UNIVERSITY OF LJUBLJANA

Faculty of Mechanical Engineering

Generation of green hydrogen with electrolysis using wind energy

Diploma thesis of the Erasmus+ Student Mobility for Studies programme

Enrique Celdrán Muñoz

Ljubljana, June 2023

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Mentor: Assist. Prof. Mitja Mori

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THESIS TOPIC APPLICATION

Erasmus+ Student: Enrique Celdrán Muñoz

Study Programme: Erasmus+ Student Mobility for Studies

Thesis topic for: Diploma Thesis

Number of the thesis topic: VS I/2011 E

Thesis topic title in English language: Generation of green hydrogen with electrolysis using wind energy

Thesis topic title in Slovene language: Proizvodnja zelenega vodika z uporabo vetrne energije

Disposition of the thesis in English language:

In the thesis, the production of green hydrogen using wind energy is studied. Green hydrogen is very important for the green energy transition in Europe and its production needs to be studied in more detail. The work investigates the energy conversion from wind kinetic energy to electricity using wind turbines and the production of green hydrogen using a proton exchange membrane water electrolyzer (PEMWE), where water is split into hydrogen and oxygen. All the technologies involved have technical and operational limitations and linking them together to form an energy system means that the fundamental properties of each technology must be studied before they are integrated into the energy system. The first part of the thesis is a more theoretical part, where student study (i) the fundamentals of wind technology (wind kinetic energy, Betz law, wind turbine power curve, wind energy availability) and (ii) the fundamentals of PEMWE technology (chemical reactions, composition of PEMWE and commercial electrolyzers, polarization curve, specificity of hydrogen as fuel). In the second part, the first part will be complemented by experimental work with a micro-laboratory system consisting of a micro-wind turbine placed in a wind tunnel and a micro-PEMWE for green hydrogen production. Based on the measurements of the characteristics of the wind turbine and the limitations of the PEMWE, the operation of the system must be optimized to produce a maximum amount of hydrogen by coupling the two technologies. The student tasks will be to:

- Conduct a literature review on the characteristics of wind turbines and electrolyzers.
- Describe the experimental system to be used and its characteristics.
- Create an experimental matrix for the experimental work.
- Perform measurements according to the experimental plan.
- Analyze the results and compare the obtained results with the theoretically expected ones.

Note: Thesis must be submitted in linguistically and terminologically correct English language. The student must submit and defend his/her thesis during his/her study exchange at the Faculty of Mechanical Engineering, University of Ljubljana.

- Draw relevant conclusions and provide an outlook for future work.

Disposition of the thesis in Slovene language:
V diplomskem delu je obravnavana proizvodnja zelenega vodika z uporabo vetrne energije. Zeleni vodik je zelo pomemben za zeleni prehod na področju rabe energije v Evropi in njegovo proizvodnjo je treba podrobneje preučiti. Delo raziskuje pretvorbo energije iz kinetične energije vetra v električno energijo z uporabo vetrnih turbin in proizvodnjo zelenega vodika z uporabo elektrolizerja s protonsko izmenjevalno membrano (PEMWE), kjer se voda razcepi na vodik in kisik. Vse obravnavane tehnologije imajo tehnične in obratovalne omejitve in njihovo povezovanje v enoten energetski sistem pomeni, da je treba preučiti temeljne lastnosti vsake tehnologije, preden se vključi v energetski sistem. Prvi del diplomske naloge je bolj teoretični del, kjer študent preučuje (i) osnove vetrne tehnologije (kinetična energija vetra, Betzov zakon, krivulja moči vetrnih turbin, razpoložljivost vetrne energije) in (ii) osnove tehnologije PEMWE (kemijske reakcije, sestava PEMWE in komercialnih elektrolizerjev, polarizacijska krivulja, specifičnost vodika kot goriva). V drugem delu bo teoretičen del dopolnjen z eksperimentalnim delom z mikro-laboratorijskim sistemom, ki ga sestavljata mikro-vetrna turbina postavljena v vetrovniku in mikro-PEMWE za proizvodnjo vodika. Na podlagi meritev značilnosti vetrne turbine in omejitev PEMWE je potrebno delovanje sistema optimizirati za proizvodnjo največje količine vodika. Naloge kandidata bodo:

- Narediti pregled literature o značilnostih vetrnih turbin in elektrolizerjev.
- Opisati eksperimentalni sistem, ki bo uporabljen.
- Narediti načrt eksperimenta.
- Izvesti meritve po eksperimentalnem načrtu.
- Analizirati rezultate in dobljene rezultate primerjati s teoretično pričakovanimi.
- Narediti ustrezne zaključke in podati napotke za nadaljnje delo.

Mentor: Asst. Prof. Mitja Mori

Date of topic approval: 15. 5. 2023

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Note: Thesis must be submitted in linguistically and terminologically correct English language. The student must submit and defend his/her thesis during his/her study exchange at the Faculty of Mechanical Engineering, University of Ljubljana.

Acknowledgments

I would want to sincerely thank my family for their unfailing support and encouragement throughout the completion of my thesis. I owe a great deal of gratitude to my devoted mentor Prof. Mori and my colleague Maj for their essential advice and knowledge. The success of this study has been greatly influenced by their suggestions and help. Their participation was essential to the success of this thesis. Finally, I want to express my gratitude to the academic community for creating an atmosphere that is favourable for both learning and research.

Declaration

1. I, the undersigned Enrique Celdrán Muñoz, born 6 January 2000 in Alicante, Erasmus+ student at the Faculty of Mechanical Engineering at the University of Ljubljana, hereby declare that this final undergraduate thesis titled *Generation of green hydrogen with electrolysis using wind energy* is my own original work created under the supervision of my advisor Asst. Prof. Mitja Mori.

