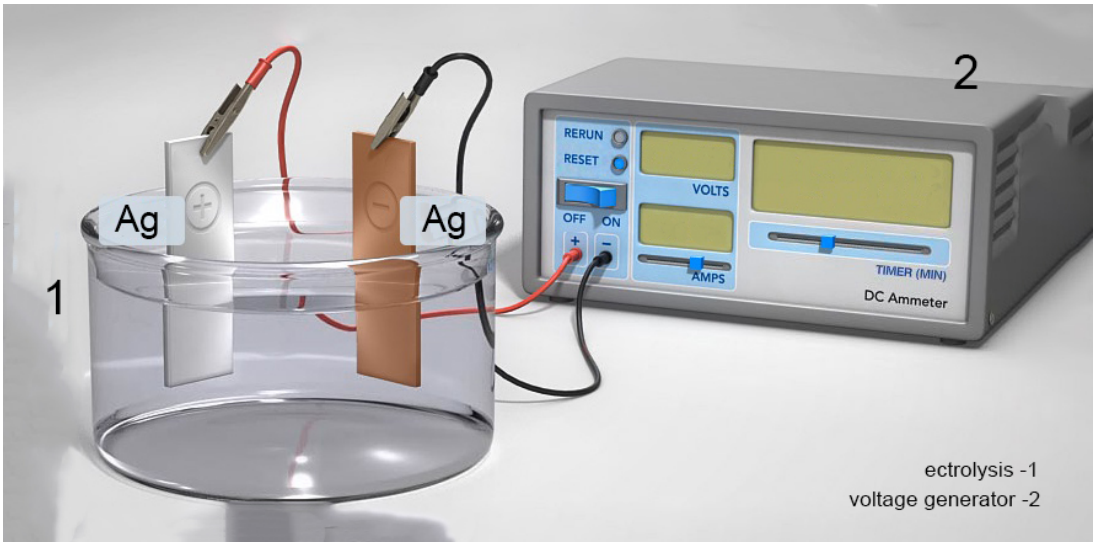


Figure 4.2: voltage generator(alternative to a wind turbine)With Electrolyzer

1. Voltage Generator: produces electrical energy.

2. Power Generation: The electrical energy produced by the voltage generator is used to power the electrolyzer.

3. Electrolyzer: The electrolyzer splits water (H2O) into hydrogen (H2) and oxygen (O2) through the process of electrolysis, using the electrical energy supplied by the voltage generator.

4. Hydrogen Production: The hydrogen produced through electrolysis is collected and stored for later use. It can be stored in tanks or other storage systems.

5. Oxygen Production: The oxygen produced as a byproduct of electrolysis can also be captured and stored or released into the atmosphere.

6. System Control: A control system regulates the flow of electricity from the voltage generator to the electrolyzer, ensuring that the electrolysis process is efficient and safe.

This setup provides a way to produce hydrogen gas using electricity generated by a voltage generator, offering an alternative to using a wind turbine in an electrolyzer system. A silver electrode electrolyzer would utilize silver electrodes in the electrolysis process, typically in the form of silver plates or wires. Here's how such a system might work:

1.Electrolysis Setup: The electrolyzer consists of a container filled with an electrolyte solution, often water. The silver electrodes are immersed in the electrolyte solution.

2.Electrolysis Process: When an electric current is passed through the electrolyte solution via the silver electrodes, the water molecules are split into hydrogen gas (H2) and oxygen gas (O2) through the process of electrolysis.

3.Electrode Reactions: At the anode (positive electrode), oxygen gas is produced through the oxidation of water molecules:

$$Anode : 4OH^- \rightarrow O_2 + 2H_2O + 4e^- \tag{4.1}$$

At the cathode (negative electrode), hydrogen gas is produced through the reduction of water molecules:

$$Cathode : 4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \tag{4.2}$$

At the Overall:

$$Overall : 2H_2O \rightarrow 2H_2 + O_2 \tag{4.3}$$

4.Silver Electrodes: The choice of silver electrodes can be advantageous due to silver's high conductivity, corrosion resistance, and stability in electrolysis processes. However, the cost of silver may be a limiting factor in large-scale applications.

5.Applications: Silver electrode electrolyzers can be used in various applications where hydrogen gas is needed, such as in fuel cells, chemical processing, and hydrogen production

for industrial purposes. Overall, a silver electrode electrolyzer can be an effective and efficient means of producing hydrogen gas through electrolysis, especially in applications where the properties of silver are beneficial.

Ultrasonic Generator The ultrasonic generator is a component of the experimental model used in the study of hydrogen production through alkaline water electrolysis. Its specific function in this context could involve several possibilities:



Figure 4.3: Ultrasonic Generator

1. Enhancing Electrolysis: Ultrasonic waves can improve the efficiency of electrolysis by promoting better mixing of the electrolyte, enhancing mass transfer at the electrode surface, and reducing concentration polarization, thereby increasing the rate of hydrogen production.

2. Cleaning Electrodes: Ultrasonic waves can be used to clean the electrodes, removing any accumulated deposits or impurities that may hinder the electrolysis process.

3. Bubble Management: Ultrasonic waves can control the formation and behavior of bubbles during electrolysis, which can affect the efficiency of gas separation and overall electrolysis performance.

4. Experimental Control: The ultrasonic generator could be used as a variable in the experiment to study its effects on electrolysis efficiency and hydrogen production under different conditions.

In summary, the ultrasonic generator likely plays a role in improving the efficiency and effectiveness of the electrolysis process in the experimental setup.

Computer, Gas Sensor, and Arduino Card The computer, gas sensor, and Arduino card are essential components of the experimental model for studying hydrogen production through alkaline water electrolysis. Here's a brief overview of their roles:



Figure 4.4: Gas Sensor and Arduino Card

1. Computer: The computer is used for monitoring and controlling the experiment. It can gather data from various sensors and devices, control the operation of the electrolyzer and other components, and analyze the results of the experiment. The computer provides a centralized interface for managing the experimental process.

2. Gas Sensor: The gas sensor is used to detect and measure the gases produced during electrolysis, such as hydrogen and oxygen. It provides real-time data on gas production rates and can be used to monitor the efficiency of the electrolysis process.

3. Arduino Card: The Arduino card is likely used for data acquisition and control within the experimental setup. It can interface with various sensors and devices, including the gas sensor and possibly other components of the electrolyzer. The Arduino card can be programmed to perform specific tasks related to the experiment, such as controlling the voltage generator or collecting data from sensors.

Overall, these components work together to provide a comprehensive and controlled experimental setup for studying hydrogen production through alkaline water electrolysis.

Fuel Cell A fuel cell is an electrochemical device that converts the chemical energy of a fuel, such as hydrogen, directly into electrical energy. It operates similar to a battery but can produce electricity continuously as long as fuel is supplied. The basic components of a fuel cell include:



Figure 4.5: Fuel Cell

1. Anode: Where the fuel (e.g., hydrogen) is oxidized, releasing electrons.

2.Cathode: Where oxygen (usually from the air) is reduced by the electrons and typically a catalyst.

3. Electrolyte: A substance that allows ions (charged particles) to move between the anode and cathode, but prevents the mixing of the fuel and oxidant.

4.Electrical Circuit: Connects the anode and cathode, allowing the flow of electrons and generating electrical current.

5.Proton Exchange Membrane (PEM): A type of electrolyte used in PEM fuel cells that allows only protons to pass through, while blocking electrons.

6.Catalyst: Usually made of platinum or similar material, used to facilitate the reaction at the electrodes without being consumed.

Fuel cells are known for their high efficiency, low emissions, and quiet operation, making them ideal for a wide range of applications, from portable electronics to stationary power generation and transportation.

4.2 Experiment Protocol for Electrolyzer Sonohydrogen Production with Silver Electrodes

4.2.1 Objective

To evaluate the performance of an electrolyzer sonohydrogen production system using silver electrodes.

4.2.2 Equipment and Materials

- Voltage generator (alternative to a wind turbine)

- Electric wire
- Silver electrode electrolyzer
- Ultrasonic generator
- Computer
- Gas sensor
- Arduino Card
- Fuel cell

4.2.3 Experimental Setup

1. Set up the voltage generator to provide power to the electrolyzer.
2. Connect the electric wire to the electrodes of the electrolyzer.
3. Ensure the ultrasonic generator is connected to the electrolyzer for ultrasound assistance.
4. Connect the gas sensor to the system to measure hydrogen production.
5. Ensure the Arduino Card is ready to collect and process data from the sensors.

4.2.4 Procedure

1. Start the voltage generator to power the electrolyzer.
2. Activate the ultrasonic generator to assist in the electrolysis process.
3. Begin data collection on the computer to monitor hydrogen production rates.
4. Record the initial conditions, including voltage, current, and gas sensor readings.
5. Monitor the system for a specified period, collecting data at regular intervals.
6. Analyze the data to determine the efficiency and effectiveness of the system.
7. Adjust parameters such as voltage, current, and ultrasonic intensity to optimize hydrogen production.
8. Repeat the experiment with different settings to explore the system's performance under various conditions.

4.2.5 Safety Precautions

- Ensure proper ventilation in the experimental area to prevent the accumulation of hydrogen gas.
- Wear appropriate personal protective equipment, such as gloves and goggles, when handling chemicals or operating equipment.
- Follow all manufacturer instructions for the safe use of equipment and materials.

4.2.6 Data Analysis

- Calculate the hydrogen production rate based on the gas sensor readings.
- Analyze the effect of different parameters on hydrogen production, such as voltage, current, and ultrasonic intensity.
- Compare the performance of the system with silver electrodes to traditional electrolyzer systems.

4.2.7 Hydrogen Production Methods

Hydrogen can be produced via five main categories of technologies, namely, thermochemical, electrochemical, photobiological, photoelectrochemical, and the new innovative approach of sono-hydro-gen. The table below presents a brief illustration and a comparison between the five main categories of hydrogen production in terms of fundamental theory and remarks [41].