2. I hereby declare that the submitted electronic copy of this undergraduate thesis is identical to the printed copy.

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Ljubljana, 14 June 2023 Signature of the author: Enrique Celdrán

Abstract

UDC 621.548:621.357(043.2)
No.: VS I/2011 E

Generation of green hydrogen with electrolysis using wind energy

Enrique Celdrán Muñoz

Keywords: pem electrolyser
wind Energy
hydrogen
electrolysis

The transition to sustainable and clean energy sources has become a pressing global priority. Green hydrogen, produced through electrolysis using renewable energy sources, has emerged as a promising solution for energy storage and carbon-free fuel production. This thesis explores the integration of wind power and PEM electrolysis for green hydrogen production. The objective is to assess the feasibility and efficiency of this coupled system. Experimental measurements of voltage, current, and hydrogen production were conducted. The results demonstrate successful integration and high efficiency, highlighting the potential of this approach for sustainable hydrogen generation. The findings contribute to the understanding of green hydrogen production and offer insights for future research and development in renewable energy integration. This thesis provides valuable information for policymakers and industries seeking to utilize green hydrogen as a clean energy source.

Izvleček

UDK 621.548:621.357(043.2)
Tek. štev.: VS I/2011 E

Proizvodnja zelenega vodika z uporabo vetrne energije

Enrique Celdrán Muñoz

Ključne besede: pem elektrolizer
energija vetra
vodik
elektroliza

Prehod na trajnostne in čiste vire energije je postal svetovna prednostna naloga. Zeleni vodik, proizveden z elektrolizo z uporabo obnovljivih virov energije, se je izkazal kot obetavna rešitev za shranjevanje energije in proizvodnjo goriva brez ogljika. Diplomsko delo raziskuje integracijo vetrne energije in PEM elektrolize za proizvodnjo zelenega vodika. Cilj naloge je oceniti izvedljivost in učinkovitost tega povezanega sistema. Izvedene so bile meritve električne napetosti, toka in proizvodnje vodika. Rezultati kažejo uspešno integracijo in visoko učinkovitost ter poudarjajo potencial tega pristopa za trajnostno proizvodnjo vodika. Ugotovitve prispevajo k razumevanju proizvodnje zelenega vodika in ponujajo vpogled v prihodnje raziskave in razvoj integracije obnovljivih virov energije. Ta teza zagotavlja dragocene informacije za oblikovalce politik in industrijo, ki želijo uporabljati zeleni vodik kot čisti vir energije.

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Symbol	Unit	Meaning
I	A	electric current
R	Ω	electrical resistivity
t	s	time
U	V	voltage
V	m^3	volume
W	J	energy
η	/	energy efficiency

List of abbreviations

Abbreviation	Meaning
MCFC	molten carbonate fuel cell
PAFC	phosphoric acid fuel cell
PEM	proton exchange membrane alkaline fuel cell
PEMFC	proton exchange membrane fuel cell
PFSA	perfluorosulfonic acid
SOEC	solid oxide electrolyser cell
SOFC	solid oxide fuel cell

1 Introduction

1.1 Background

The world around us is driven by the escalating demand for energy brought on by the quick growth of technology. The primary problem, however, is that a sizeable amount of the world's energy and electricity come from fossil fuels, whose supplies are quickly running out. These hydrocarbon-based fossil fuels emit detrimental environmental consequences during combustion, including CO2 emissions and solid particles that contribute to atmospheric pollution. Fossil fuels have the advantage of being simple to store in designated tanks and warehouses and having the capacity to be used immediately. In contrast, renewable energy sources like solar and wind energy depend on weather conditions, making their utilization less consistent. Despite this, the global trend leans towards reducing reliance on "dirty" energy sources and adopting greener and more sustainable alternatives.

The wind power market has experienced remarkable growth and transformation in recent years. Governments, businesses, and communities worldwide have recognized the immense potential of wind energy as a renewable and sustainable power source [1]. Technological advancements, improved turbine efficiency, and favourable government policies promoting clean energy have contributed to the rapid expansion of the wind power market. According to the Global Wind Energy Council (GWEC), the cumulative installed capacity of wind energy reached a staggering 743 GW by the end of 2021, with year-on-year growth continuing to show strong momentum. Wind power projects are increasingly being deployed onshore and offshore, harnessing the abundant wind resources available in diverse geographical locations [3]. The cost competitiveness of wind energy has also improved significantly, making it an attractive choice for utilities and investors seeking to diversify their energy portfolios and reduce carbon emissions. The continuous advancement of wind power technologies, coupled with favourable market conditions and increasing public awareness of the need for clean energy, positions the wind power market as a key player in the global energy transition.

To maximize the effective utilization of renewable energy sources, it is crucial to efficiently store excess energy or electricity. This enables the availability of power even when solar or wind power plants cannot operate due to unfavourable conditions. Chemical energy storage devices offer a potential solution to the energy storage challenge. While batteries, such as Li-ion batteries, are commonly used, they have limitations in terms of lifespan, charging and discharging issues, and lower energy density, making them unsuitable for large-scale electricity storage. To address these limitations, hydrogen emerges as a viable option for energy storage. Through the process of electrolysis, energy can be converted into hydrogen, which can be conveniently stored in liquid or gas form within tanks. Subsequently, hydrogen can be reconverted into electricity and water using fuel cells, with the additional benefit of heat generation in the process.

Although the current efficiency of the hydrogen production and fuel cell cycle is not optimal, it holds immense potential for further development. Hydrogen technologies are envisioned to play a substantial role in the future electrical infrastructure, particularly in the storage of electricity obtained from renewable sources. Hydrogen storage offers greater flexibility without significant limitations, effectively addressing the challenge of maintaining a consistent electricity supply—a critical concern in the field.

1.2 Objectives

The objective of this thesis is to investigate the energy conversion from wind kinetic energy to electricity using wind turbines, as well as the production of green hydrogen through a Proton Exchange Membrane Water Electrolyser (PEMWE). The thesis is divided into two main parts: a theoretical study and an experimental investigation.

In the theoretical part, the fundamental aspects of wind technology and PEMWE technology will be explored. This includes an in-depth understanding of wind kinetic energy, the Betz law, wind turbine power curves, and wind energy availability. Furthermore, the fundamentals of PEMWE technology will be studied, encompassing chemical reactions, the composition of PEMWE and commercial electrolysers, polarization curves, and the unique properties of hydrogen as a fuel.

The second part of the thesis will involve experimental work using a micro-laboratory system comprising a micro-wind turbine placed in a wind tunnel and a micro-PEMWE for green hydrogen production. The characteristics of the wind turbine will be measured, and the limitations of the PEMWE will be identified. By coupling the two technologies, the system's operation will be optimized to achieve maximum hydrogen production. To accomplish this, a literature review on wind turbine and electrolyser characteristics will be conducted.

The specific objectives of this thesis include:

- Describing the experimental system to be used and outlining its characteristics.
- Developing an experimental matrix to guide the experimental work.
- Conducting measurements according to the established experimental plan.

- Analysing the obtained results and comparing them with the theoretically expected outcomes.
- Drawing relevant conclusions based on the analysis of results.
- Providing an outlook for future work in the field, highlighting potential avenues for further research and development.

By achieving these objectives, this thesis aims to contribute to the understanding of energy conversion from wind power to electricity and the production of green hydrogen, while also identifying potential areas for optimization and future research.

1.3 Methodology

The methodology employed in this thesis encompasses both theoretical and experimental approaches to achieve the stated objectives. The theoretical part of the study involves a comprehensive analysis of wind turbine technology and PEMWE systems. Extensive research was conducted by reviewing scholarly articles, relevant academic papers, specialized publications, and reliable online resources to acquire a profound understanding of the operational principles, performance characteristics, and efficiency aspects of wind turbines and PEMWE technology. Furthermore, a mathematical model of the wind turbine was developed to enhance the theoretical study and provide valuable insights into its behaviour.

In the experimental part, a series of carefully designed setups were implemented to validate the theoretical findings and investigate the performance of the wind turbine and the PEMWE system. The experimental setups involved the deployment of a wind turbine under controlled conditions to measure its power output, rotational speed, and other relevant parameters. Additionally, a PEMWE system was utilized to perform electrolysis experiments, capturing data on hydrogen production rates and system efficiency. The experimental configuration consists of a battery-powered PEM electrolyser, storage tanks for hydrogen and oxygen, a PEM fuel cell, a variable resistor, and voltage measuring instruments. Through the manipulation of the variable resistor, various loads and operational settings will be emulated, enabling the collection of data across a range of scenarios. Subsequently, a thorough analysis will be conducted to meticulously examine and interpret the acquired data, thereby facilitating a comprehensive characterization of the individual components comprising the system.

The experimental data collected was then analysed and compared with the theoretical predictions to assess the accuracy of the developed models and gain practical insights into the performance of the coupled wind turbine and PEMWE system.

1.4 Limitations and boundaries

1. This experimental study focuses solely on the examination of Proton Exchange Membrane (PEM) fuel cells and electrolysers, specifically utilizing a PEM model. The analysis and findings presented in this research are confined to this particular

type of technology and may not be directly applicable to other fuel cell or electrolyser variants.

2. Due to practical constraints, the experiments are conducted within a controlled indoor environment. Wind power energy is simulated using either a fan or a constant voltage source, such as a battery. It is important to note that the absence of actual outdoor wind conditions may introduce certain limitations regarding the representation and accuracy of real-world scenarios.

3. The experimental setup involves an electrolyser with a maximum power output of 1.16 W and a fuel cell with a nominal power of 500 mW. Both components operate within the voltage range of 0 V to 2 V. Consequently, this voltage limitation imposes restrictions on the testing of heavy loads or everyday devices that may require higher voltage levels.

4. An additional limitation arises from the wind turbine utilized in the experiments, which generated a significantly higher amount of energy than the electrolyser's range of values. As a result, it was necessary to implement measures to limit the turbine's energy output, ensuring compatibility and preventing potential damage to the electrolyser.

2 Theoretical background

2.1 Wind power systems

2.1.1 History

Over the course of human history, the utilization of wind power systems has evolved significantly, transforming from simple mechanical devices into sophisticated renewable energy solutions. The concept of harnessing wind energy dates back thousands of years, with early civilizations recognizing the power of wind for various purposes. Ancient civilizations, such as the Persians and the Egyptians, used wind to propel sailing ships and grind grains with the help of windmills.

Through the Middle Ages and the Renaissance, when windmills started to proliferate throughout Europe, wind power systems continued to evolve. These early windmills were mostly used for agricultural tasks like pumping water and crushing grain. However, wind power systems underwent tremendous breakthroughs in the 19th and 20th centuries. Wind turbines started to be utilized for producing electricity on a greater scale with the invention of electricity. Charles F. Brush and Poul la Cour, two innovators, were instrumental in creating and improving wind turbines that produce power.

The demand for sustainable and renewable energy sources has increased globally in recent decades, which has accelerated the development of wind power systems. Modern wind turbines that can produce significant amounts of electricity have been developed because to technological advancements [8]. The overall effectiveness and dependability of wind power systems have greatly risen thanks to better design, bigger rotor diameters, and effective power conversion systems. Today, wind energy systems are an essential part of the world's renewable energy mix.

2.1.2 Operation of wind turbines

A wind turbine is a machine that transforms mechanical energy—which is later converted into electrical energy—from wind's kinetic energy. The rotor, generator, gearbox, and control system are some of its essential parts [figure 2.1]. The rotor, which is normally furnished with two or three blades of aerodynamic design, absorbs the kinetic energy of the wind as it passes. The wind's force propels the rotor in its rotation. A gearbox then transmits this rotating motion to the generator, increasing the rotational speed to meet the generator's needs. The generator transforms mechanical energy into electrical energy, which is then available for use right away or storage.