Method	**Fundamental Theory**	**Remarks**
Thermochemical	High-temperature reactions (e.g., steam gas reforming)	Not environmentally friendly; high CO_2 emissions
Electrochemical	Electrical power to split water (water electrolysis)	Requires high electrical power
Photobiological	Natural photosynthesis (bacteria/green algae)	Slow production rate
Photoelectrochemical	Solar energy for water splitting in one step	Instability of semiconductor materials
Sono-Hydro-Gen (Innovative)	Ultrasound waves to liquid water	Potentially efficient; infinite production

Table 4.1: Comparison of Hydrogen Production Methods

4.2.7.1 Sono-Hydro-Gen Process

When ultrasound waves with high frequency pass through liquid water, they lead to severe vibrations of water that result in generating acoustic cavitation bubbles. Intense ultrasonic waves within the frequency range of 20 to 1100 kHz traveling through liquids trigger small acoustic cavities that grow, oscillate, enlarge, and implode in a sequence, creating a tremendous amount of heat. When the bubbles oscillate, they create high-velocity jets and shear forces on the bulk water surrounding them. The collapse generates a shock wave with very high amplitude that can reach up to 10,000 atmospheres. The intensity of the shock wave mostly depends on different aspects, including the ultrasound frequency, the acoustic power, and the bulk temperature.

After the collapse, enormous temperature and pressures are generated due to the absorption of sound waves; the temperature can reach up to 5000 K, and the pressure can go up to 2000 atmospheres within the bubbles. These extreme conditions provide an unusual chemical environment. When the collapse takes place, each bubble acts as a microreactor within which typical flame reactions occur. These microbubbles are effectively acting as microcombustors where a combustion chemistry or reaction takes place. The collapse due to the impact of the ultrasound waves leads to the formation of hydrogen molecules, as illustrated in Figure 4.6.

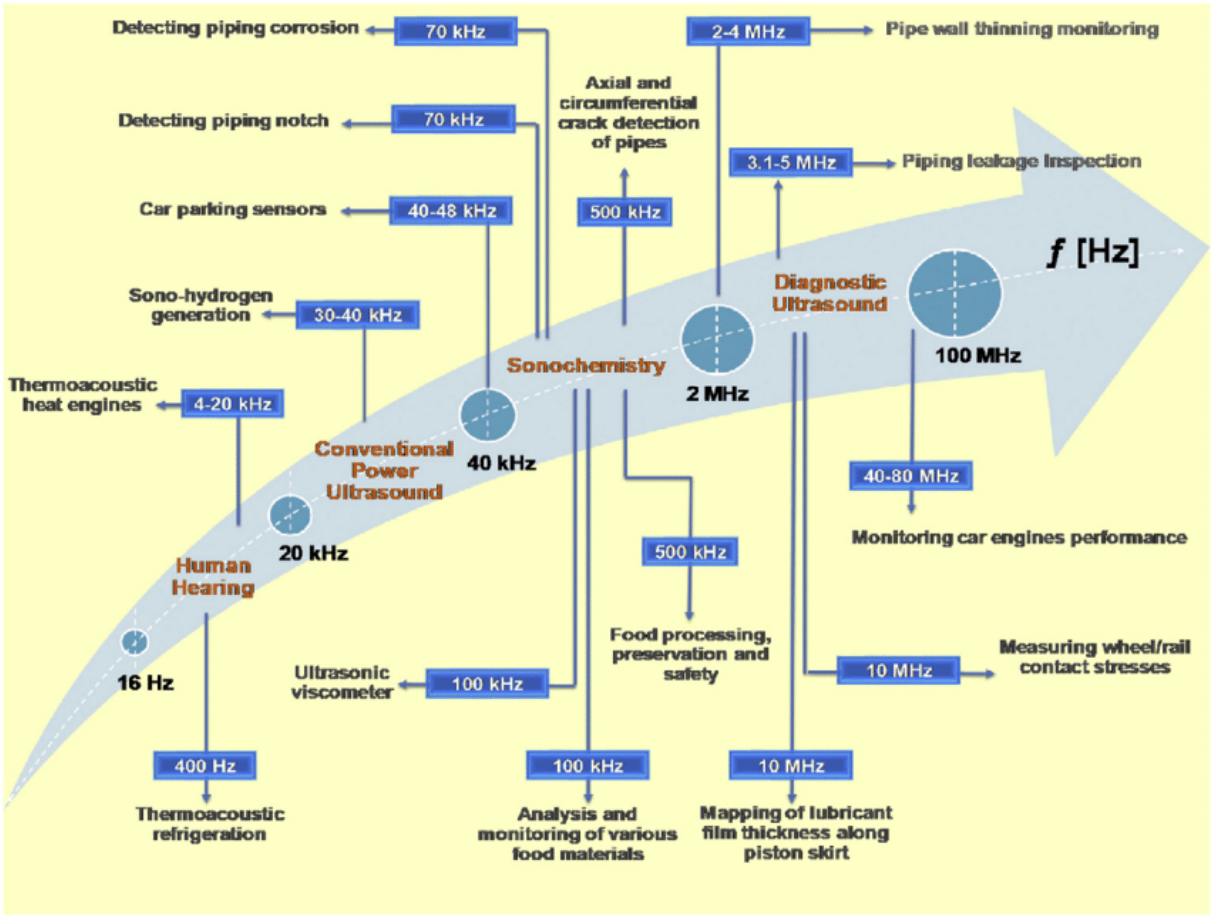


Figure 4.6: A summary of sound wave industrial applications.

The process involves five consecutive stages:

(a) An ultrasound probe immersed in a water container emits sound waves through the water with a frequency range between 20 and 40 kHz.

(b) Acoustic cavitation bubbles are generated at the bottom-fixed surface of the water container.

(c) Sequence and dynamics of acoustic cavitation bubbles involve four consecutive and instantaneous stages: (1) bubble formation, (2) successive growth, (3) collapse, and (4) microjets.

(d) The water vapor molecules dissociate into highly reactive hydroxyl and hydrogen radicals.

(e) The highly reactive radicals combine together to form hydrogen molecules and oxygen.

Table 4.2: A conceptual illustration of different hydrogen production methods

Hydrogen Production Methods	**Theory Beyond Each Method**	**Remarks [Commercial]**
Thermochemical (steam reforming)	$CH_4 + 2H_2O + h_{\text{thermal}} \rightarrow 4H_2 + CO_2$	Not environmentally friendly as carbon dioxide is produced (9–12 t of CO_2/1 t H_2)[3]
Electrochemical (water electrolysis)	$H_2O + h_{\text{electrical}} \rightarrow H_2 + \frac{1}{2}\ O_2$	Not environmentally friendly as it requires high electrical energy in the range of (53.4–70.1 kWh/1 kg of hydrogen)[4]
Photobiological	$2H_2O + CO_2 +$ algae/cyanobacteria $+ h_{\text{solar}} \rightarrow O_2 + 4e^- + 4H^+ \rightarrow 2H_2$	Environmentally friendly, however, it has very low and slow production rate in the range of (0.07–96 mmol H_2 L^{-1} h^{-1})[5]
Photoelectrochemical	$H_2O + h_{\text{solar}} \rightarrow H_2 + \frac{1}{2}\ O_2$	Environmentally friendly, the challenge lies on the durability material and the steady operation. The cost of hydrogen production is (17.3 \$/kg of H_2)[6]
Sono-hydro-gen	$H_2O + h_{\text{sound}} \rightarrow OH^* + H^*$ $OH^* + H^* \rightarrow H_2 + O$	Environmentally friendly, sustainable, durable, and low-energy consumption. Production rate of 0.8 μM min^{-1} at acoustic intensity of (0.6 W cm^{-2})[7]

4.2.7.2 Technology that increases green hydrogen production 14-fold at lower cost

Australian researchers have introduced a groundbreaking technology that can produce green hydrogen more affordably and efficiently. Scientists from the Royal Institute of Technology in Melbourne (RMIT) have demonstrated a method to significantly increase clean fuel production using sound waves during electrolysis, compared to traditional techniques. This innovation is poised to have a profound impact on the costly and rare materials presently employed in the electrolysis process. Green hydrogen is regarded as an ideal solution for industries with challenging emissions reductions, playing a crucial role in mitigating carbon emissions and addressing the climate crisis. Produced by splitting water molecules into hydrogen and oxygen through water electrolysis using renewable energy sources, green hydrogen currently accounts for a small fraction of global hydrogen production due to its high production costs and energy requirements.

The recent study, published in Advanced Energy Materials, reveals that sound waves can enhance hydrogen production during electrolysis by up to 14 times compared to

conventional methods. This advancement could significantly reduce the costs associated with green hydrogen production.

Lead researcher, Assistant Professor Amjad Rizk, highlighted that the technology addresses key challenges in clean hydrogen production, particularly the high cost of electrode materials like platinum or iridium. By utilizing sound waves to facilitate hydrogen extraction from water, the necessity for expensive and corrosive materials can be eliminated.

Rizk explained, "Since water is not a corrosive electrolyte, more affordable electrolytic materials, such as silver, can be used." This breakthrough opens up possibilities for using low-cost electrode materials and avoiding highly corrosive electrolytes, potentially revolutionizing the economics of green hydrogen production.

The research also addressed the issue of hydrogen and oxygen bubble accumulation on electrodes, which impedes the electrolysis process. By utilizing sound waves, the researchers were able to prevent bubble build-up, enabling faster electrolysis rates. This development enhances electrode conductivity and stability, improving conversion efficiency and resulting in a 27% net energy saving.

Professor Leslie Yu, also from RMIT, noted that this discovery could be applied to other applications where bubble accumulation on electrodes is problematic, further extending the impact of this technology.

4.3 Conclusion

The experiment aimed to evaluate the feasibility of using the electrolyzer (sono_hydro_gen) with silver electrodes to produce sonic hydrogen as a clean and sustainable energy source.

Furthermore, the experiment demonstrates that producing sonohydrogen using silver electrodes could be a viable option for clean energy generation. This process is efficient, producing high-quality hydrogen with minimal energy input. Additionally, the use of silver electrodes reduces the environmental impact compared to traditional electrodes, making them a more sustainable option.

The production of sonohydrogen using silver electrodes is a promising source of clean and sustainable energy that requires further research and development.

Chapter 5

Simulations and Result of System

5.1 Introduction

This chapter presents the results of the simulation conducted to evaluate the hydrogen extraction system powered by wind energy with integrated storage solutions. The primary focus of this study is to analyze the performance and efficiency of the system components, which include wind turbines, electrolyzers, and storage units, in the overall hydrogen production process. The system under investigation harnesses wind energy to power an electrolyzer that splits water into hydrogen and oxygen. The hydrogen produced is stored for later use, ensuring a continuous and reliable supply of hydrogen even when wind conditions are variable. The block diagram of the system is depicted in Figure 5.1.