Comprehending the concepts of electromagnetic and aerodynamics is necessary for comprehending the theory and mathematics of wind turbines. The Betz limit, so named in honour of German physicist Albert Betz, governs how well a wind turbine works. According to Betz's law, no wind turbine can extract more kinetic energy from the wind than 59.3 %. The conservation of mass and momentum in the airflow traveling through the rotor is to blame for this. The swept area of the rotor and the cube of the wind speed determine how much power can be captured from the wind. Therefore, increasing the rotor's size and maximizing wind speed are essential for improving a wind turbine's ability to produce electricity.

The operation of a wind turbine is based on the principle of the Bernoulli effect and the concept of lift, similar to an airplane wing. As the wind flows over the curved surfaces of the rotor blades, it creates a pressure difference between the upper and lower surfaces. This pressure difference generates lift, causing the blades to rotate. The rotational motion is then converted into electrical energy through the generator. To optimize the efficiency of a wind turbine, various factors need to be considered, such as the aerodynamic design of the blades, the control of the pitch angle to adjust for varying wind speeds, and the yaw control to ensure the rotor is facing the wind direction [9]. Mathematical models, such as the Blade Element Momentum (BEM) theory, are used to analyse and predict the performance of wind turbines by taking into account the aerodynamic forces acting on the rotor blades.

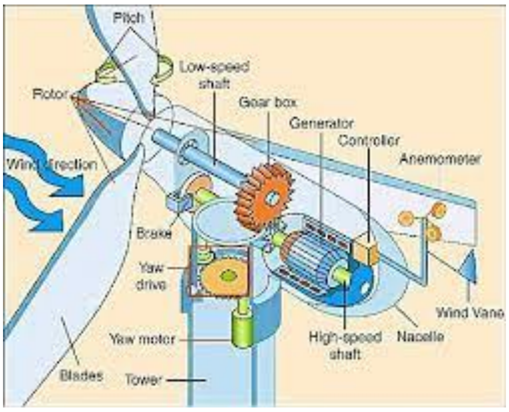

Figure 2.1: Wind turbine components [2]

A typical power curve that shows how well a wind turbine performs at various wind speeds governs how it operates. The relationship between wind speed and the power production of the turbine is depicted by the power curve. The cut-in speed, which is normally between 3 m/s and 4 m/s at lower wind speeds, is when the turbine begins to produce power. According to a cubic connection, the power output of the turbine also grows as the wind speed does. At the rated wind speed, which is typically between 10 m/s and 15 m/s, the turbine produces its rated amount of power. When the wind speed hits the cut-out wind speed, which is normally between 25 m/s and 30 m/s, the turbine continues to run at its rated power until it shuts down for safety [figure 2.2]. For maximizing wind turbine performance and choosing the best sites for wind farm construction, understanding the power curve is essential. Wind turbines can run effectively and produce substantial amounts of clean, renewable energy by catching a wide variety of wind speeds.

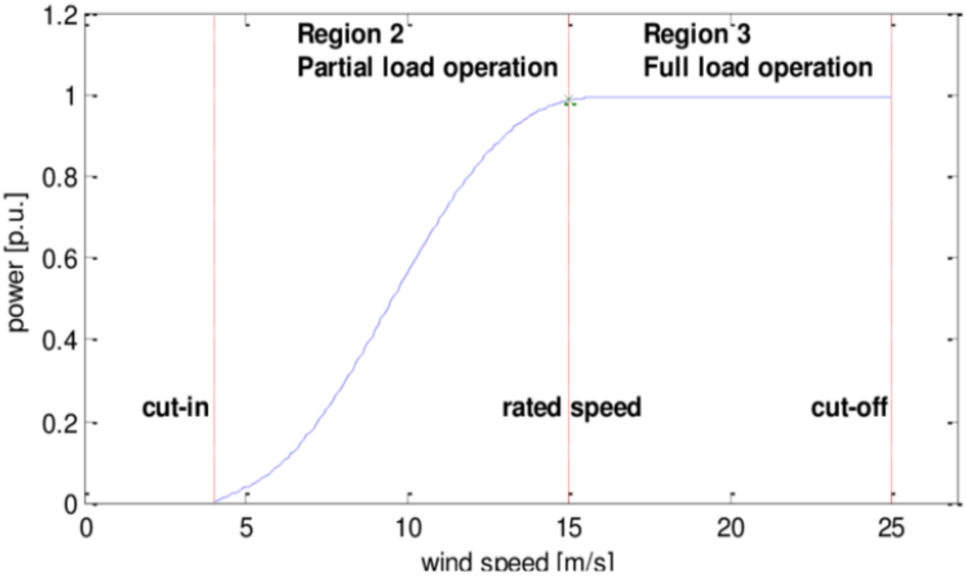

Figure 2.2: Wind turbine operation curve [4]

2.1.3 Types of wind turbines

In the modern era, several types of wind turbines have emerged as prominent solutions for harnessing wind energy efficiently. These turbines vary in their design, power output, technical features, and applications. Here are four commonly used types of wind turbines:

- **Horizontal Axis Wind Turbine (HAWT):**
  Power Range: Several hundred kilowatts to several megawatts.
  Technical Features: Consists of two or three blades mounted on a horizontal axis, facing the wind. It utilizes a yaw mechanism to align with wind direction for optimal performance.
  Operation: The blades capture wind energy, which causes them to rotate. The rotation drives a generator, converting mechanical energy into electrical energy.
  Applications: HAWTs are extensively used in utility-scale wind farms, supplying electricity to the grid. Their versatility and high-power output make them suitable for large-scale power generation.
  Costs and Future Relevance: Costs have reduced over the years due to technological advancements and economies of scale. HAWTs will continue to be relevant in the future, contributing to the expansion of onshore and offshore wind power installations.

- **Vertical Axis Wind Turbine (VAWT):**
  Power Range: A few kilowatts to several hundred kilowatts.
  Technical Features: The rotor shaft is vertical, and the blades rotate around it. VAWTs can have various configurations, such as the Darrieus, Savonius, or helical designs.
  Operation: Wind forces the blades to rotate, and the motion is converted into electrical energy using a generator.
  Applications: VAWTs are suitable for small-scale applications, including residential, commercial, and rural settings. They are often used in off-grid or hybrid systems to power individual buildings or remote areas.
  Costs and Future Relevance: VAWTs generally have lower manufacturing and installation costs compared to HAWTs. They have potential in decentralized energy systems and can be integrated into urban environments.
- **Offshore Wind Turbine:**
  Power Range: Several megawatts to tens of megawatts.
  Technical Features: Similar to HAWTs, offshore wind turbines are typically large-scale horizontal axis turbines specifically designed for installation in offshore environments, including coastal areas and deep waters.
  Operation: Offshore wind turbines operate similarly to onshore HAWTs, utilizing wind energy to generate electricity.
  Applications: Offshore wind farms are constructed in bodies of water to capture stronger and more consistent wind resources. They contribute significantly to renewable energy generation and play a vital role in reducing carbon emissions from electricity production.
  Costs and Future Relevance: Offshore wind turbines have higher installation and maintenance costs due to the challenges of constructing in marine environments. However, ongoing technological advancements and increasing economies of scale are making offshore wind more cost-competitive. Offshore wind has a promising future, offering vast untapped potential for renewable energy expansion.
- **Floating Wind Turbine:**
  Power Range: Typically, several megawatts.
  Technical Features: Floating wind turbines are designed to be deployed in deep waters where traditional fixed-bottom installations are not feasible. They are tethered to the seabed using mooring systems or tension-leg platforms.
  Operation: Floating wind turbines operate similarly to their onshore or offshore counterparts, harnessing wind energy to generate electricity.
  Applications: Floating wind turbines enable the exploitation of wind resources in deep waters, opening up new areas for offshore wind development. They have the potential to provide clean energy to coastal regions and island communities.
  Costs and Future Relevance: Floating wind technology is still in the early stages of development and deployment. Costs are currently higher compared to traditional offshore wind, but continued innovation and learning curves are expected to drive down costs.

In recent years, wind turbine efficiency has greatly increased, making them a more viable and sustainable source of electricity. Many commercial models of today's wind turbines can operate at 40 % to 50 % efficiency, which is an excellent degree of efficiency. These efficiency advances have been made possible by improvements in control systems, rotor blade materials, and aerodynamic design. Wind turbines can now harness higher wind speeds at greater heights thanks to taller turbine towers and bigger rotor diameters, greatly enhancing their performance [9]. The efficiency of wind turbines is anticipated to keep rising with continued research and development activities, making them even more competitive in the renewable energy market.

2.1.4 Advantages and disadvantages of wind turbines

Modern wind turbine technology has several benefits, including the ability to generate sustainable electricity and its renewable nature. A clean and plentiful resource, wind energy lessens reliance on fossil fuels and cuts greenhouse gas emissions. Onshore and offshore installations of wind turbines allow for site flexibility and increase energy output. Additionally, wind energy offers energy diversification, lowering dependency on conventional power sources and boosting the electrical grid's resiliency. In addition, improvements in wind turbine design, such as larger towers and longer blades, have resulted in improved power output and efficiency. Small community-based installations all the way up to massive utility projects can be accommodated by the scalability of wind farms, opening up possibilities for local economic growth and decentralized energy production.

Despite its numerous advantages, modern wind turbine technology also has certain limitations and disadvantages. One challenge is the intermittent nature of wind, which can result in variable power output and the need for backup energy sources or energy storage systems. The visual impact and potential noise generated by wind turbines are other concerns, especially in areas with strict aesthetic regulations or nearby residential communities. Additionally, the initial investment and maintenance costs associated with wind farms can be substantial, requiring significant financial resources. The availability of suitable wind resources is another limitation, as not all regions have consistent and strong enough winds to support viable wind energy projects. Furthermore, the environmental impact on bird and bat populations, as well as potential disturbances to local ecosystems, must be carefully assessed and mitigated during wind farm planning and operation.

2.2 Hydrogen technology

2.2.1 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. But it wasn't until the latter half of the 18th century that hydrogen's potential started to be utilized, owing to the ground-breaking work of English scientist Henry Cavendish, who separated and recognized hydrogen as a unique element.

When the 20th century arrived, hydrogen technology had made considerable strides. Sir William Grove developed the fuel cell idea in the early 1800s, which set the stage for the use of hydrogen in the production of electricity. Later innovations in the middle of the 20th century raised the bar for hydrogen technology, 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). Fuel cells were adopted by the space industry as a clean and dependable energy source for spacecraft, demonstrating the usefulness of hydrogen-based energy systems.

Recently, there has been a resurgence of interest in hydrogen technology due to the pressing need to address climate change and move toward a low-carbon economy. Its potential to decarbonize numerous industries, including transportation, manufacturing, and electricity generation, has been acknowledged by governments, businesses, and researchers worldwide. As a clean and sustainable substitute for traditional fossil fuels, the idea of "green hydrogen", created through electrolysis powered by renewable energy sources, has gained popularity. Significant improvements in fuel cell efficiency, robustness, and cost reduction have been made over the course of hydrogen technology development. Additionally, sophisticated electrolyser technologies have been created for effective hydrogen synthesis.

We may grasp the state of the sector now and the enormous potential it offers for a sustainable energy future by comprehending the historical context and the ongoing progress of hydrogen technology.

2.2.2 Fuel cells

A fuel cell is an electrochemical device that, often through a redox reaction, converts the chemical energy held in a fuel into electrical energy. It works by continually providing fuel and an oxidant to the cell, enabling the fuel's energy to be transformed into heat and electricity throughout the oxidation process. Fuel cells provide a more direct and effective energy conversion method than conventional heating plants, which rely on multi-stage conversions and mechanical energy generation.