5.1.1 simulations of the system

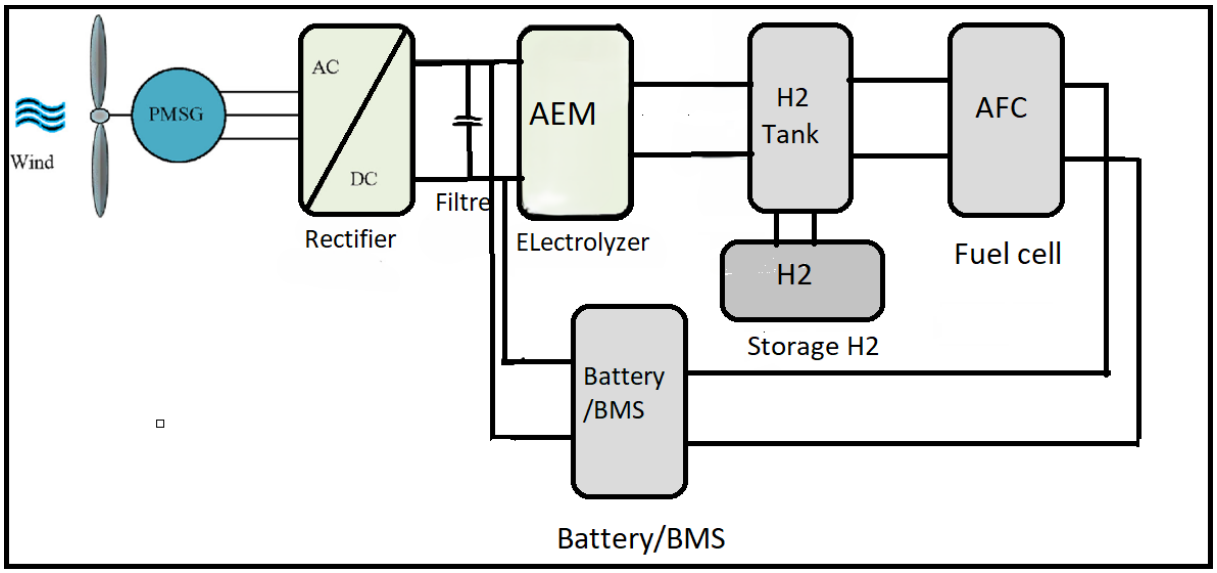


Figure 5.1: Schema of the General system

The simulations were carried out using the SimPowerSystems tool within the SimScape environment in Matlab. The input wind energy was modeled to simulate varying wind conditions, providing realistic scenarios for the system's operation. Key metrics analyzed in this study include the performance of the electrolyzer, the efficiency of hydrogen production, and the effectiveness of the storage solutions. A Boost converter is employed in the system to manage the voltage levels between the wind turbine output and the electrolyzer input. This converter plays a crucial role in optimizing power transfer and ensuring efficient operation of the electrolyzer. Additionally, the integration of storage systems allows excess hydrogen produced during periods of high wind availability to be stored and utilized during periods of low wind, thereby enhancing the system's overall efficiency and reliability. This chapter details the simulation setup, presents the results, and provides a comprehensive analysis of the system's behavior under different operational conditions. The findings offer valuable insights into the viability and effectiveness of using wind energy coupled with storage solutions for sustainable hydrogen production.

5.1.2 Simulation Setup

This section describes the simulation setup, including details about the wind energy input, electrolyzer configuration, storage solutions, and the Boost converter specifications.

5.1.2.1 Wind System and Electrolysis

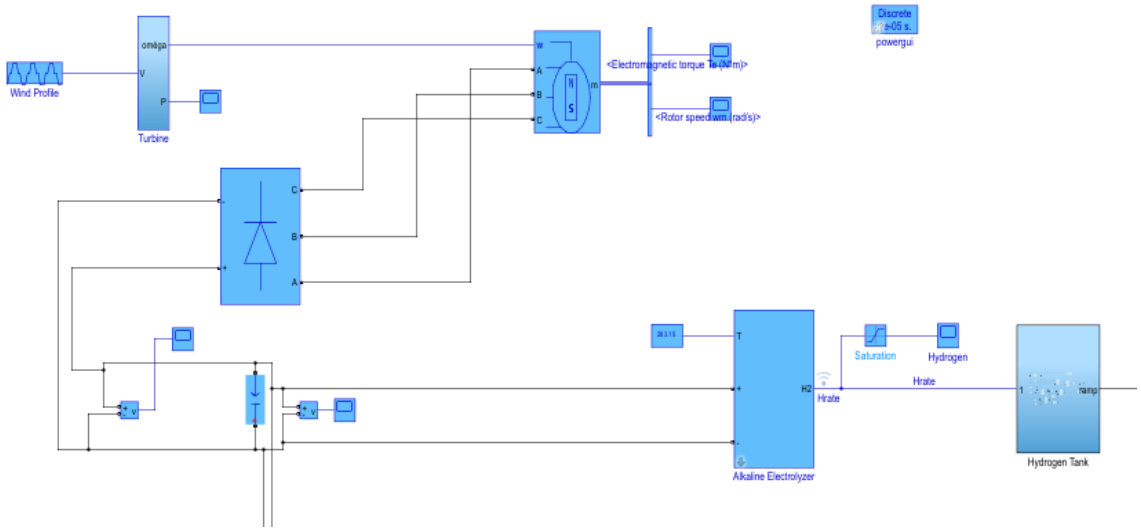


Figure 5.2: Block representation of Wind and Electrolysis system model in MATLAB/Simulink

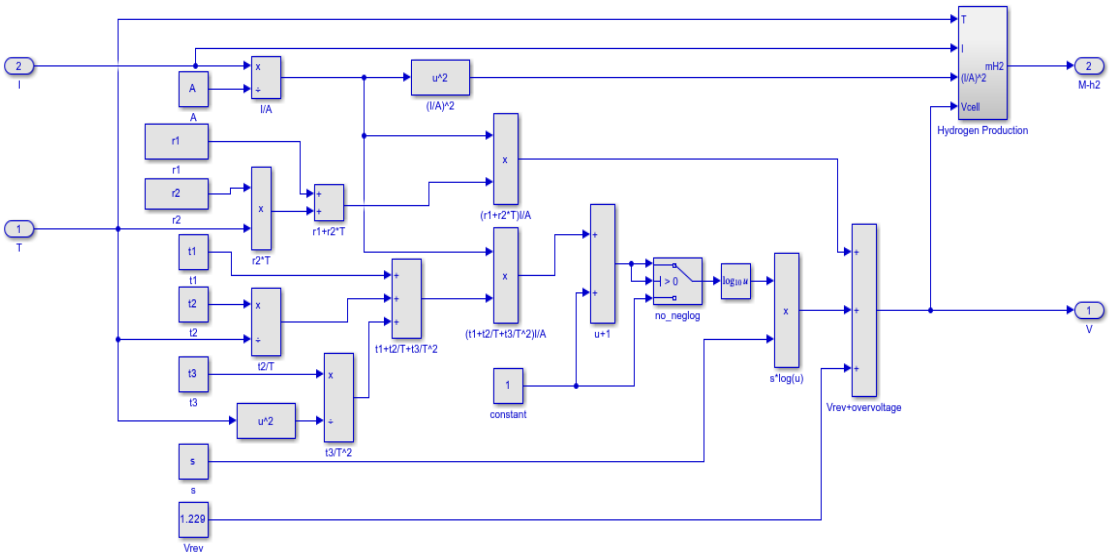


Figure 5.3: Block representation of Electrolysis system model in MATLAB/Simulink

5.1.2.2 Storage System

Battery system

The battery system displayed in the following illustration exhibits the components connected to it. As the battery scope displays the state of charge, output voltage and current of the battery.

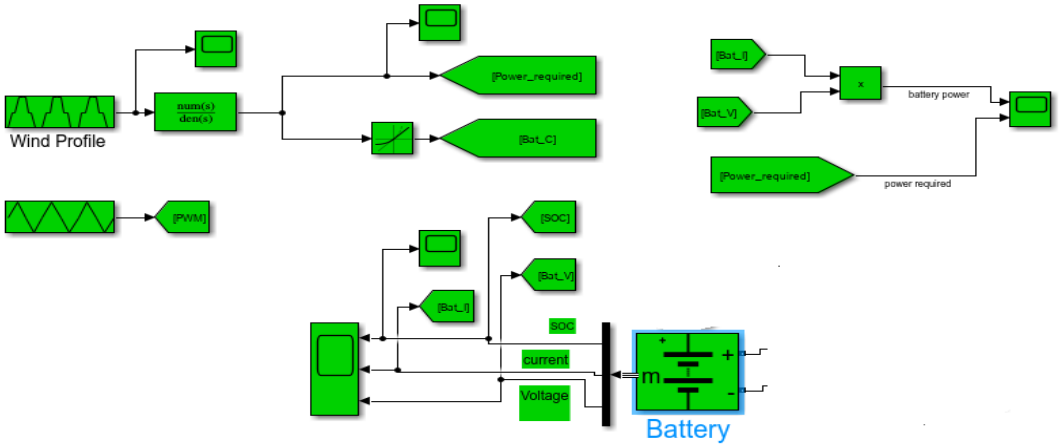


Figure 5.4: Block representation of Battery system model in MATLAB/Simulink

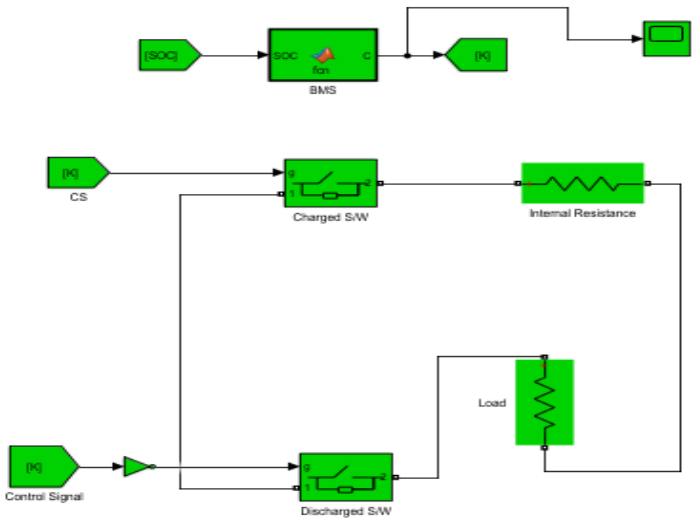


Figure 5.5: Block representation of Battery management systems model in MATLAB/Simulink

Fuel cell

In this study, one system (such as 2.4 kW – 48 Vdc) has been considered, and the basic block diagram of this system is shown in Figure 5.6 . By definition, it is well known that the Ramp function is a unary real function, simply estimable as the mean of the independent variable and its absolute value. It serves as the input source of this test system.