Fuel cells' capacity to complete this energy conversion in a single step eliminates the need for additional conversions and minimizes energy losses. This is one of their main advantages. Additionally, because there are no moving parts in fuel cells, there are fewer energy losses and no mechanical wear. When compared to conventional methods and technologies, this attribute not only improves overall efficiency but also helps to the minimal maintenance needs of fuel cell systems.

Fuel cells are relatively inexpensive to manufacture since there are fewer parts that need to sustain high loads and temperatures [10]. A fuel cell typically comprises of a housing and an electrolyte membrane that is permeable and speeds up the required chemical reactions. Because of their straightforward design, they are more affordable and have a greater chance of being widely used in a variety of applications.

2.2.2.1 Use of fuel cells

Fuel cells offer a wide range of applications and possess significant advantages over traditional energy harvesting devices. One of their notable characteristics is their exceptional energy conversion efficiency, enabling the extraction of more energy from the same amount of fuel. Moreover, fuel cells serve as a promising alternative to fossil fuels due to their minimal emissions. The by-products of hydrogen oxidation in fuel cells are primarily heat, making them environmentally friendly. The production of hydrogen, however, remains a concern in terms of emissions. The three main categories of hydrogen production are grey hydrogen, obtained from natural gas; blue hydrogen, derived from natural gas with captured CO_2 emissions; and green hydrogen, produced through electrolysis. Green hydrogen, being the most ecologically sound, is experiencing an increase in production, making fuel cells even more appealing.

The automotive industry sees significant potential in fuel cells, particularly for electric vehicles. Fuel cells offer greater driving range compared to batteries and eliminate the need for extended charging periods. Their application extends beyond cars and includes buses, ships, trucks, and even vehicles used in warehouses, delivery services, and forklifts. Hydrogen-powered fuel cells are also being explored for aviation and space projects. Prototypes like Pathfinder and Helios are investigating the feasibility of using fuel cells in aircraft, while hybrid fuel cell systems powered by solar cells have been implemented in unmanned aircraft, theoretically enabling unlimited or continuous flight.

Fuel cells are also finding use in stationary applications. They serve as backup generators in uninterruptible power supply (UPS) systems, providing reliable power for hospitals and data centres. In fact, companies like Microsoft have successfully powered entire data centres using hydrogen cells for up to two days. Portable fuel cells are gaining traction as mobile generators, proving advantageous for camping due to their quieter operation, lighter weight, and increased power output compared to traditional internal combustion engine generators. The concept of portable fuel cells originated from NASA, where they were initially developed for heat, electricity, and water generation in rockets and space vehicles [11]. Additionally, the quiet operation, low exhaust temperature, and long-term usability make fuel cells suitable for submarine propulsion.

2.2.2.2 Types of fuel cells

The Phosphoric Acid Fuel Cell (PAFC) utilizes a phosphoric acid solution (H_3PO_4) as the electrolyte, trapped between two platinum-coated graphite electrodes. It operates optimally at temperatures between 180 °C and 210 °C. PAFCs offer excellent reliability and durability, with low operating costs due to the affordability of the electrolyte. However, high-temperature operation requires electrolyte replenishment as it evaporates. PAFCs also rely on expensive platinum catalysts and are susceptible to carbon monoxide and sulphur contamination from impure fuels.

Molten Carbonate Fuel Cells (MCFCs) use alkali metal and carbon compounds (Li_2CO_3 or K_2CO_3) as electrolytes. CO_2 is necessary for their operation, and they function at temperatures between 600 °C and 700 °C, generating electricity and heat. MCFCs require expensive materials prone to rapid degradation due to the corrosive electrolyte. The most powerful MCFC cell plant currently has a capacity of 2.5 MW and covers an area of 500 m^2.

Solid Oxide Fuel Cells (SOFCs) employ solid ceramic electrolytes. They operate at high temperatures ranging from 600 °C to 1000 °C. SOFCs face challenges such as thermal expansion of materials, sealing methods, and overall reliability. They offer high efficiency, around 90 %, with electricity and heat production. Due to their flexibility in fuel usage, they are often employed for heat generation. Despite their reliability, they are not yet widely adopted. Siemens Westinghouse is an example of an SOFC with a power output of 220 kW.

The Alkaline Fuel Cell (AFC) operates using a potassium hydroxide (KOH) solution as an electrolyte. It requires pure hydrogen and oxygen and has a working temperature range of 120 °C to 250 °C. AFCs do not need costly precious metal catalysts and have low electrolyte costs. However, they are sensitive to carbon dioxide (CO_2) concentration, which can degrade the electrolyte and hinder cell functionality. Water removal from the anode is crucial for AFCs to function properly.

Proton Exchange Membrane Fuel Cells (PEMFCs) employ a polymer membrane that selectively allows the passage of protons. Also known as "proton exchange membrane" fuel cells, PEMFCs will be explored in detail in the subsequent chapter.

2.2.2.3 Operation of fuel cells

A fuel cell is an electrochemical device that converts the chemical energy of fuel into electrical energy directly, without the need for prior conversion into heat. Various types of fuel cells operate based on this fundamental principle. Modern fuel cells typically consist of three essential components: the anode, the cathode, and the intermediate electrolyte, which selectively allows specific ions to pass through while inhibiting the transfer of unwanted electrons [figure 2.3].

In the case of Proton Exchange Membrane (PEM) fuel cells, hydrogen is supplied to the anode, where it undergoes a process called electrolysis, breaking down into positive hydrogen ions (H^+) and negative electrons (e^-). The positive ions travel through the electrolyte to the cathode, while the electrons flow through an external circuit, generating an electric current that can be utilized for various applications. At the cathode, oxygen is supplied, which undergoes reduction by accepting the electrons. The hydrogen ions and oxygen combine at the cathode, resulting in the production of water as a by-product.

The basic principle of operation remains similar across different fuel cell types, such as alkaline cells where OH^- ions are transported via the electrolyte, or Solid Oxide Fuel Cells (SOFCs) where oxygen ions (O^{2-}) play a role. The specific cathode and anode materials, as well as the fuel used, may vary, but the controlled reaction is enabled by the selective passage of ions through the electrolyte.

To ensure smooth operation, fuel cells require proper gas distribution to the electrodes. This is facilitated by the use of porous electrode materials coated with catalysts that enhance the electrochemical reaction. Since the energy released during an electrochemical reaction is relatively low, fuel cells are connected in series in a stack configuration to obtain higher voltage. These cells are interconnected through bipolar plates, enabling efficient power generation.

It is worth noting that fuel cells have a significantly higher energy conversion efficiency compared to traditional heat-based energy conversion methods. Only a small proportion of the energy is converted into heat, typically around 20 %, with the majority being converted into usable electrical energy. The efficiency of a fuel cell depends on its operating point and can vary based on different factors.

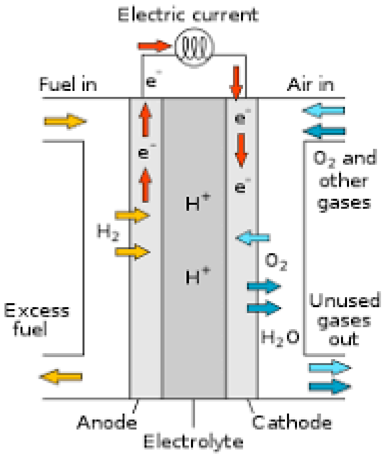

Figure 2.3: Internal structure of a fuel cell [5]

2.2.2.4 Advantages and disadvantages of fuel cells

Fuel cells offer significant advantages compared to traditional heat engines. Their higher efficiency, reaching around 70 %, is attributed to the electro-chemical process they rely on, which is not constrained by the limitations of the Carnot process or the second law of thermodynamics. In contrast, conventional engines, like gas turbines, typically have lower efficiencies of approximately 58 %, influenced by factors such as lubrication, wear, stretching, and humidity. Moreover, fuel cells produce minimal or no emissions as the reaction between hydrogen and oxygen results in water, making hydrogen a virtually emission-free fuel.

Another notable advantage of fuel cells is their quiet operation since they lack moving parts. Additionally, fuel cells can be flexibly employed across various applications and voltage ranges. By connecting multiple fuel cells in a stack, the voltage and power output can be regulated. However, the technology still faces challenges. Limited production scale leads to higher production costs, necessitating further debugging and optimization of production processes. The efficiency of fuel cells is influenced by fuel purity, gas distribution within the cell, temperature fluctuations, and the degradation of components like bipolar plates, membranes, and catalysts over time.

The production of pure hydrogen can be demanding and expensive, posing a disadvantage in certain cases. Moreover, the materials used in fuel cell construction, including catalysts and membranes such as platinum metals (PGM) or rare earth elements (REE), are costly and require high-temperature and corrosion-resistant properties [12]. The inconsistent production of these materials further compounds the issue. Despite these challenges, ongoing research and development efforts aim to address these limitations and enhance the widespread adoption of fuel cell technology in various industries.

2.2.3 Electrolysers

An electrolyser is a device designed to separate water molecules into oxygen and hydrogen atoms through a process called electrolysis. During electrolysis, the oxidation and reduction of chemical compounds occur at the cathode and anode under the influence of a direct electric current. The efficiency of electrolysis relies on factors such as the threshold breakdown voltage specific to each compound, as well as the properties of the electrodes and electrolytes used. The theoretical minimum voltage required to split water, known as the Gibbs free energy, is 1.23 V under standard ambient conditions of pressure and temperature (SATP) at 25 °C and 1 bar.

To facilitate the electrolysis process, additional energy in the form of heat or electricity must be introduced into the system, accounting for the energy difference between the reaction enthalpy of hydrogen and the Gibbs free energy. The operating conditions of electrolysers will be discussed further in detail. As electrolysers become increasingly efficient, particularly at large input power scales, the widespread adoption of electrolysers and fuel cells in various industries will become more feasible, promising a future where these technologies are extensively utilized.

2.2.3.1 Use of electrolysers

Although the production of hydrogen through electrolysis is currently only a minor portion of total hydrogen production, it is the major application of electrolysers in industry. It is mostly created as a by-product of the electrolysis of water with an electrolyte, which also produces sodium hydroxide and chlorine often. The most common usage of electrolysis is in this industrial context.

$2NaCl + 2\,H_2O \rightarrow H_2 + Cl_2 + 2NaOH$ [6]

Numerous additional situations also make use of electrolysis. For example, it is used to produce oxygen in submarines and space missions by employing easily available resources like seawater and electric current. Additionally, the extraction of copper from ore requires the use of electrolysis. The ore is combined with sulfuric acid and salt during the electrolysis process, which causes pure copper to build up on the electrodes. Copper extraction is made significantly simpler and more successful using electrolysis, providing a more economical method. Similar to this, electrolysis is used to refine aluminium. Furthermore, by eliminating heavy metals, contaminants, and pollutants, electrolysis is a useful technique for cleaning up dirty wastewater. This application is commonly employed in treating wastewater from refineries, textile plants, and chemical facilities, aiming to eliminate as many impurities as possible.

A thin layer of metal is deposited onto a base material during the electroplating process, which is commonly used in industrial settings. This method improves the qualities and look of the treated products while also serving decorative and functional functions. The antithesis of electroplating, electrolysis is also used in an electrochemical treatment procedure that includes the removal of material rather than its addition.

2.2.3.2 Electrolyte

Pure water acts as a semiconductor but has a low conductivity for electric current. Consequently, unless a high potential is provided, causing autoionization, pure water would electrolyze slowly. An electrolyte is added to water to dramatically increase its conductivity in order to get around this restriction. The preferred electrolysis by-products will choose the electrolyte to use.