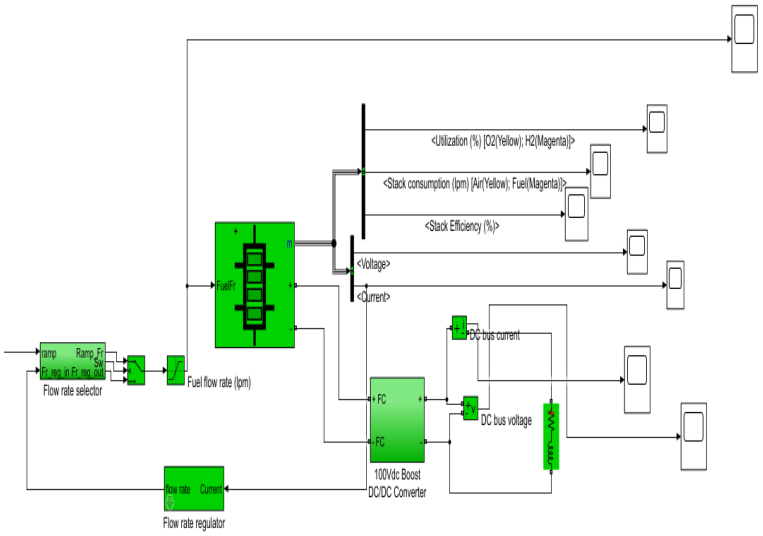


Figure 5.6: Block representation of model in MATLAB/Simulink

In this study, a Boost converter5.7 is used as a DC to DC power converter with an elevated output voltage compared to its input voltage. When the operating key is opened, the current will be minimized as the impedance is high. Initially, a magnetic field is created, but it will be destroyed to maintain the current flow towards the load. Therefore, the polarity will be reversed (meaning the left side of the inductor will now be negative). As a result, two sources will be in series causing a high voltage to charge the capacitor through the diode D.

The DC input to a Boost converter can come from various sources such as batteries, rectified AC from the mains supply, or DC from fuel cells, DC generators, and dynamos. This is the reason for using a Boost Converter in this study. The converter is loaded by an RL element in three systems, and the value of the RL element can be varied by this system. For instance, since the system is 2.4 kW – 48 Vdc, the value of the RL element is 2.4 kW with a time constant of 1 second.

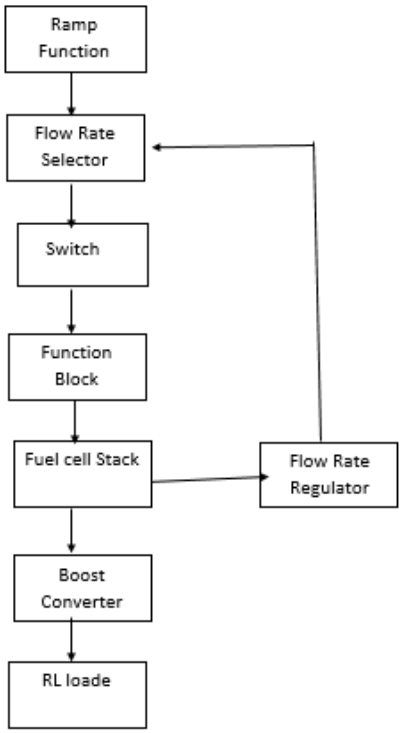


Figure 5.7: Block representation of 2.4 kW – 48 Vdc AFC system

Inside representation of Fuel Cell Stack (above Figure **??**) has been presented in Figure 5.8 below.

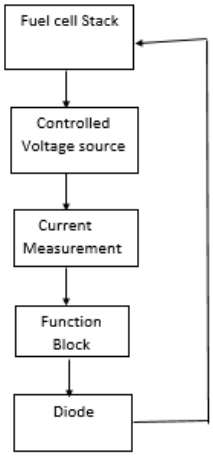


Figure 5.8: Block representation of Fuel cell stack

The prime essence which has driven the boost converter is the propensity of an inductor to endure changes in flow of electrons by generating as well as wrecking a magnetic field. It has been known to all, in a boost converter, the output voltage is always higher than the input voltage. A block representation of boost converter is shown in Figure 5.9. When the switch has been closed, current flows through the inductor in clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.

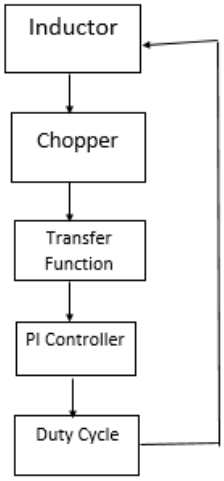


Figure 5.9: Block representation of Boost Converter

5.2 Results and Analysis

This section presents and analyzes the simulation results, focusing on the performance of the electrolyzer, the efficiency of hydrogen production, the effectiveness of the storage solutions, and the overall system efficiency under varying wind conditions.

5.2.1 Wind System Results

The following results reveal the generation of power from the wind system with respect to wind displacement, velocity, and the response of voltage in accordance with the power of a turbine. We applied variable wind speeds (6 m/s, 9 m/s, and 12 m/s). to obtain the following results:

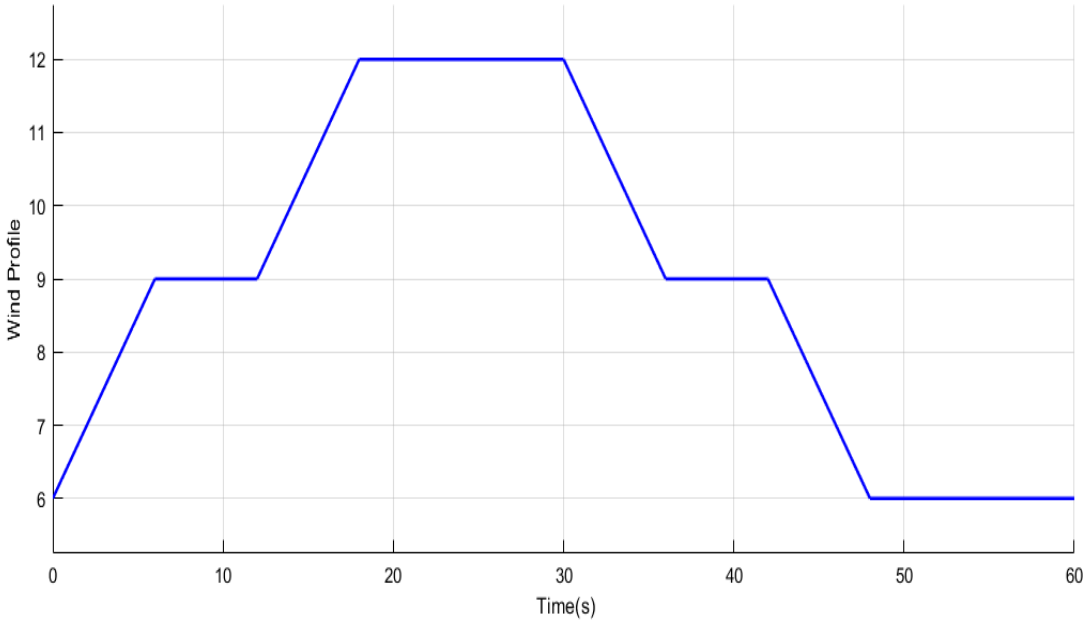


Figure 5.10: Wind Profile

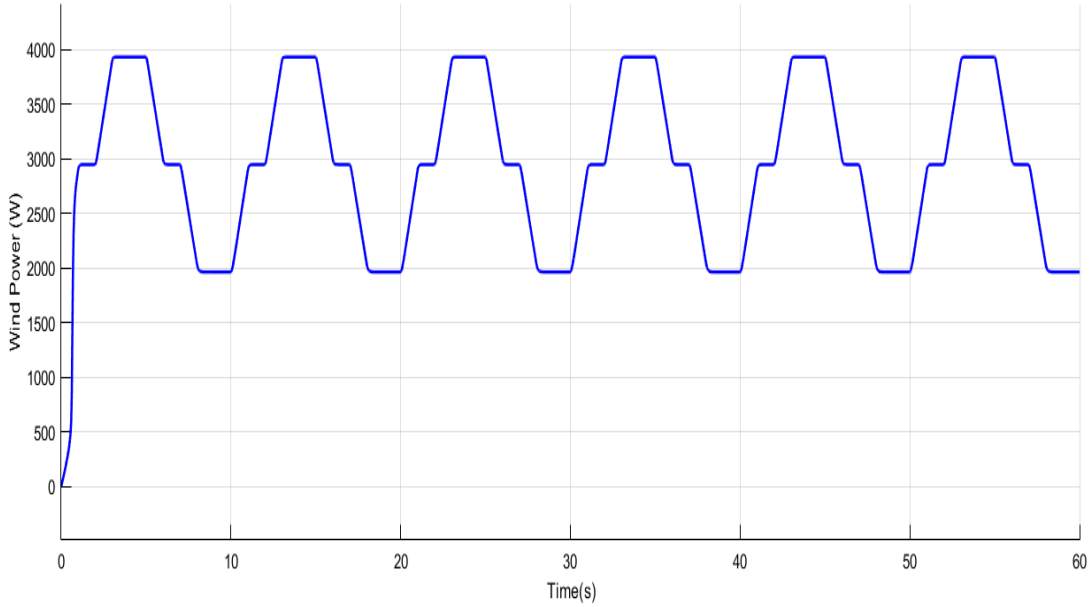


Figure 5.11: Wind Power

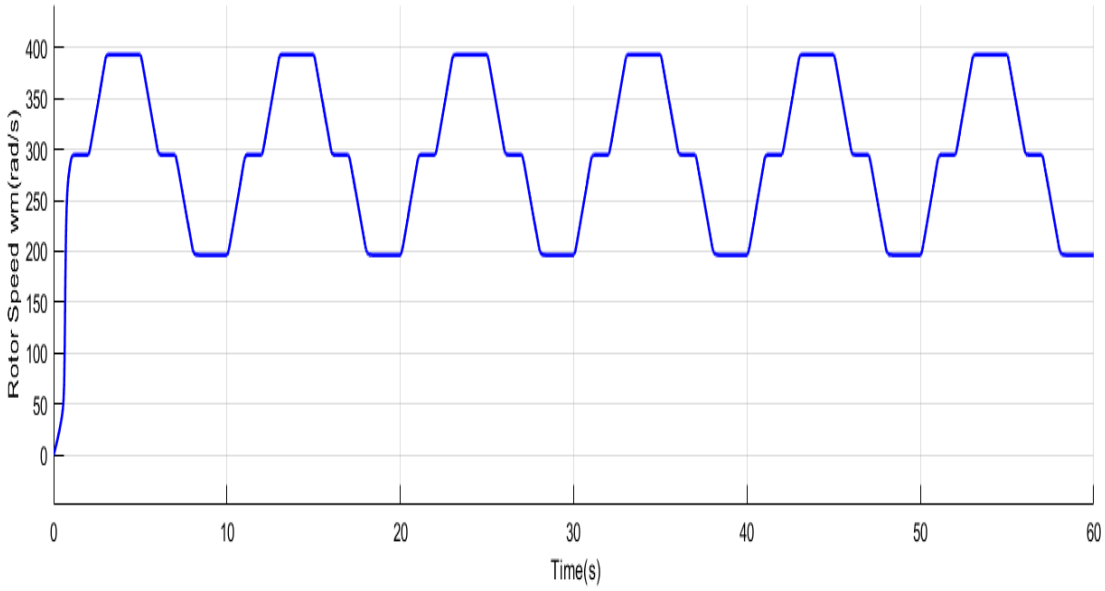


Figure 5.12: Rotor Speed

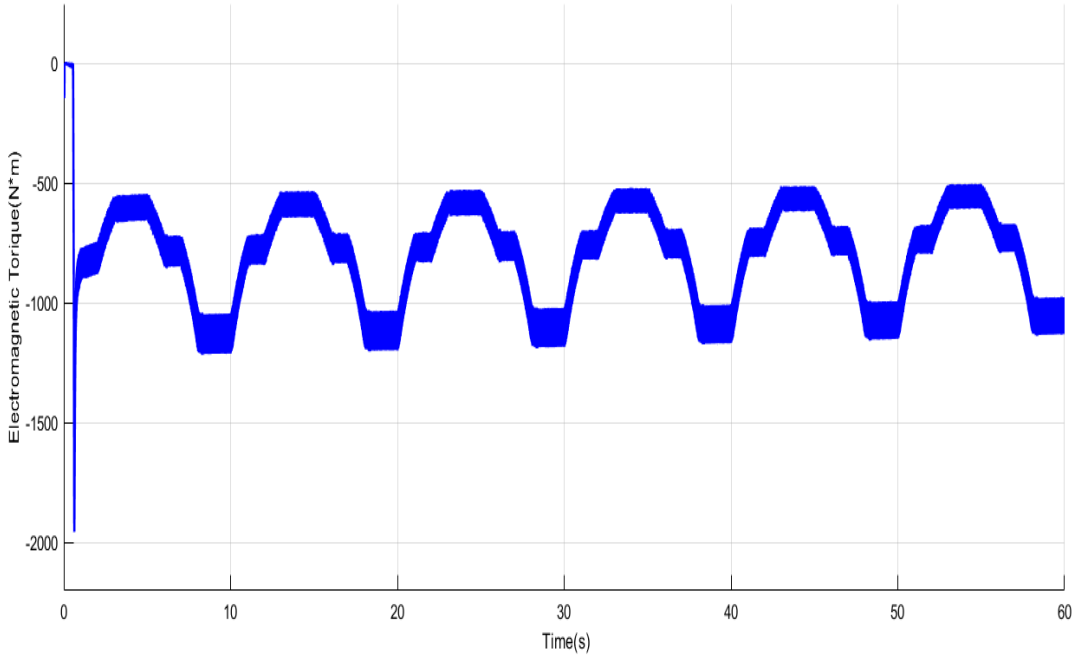


Figure 5.13: Electromagnetic Torique

5.2.2 Electrolysis Results

we present the results of the electrolysis process under variable wind speeds of 6 m/s, 9 m/s, and 12 m/s.

5.2.2.1 Hydrogen flow rate

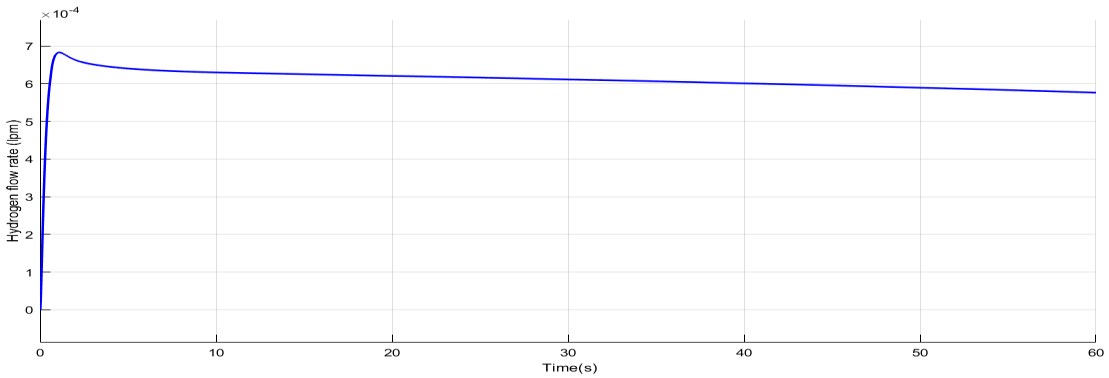


Figure 5.14: Hydrogen flow rate

5.2.2.2 The hydrogen storage system

The hydrogen storage system is an important component of the simulation process. The simulation results are analyzed to evaluate the performance of the system. Figure 5.15 shows the MATLAB/Simulink model of the hydrogen storage system.

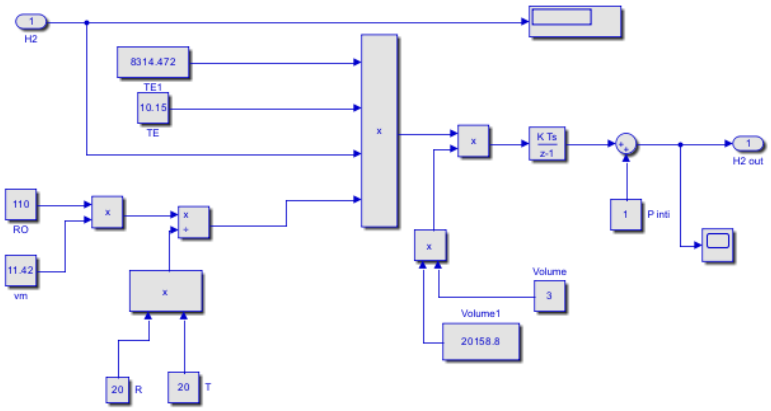


Figure 5.15: MATLAB/Simulink model of the hydrogen storage system

where P, P_{bi}, R, T_{b}, V_{b}, and T are the pressure of the tank in Pascals, the storage tank initial pressure in Pascals, the universal gas constant (J/kmol K), the operating temperature (K), the tank volume in m^3, and the temperature (T), respectively [39].

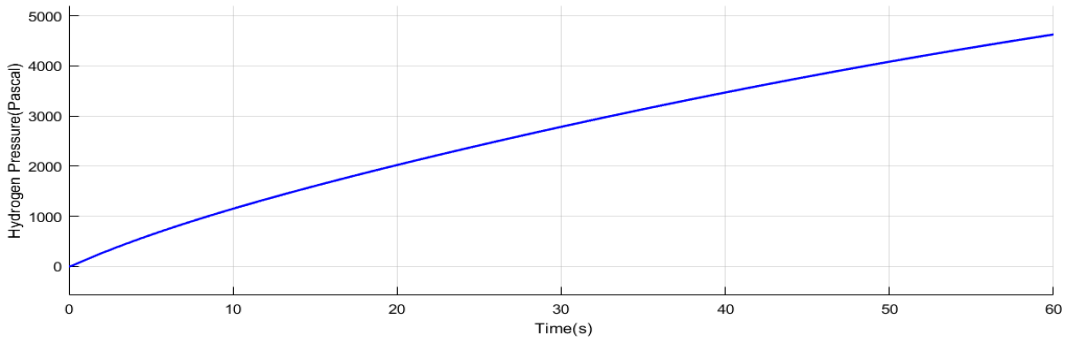


Figure 5.16: Pressure of compressed hydrogen tank

5.2.3 Storage Results

5.2.3.1 Battery system Results

The subsequent results shown in Figure 5.17 give the state of charge (SOC) with respect to the voltage and current. By knowing SOC, we can consider the capacity of a battery if it is completely charged or not. Also, the storage result of the battery:

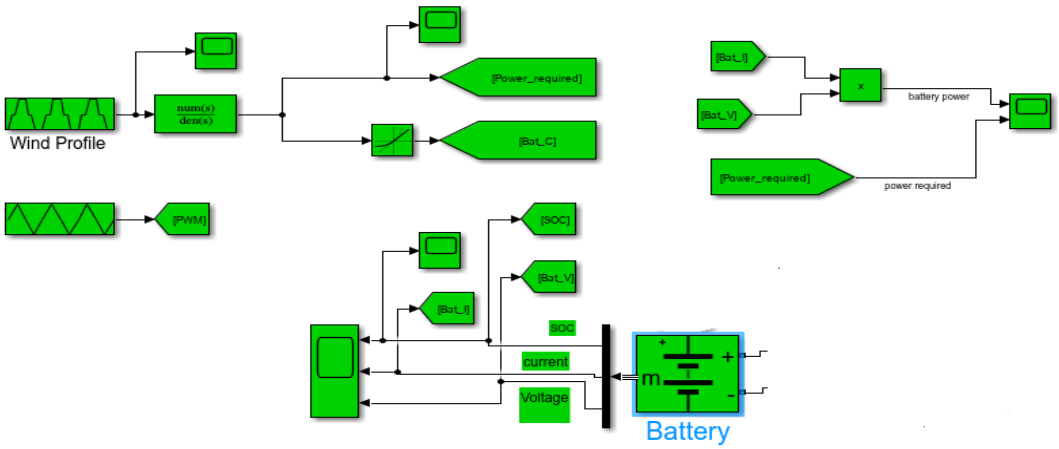


Figure 5.17: Battery Power

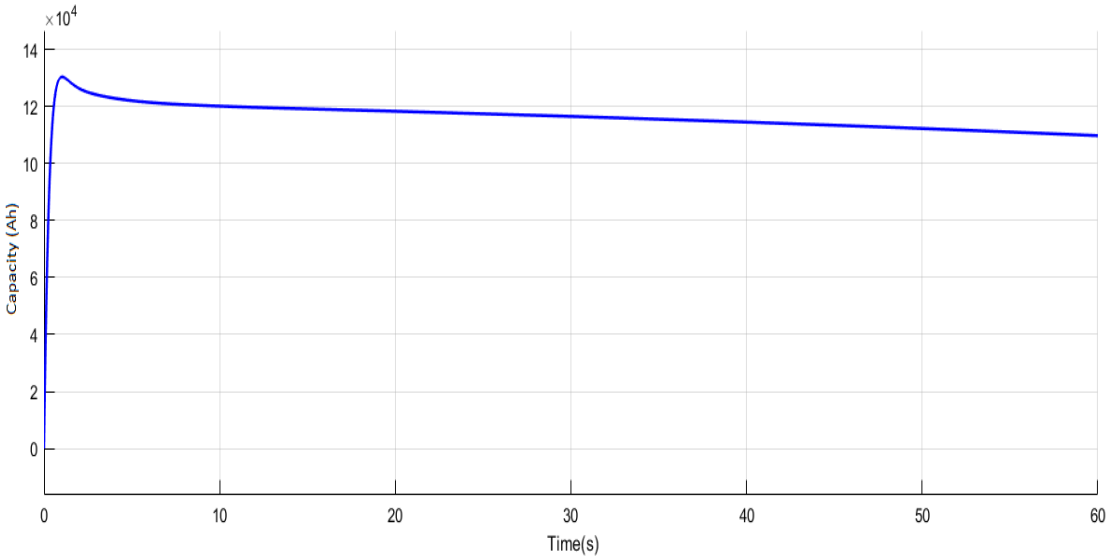


Figure 5.18: Capacity of battery

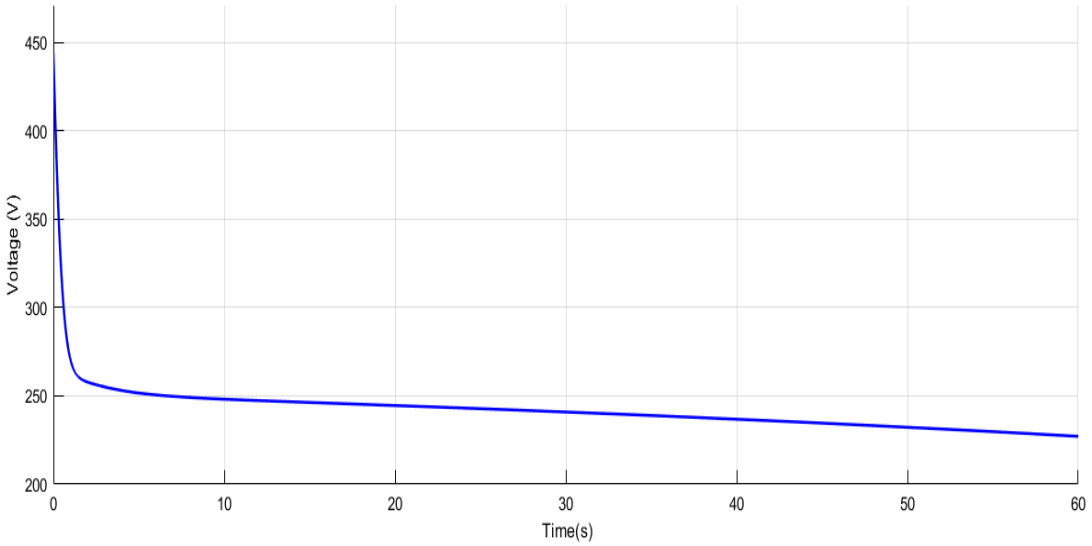


Figure 5.19: Voltage

5.2.3.2 State of Charge Measurement

The state of charge can be measured from the battery voltage. The following Figure 5.20 is taken from the built model which represents the discharge voltage graphical representation for the estimation of SOC.

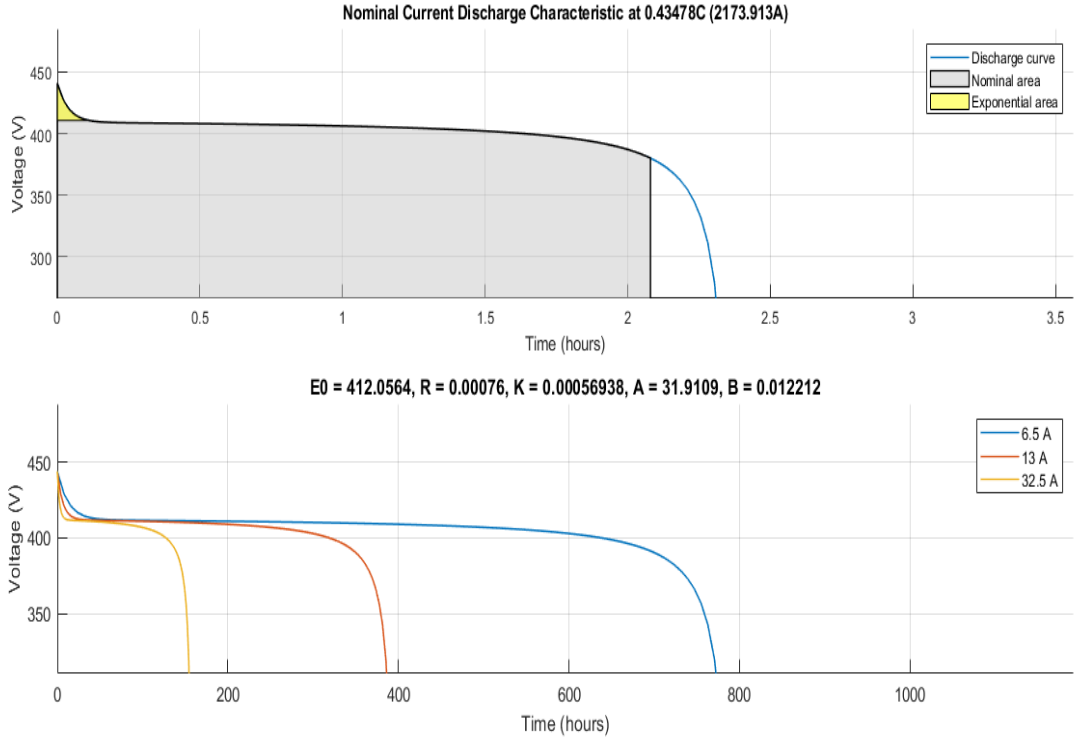


Figure 5.20: Discharge curve

5.2.3.3 Fuel cell Results

we present the results of the fuel cell system :

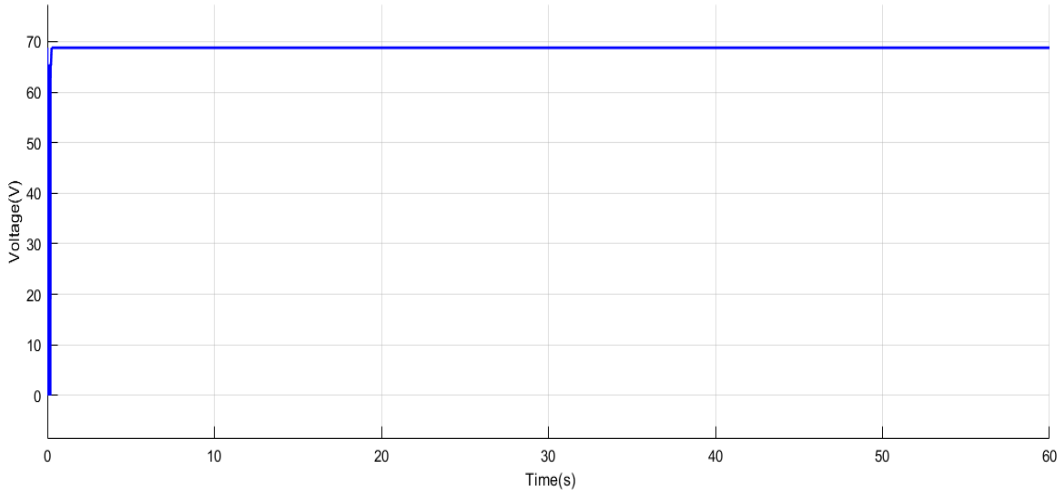


Figure 5.21: Voltage of Fuel cell

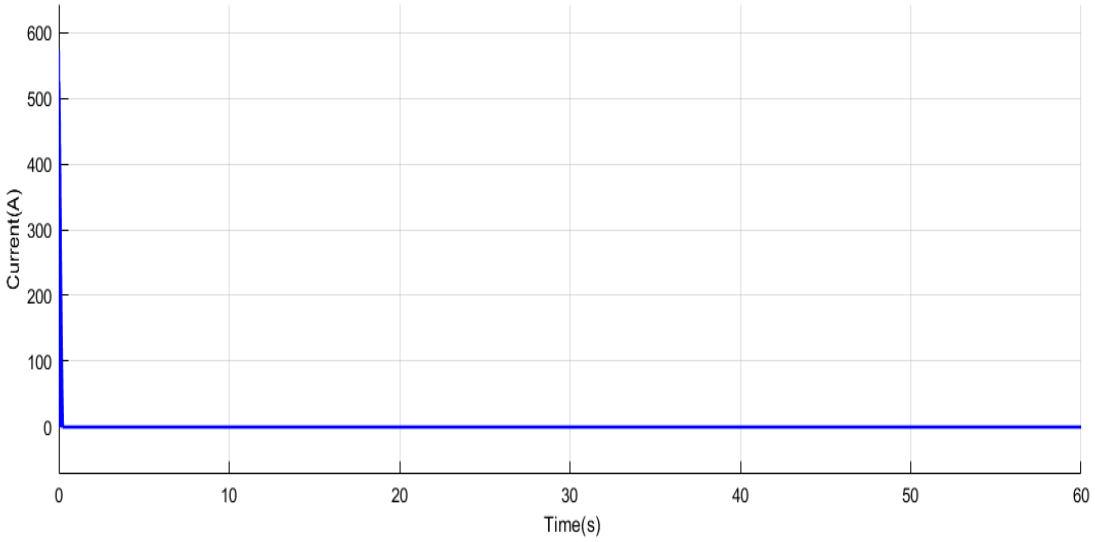


Figure 5.22: Current of Fuel cell

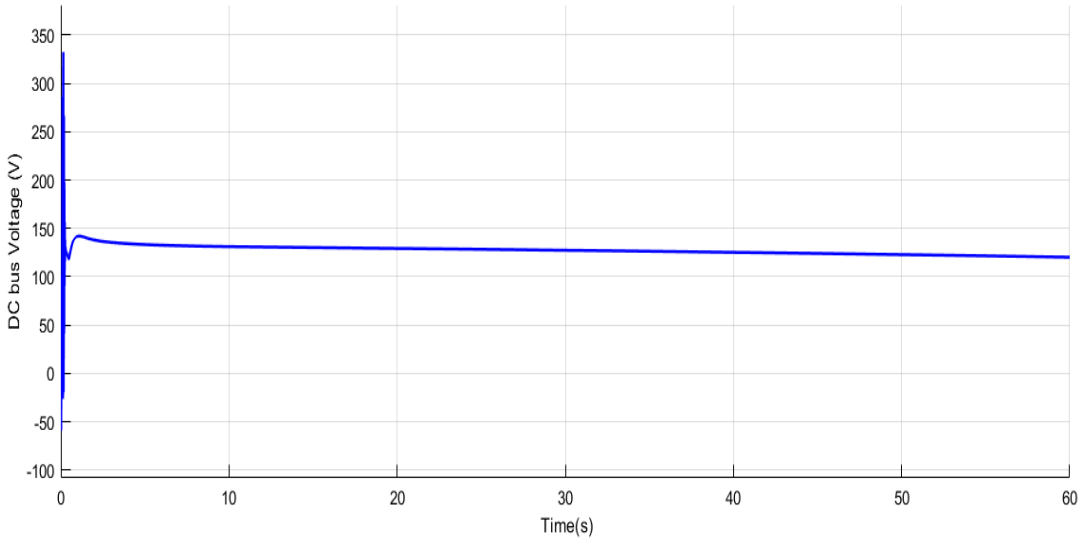


Figure 5.23: Voltage of Hacheur Boost

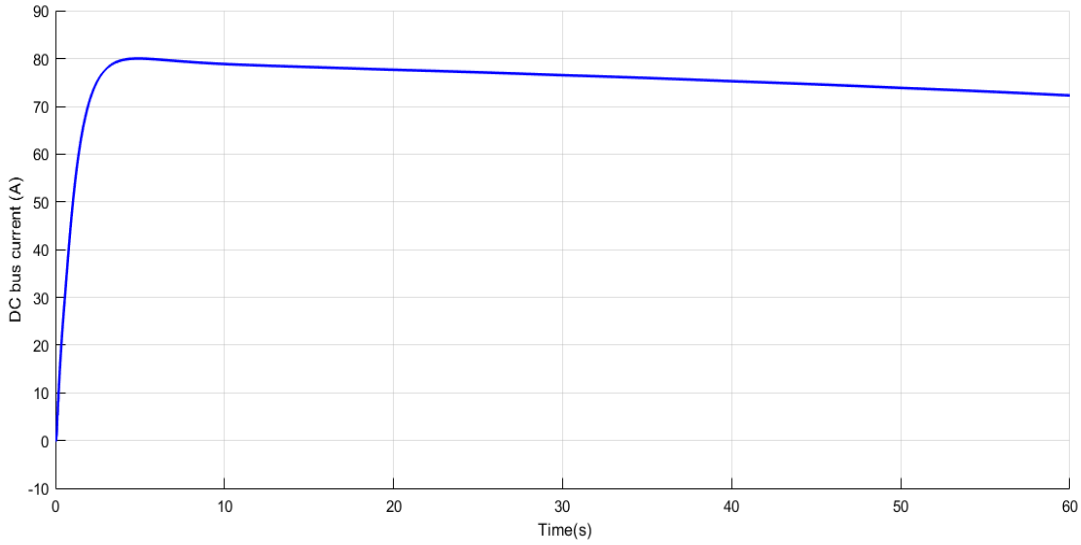


Figure 5.24: Current of Hacheur Boost

5.2.3.4 State of Charge Measurement

The state of charge can be measured from the fuel cell voltage. The following Figure 5.25 is taken from the built model which represents the discharge voltage graphical representation for the estimation of SOC.

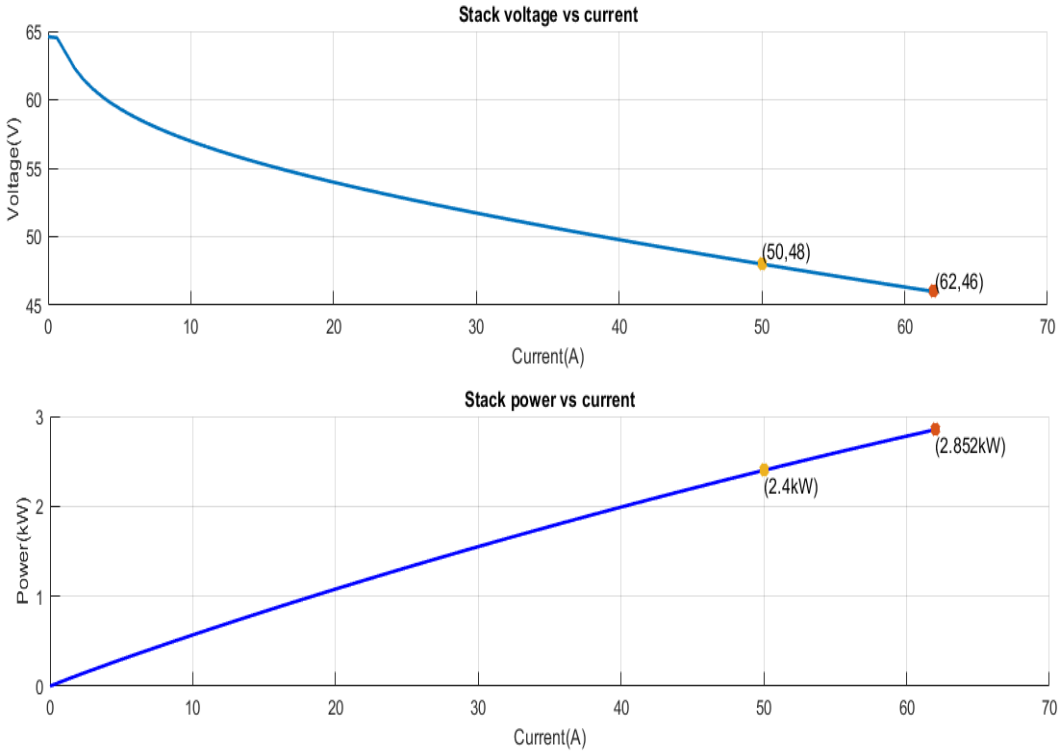


Figure 5.25: Discharge curve

5.3 Conclusion

The simulation results indicate that the hydrogen extraction system powered by wind energy with integrated storage solutions is a feasible and effective method for hydrogen production. The performance and efficiency of the system components—wind turbines, electrolyzers, and storage units—demonstrate the viability of this approach. By harnessing wind energy, the system ensures a sustainable and renewable source of power for hydrogen production. The ability to store hydrogen allows for a consistent and reliable supply, mitigating the variability of wind conditions. Overall, the study confirms that this integrated approach holds significant potential for contributing to the development of clean and sustainable energy solutions.

General Conclusion

The quest for sustainable energy solutions has propelled the development of advanced technologies for hydrogen production. This thesis explored the innovative integration of wind energy and ultrasound technology in electrolyzer systems, specifically focusing on the production of hydrogen through electrolyzer sonohydrogen production.

In Chapter I, we provided a comprehensive overview of hydrogen, including its historical context, various types, sources, and forms. We delved into the concept of green hydrogen, examining its production methods, properties, storage techniques, and applications, alongside an evaluation of hydrogen's advantages and disadvantages as an energy carrier. Furthermore, we explored water electrolysis technologies, with a particular emphasis on alkaline, proton exchange membrane, and anion exchange membrane electrolyzers. The chapter concluded with an in-depth discussion on wind energy, its theoretical foundations, and its integration with electrolyzers for hydrogen production, highlighting the synergies between these technologies.

Chapter II focused on the modeling and simulation of systems involved in wind energy conversion, covering synchronous generators such as Permanent Magnet Synchronous Generators (PMSGs), power converters including diode rectifiers and voltage inverters, and electrolyzers, particularly alkaline electrolyzers and their boundary conditions.

In Chapter III, we introduced various energy storage systems, discussing their classification and methods. We examined batteries (accumulators), the control mechanisms of Battery Management Systems (BMS), and fuel cells, as well as their integration with the system. The chapter provided a detailed analysis of the role of energy storage in ensuring the reliability and efficiency of hydrogen production systems.

Chapter IV detailed the realization of the electrolyzer sonohydrogen production system, describing the experimental apparatus and protocol, including the use of silver electrodes. We outlined the objective, equipment, experimental setup, procedure, safety precautions, and data analysis methods, as well as the potential application of ultrasound in enhancing hydrogen production efficiency.

Chapter V presented the outcomes of our system, beginning with an introduction to

the section's focus on results and analysis. We described the simulation setup, including configurations for the wind system, electrolysis, and storage system, and provided a detailed presentation and analysis of the simulation results. This analysis is crucial for understanding the system's performance and its potential for real-world applications.

The integration of ultrasound technology into electrolyzers, combined with the utilization of wind energy, offers a compelling solution for sustainable hydrogen production. The experimental and simulation results demonstrated the efficiency and reliability of the proposed system, showcasing its potential to revolutionize the field of hydrogen production.

In conclusion, this thesis has laid the groundwork for future research and development in the area of sustainable hydrogen production. The findings highlight the feasibility and advantages of using electrolyzer sonohydrogen production with wind energy, paving the way for further innovations and real-world applications in the pursuit of a greener and more sustainable energy future.

5.4 Future work

Future work could focus on optimizing the system's efficiency, exploring other renewable energy sources, and scaling up the technology for industrial applications.

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Appendix A

Project Guide

A.1 Project Proposal: Electrolyzer (Sono_Hydro_Gen) for Hydrogen Extraction by Wind System with Storage

A.1.1 Project Idea

The project aims to develop an innovative system that utilizes wind energy to produce hydrogen through an advanced electrolyzer, Sono_Hydro_Gen. This electrolyzer uses ultrasound technology to enhance the electrolysis process, thereby increasing efficiency and hydrogen yield. The system is designed to include an efficient storage solution, ensuring the availability of hydrogen for various applications, even when wind conditions are not ideal.

A.1.2 Proposed Values

— Innovation: Integrating wind energy with ultrasound-enhanced electrolysis technology.
— Sustainability: Providing a renewable and clean energy source, reducing reliance on fossil fuels.
— Efficiency: Improving hydrogen production efficiency through advanced electrolysis and optimized energy storage.
— Scalability: Designing a system that can be scaled for various applications, from small-scale setups to large industrial plants.

A.1.3 Work Team

— Project Manager: Amira Laghouati
— Technical Lead: Amira Laghouati

— Scientific Advisor: Pr. Moualdia Abdelhafidh and ZEMIRLINE Nassim
— Electrical Engineer: [Name], Specialist in Wind Energy Systems
— Mechanical Engineer: [Name], Specialist in System Integration and Design
— Software Engineer: [Name], Responsible for Simulation and Modeling
— Research Scientist: [Name], Focus on Hydrogen Production and Storage Technologies
— Environmental Analyst: [Name], Evaluating the Environmental Impact and Sustainability
— Economic Analyst: [Name], Conducting Cost Analysis and Feasibility Studies

A.1.4 Project Objectives

— Design and Development: To design and develop an integrated system combining wind energy, Sono_Hydro_Gen electrolyzer, and storage.
— Optimize Efficiency: To optimize the efficiency of hydrogen production through ultrasound-enhanced electrolysis.
— Performance Evaluation: To evaluate the system's performance under various wind conditions.
— Economic Viability: To assess the economic feasibility and potential market applications.
— Environmental Impact: To analyze the environmental benefits and sustainability of the system.

A.1.5 Timetable for Achieving the Project

1. Research and development phase.
2. Design and simulation phase.
3. Prototyping and testing phase.
4. Scaling up and deployment phase.

1.2 Innovative Aspects

1.2.1 Nature of Innovations

— Technological Innovation: Development of a novel ultrasound-enhanced electrolyzer.
— Process Innovation: Optimization of hydrogen extraction process for higher efficiency.
— Design Innovation: Creative system design for improved integration and performance.
— Material Innovation: Use of advanced materials for enhanced durability and efficiency.

— Integration Innovation: Innovative integration of wind energy, electrolyzer, and storage systems.

1.2.2 Areas of Innovations

— Efficiency: Higher efficiency in hydrogen production and storage.
— Cost-Effectiveness: Reduced cost of hydrogen production and storage.
— Environmental Impact: Lower environmental impact of hydrogen production and use.
— Scalability: Increased scalability for different applications and sizes.
— Reliability: Improved reliability and durability of the system.

1.3 Strategic Market Analysis

1.3.1 Market Sector Analysis

— Identification: Renewable energy sector.
— Market Size: Estimated market size of X billion.
— Growth Potential: High growth potential due to increasing demand for clean energy.
— Market Trends: Shift towards sustainable technologies, government incentives for renewable energy.

1.3.2 Competition Intensity

— Competitor Analysis: Major competitors include companies A, B, and C.
— Market Share: Competitors A, B, and C hold 60% of the market.
— Barriers to Entry: High initial investment, complex technology, and established brand presence are barriers to entry.

1.3.3 Marketing Strategy

— Target Audience: Industrial companies, government agencies, and research institutions.
— Value Proposition: Unique ultrasound-enhanced electrolyzer technology for higher efficiency and lower costs.
— Marketing Channels: Online advertising, industry conferences, partnerships with renewable energy organizations.
— Sales Strategy: Competitive pricing, direct sales to large customers, distribution partnerships for smaller customers.

— Promotion Plan: Advertising campaigns highlighting technology advantages, press releases, participation in industry events.

1.4 Production and Organization Plan

1.4.1 Production Process

— Step 1: Raw Material Procurement: Identify and procure high-quality materials needed for the electrolyzer and storage systems.
— Step 2: Manufacturing: Use advanced manufacturing techniques to produce the components of the Sono_Hydro_Gen electrolyzer.
— Step 3: Assembly: Assemble the components into a fully functional system, integrating wind turbines, electrolyzers, and storage units.
— Step 4: Testing and Quality Control: Conduct rigorous testing and quality control to ensure the system meets performance and safety standards.
— Step 5: Packaging and Distribution: Package the final products securely and distribute them to customers or deployment sites.

1.4.2 Supply

— Suppliers: Identify reliable suppliers for raw materials and components.
— Supply Chain Management: Develop a robust supply chain management strategy to ensure timely delivery of materials.
— Inventory Management: Implement an efficient inventory management system to track materials and components.

1.4.3 Labor

— Skilled Labor: Hire skilled workers with expertise in manufacturing, assembly, and quality control.
— Training Programs: Develop training programs to ensure all employees are proficient in the latest technologies and processes.
— Labor Management: Implement labor management practices to optimize productivity and maintain high morale among workers.

1.4.4 Key Partnerships

— Technology Partners: Collaborate with technology partners to access cutting-edge advancements and expertise.
— Research Institutions: Partner with research institutions for ongoing innovation and development.
— Industry Collaborations: Establish partnerships with other companies in the renewable energy sector to enhance market reach and share resources.
— Government and Regulatory Bodies: Work with government and regulatory bodies to ensure compliance with standards and access to incentives.

1.5 The Financial Plan

1.5.1 Costs and Burdens

1.5.2 Business Number

1.5.3 Table of Calculations of Expected Results

1.5.4 Treasury Plan

Appendix B

Business Model Canvas

Table B.1: Business Model Canvas for (Sono_Hydro_Gen) Project

<table>
<tr>
<td rowspan="2">Key Partners
•Technological partners for the development and integration of the electrolyzer and storage systems
•Manufacturing partners for mass production of the electrolyzer
•Distribution partners to reach target customers</td>
<td>Key Activities
•Research and development to improve electrolyzer technology
•Marketing and sales activities
•Customer support and feedback management</td>
<td rowspan="2">Value Propositions
•Sustainable hydrogen production using renewable energy sources
•High efficiency and reliability of the electrolyzer
•Scalability for various applications, from small-scale to large-scale hydrogen production</td>
<td>Customer Relationships
•Online customer support for troubleshooting and inquiries
•Regular updates on product features and improvements
•Gathering customer feedback to enhance the product</td>
<td rowspan="2">Customer Segments
•Industrial companies seeking sustainable energy solutions
•Transportation companies looking for alternative fuels
•Renewable energy advocates promoting green energy initiatives</td>
</tr>
<tr>
<td>Key Resources
•Electrolyzer technology and intellectual property
•Manufacturing facilities
•Research and development team
•Sales and marketing team</td>
<td>Channels
•Online sales through company website and social media
•Partnerships with industrial and transportation companies
•Participation in trade shows and industry events</td>
</tr>
<tr>
<td colspan="3">Cost Structure
•Research and development costs
•Manufacturing and production costs
•Marketing and sales expenses
•Customer support and maintenance costs</td>
<td colspan="2">Revenue Streams
•Sales of electrolyzers
•Licensing the technology to other companies
•Maintenance and support services</td>
</tr>
</table>

Appendix C

Fuel Cell Characteristic

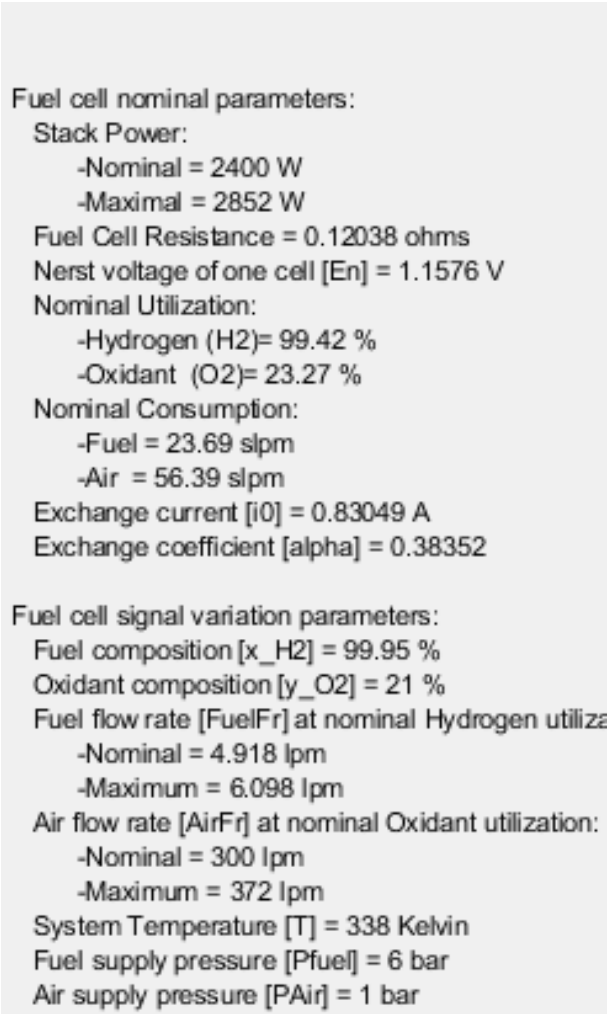


Figure C.1