Because the anions in an electrolyte might compete with hydroxide ions for electron donors, care must be taken while choosing one. In the absence of oxygen release, an anion with a lower electrical potential will give up an electron rather than a hydroxide ion. Likely to donate an electron and prevent hydrogen release is a cation that has a higher electric potential than the hydrogen ion.

Suitable cations with higher electrical potential include Li^+, Sr^{2+}, K^+, Ba^{2+}, Rb^+, Ca^{2+}, Na^+, Cs^+, and Mg^{2+}. Sodium and lithium are commonly utilized as they readily form soluble and cost-effective salts. In instances where an acid or base is employed as the electrolyte, issues with electron emission and acceptance are mitigated as they are challenging to oxidize. Strong acids such as sulfuric acid (H_2SO_4), or bases like potassium hydroxide (KOH) and sodium hydroxide (NaOH), are commonly utilized as electrolytes due to their excellent electron conductivity.

2.2.3.3 Types of electrolysers

PEM, alkaline, and solid oxide electrolysers are the three main categories of electrolysers, which are separated by the substance of the electrolyte.

The SOEC, also known as a "solid oxide electrolyser cell"[figure 2.4-C], performs regenerative fuel cell operations or runs in reverse. It uses solid oxides or ceramics as the electrolyte and runs at high temperatures between 600 °C and 1000 °C. The most often utilized substance is zirconium dioxide (ZrO_2) because of its high melting point, resistance to corrosion, and strength. Hydrogen and water are released at the cathode, whereas oxygen is released at the anode. However, the relative scarcity of zirconium makes their use more expensive, which restricts the spread of SOECs on the market.

The chemical industry uses **alkaline electrolysers** [figure 2.4-B] extensively because the gases and products generated during electrolysis rely on the electrodes and electrolyte that are used. Despite being capable of doing so, the choice of electrolyte is quite important. Electrolytes for water electrolysis can be sodium hydroxide (NaOH) or phosphorus hydroxide (KOH). In this procedure, the anode releases oxygen and water while the cathode releases hydrogen and water. The operating temperature range for alkaline electrolysers is 65 °C to 220 °C. They use more affordable catalysts than PEM electrolysers do, and they are more durable due to less anode catalyst degradation. Alkaline electrolyte also encourages improved gas purity by reducing gas diffusivity.

PEM electrolysers [figure 2.4-A] stand out among the many varieties as being particularly noteworthy. They have the benefit of producing high-quality hydrogen, requiring little maintenance, and—most importantly—responding quickly to fluctuating voltages from renewable energy sources. They operate between 40 and 80 degrees Celsius. PEM electrolysers are therefore ideal for generating energy from renewable sources. They are also better at handling large electric currents than alkaline electrolysers are. In chapter 2.2.3.5, more information on PEM electrolysers will be given.

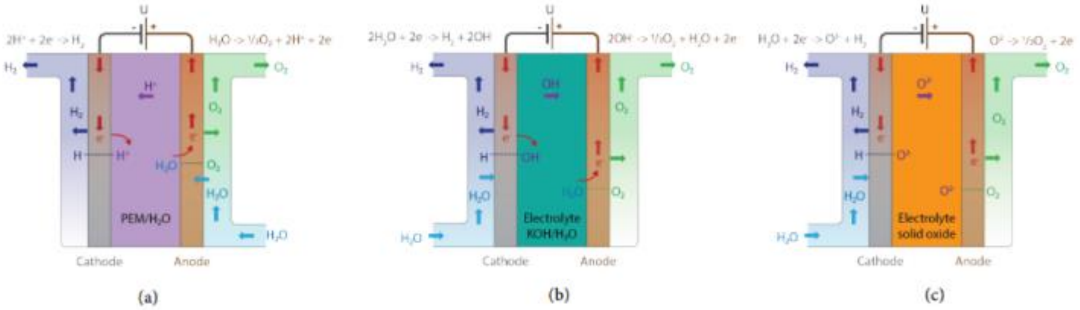

Figure 2.4: Internal structure of different types of electrolysers [7]

2.2.3.4 Operation of electrolysers

Anode, cathode, and electrolyte are the three main parts of an electrolyser. Depending on the type of electrolyser used, a different electrolyte may be used.

The electrolyte is positioned between the separated anode and cathode. Water (H_2O) undergoes electrolysis or breakdown at the anode. At this point, hydrogen ions with positive charges, oxygen, and electrons are liberated. In the direction of the cathode, the free electrons move via the electrical conductor. The positively charged hydrogen ions move through the electrolyte at the same time, eventually joining the free electrons at the cathode [figure 2.5].

Two chemical equations for the anode and cathode reactions can represent this process:

$2\ H_2O \rightarrow O_2 + 4\ H^+ + 4\ e^-$

[13]

$4\ H^+ + 4\ e^- \rightarrow 2\ H_2$

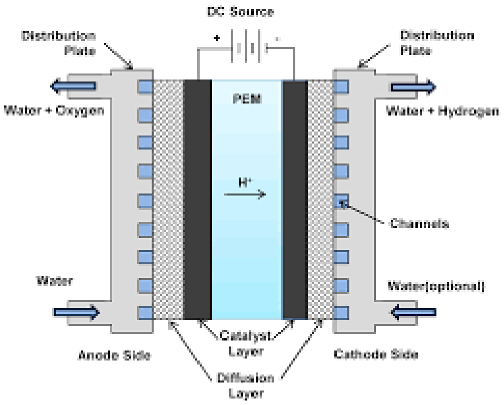

Figure 2.5: Internal structure of a PEM electrolyzer [14]

2.2.3.5 PEM electrolyser

PEM (Proton Exchange Membrane) electrolysers are reversible devices that can work as both fuel cells, which use fuel to produce electricity, and electrolysers, which use voltage to produce hydrogen. PEM electrolysers have a number of benefits over alkaline electrolysers, including reduced mass and dimensions, lower energy usage, higher efficiency, improved voltage tolerance, production of purer gases during electrolysis, improved safety and reliability, and the ability to compress hydrogen for storage.

When General Electric created the first electrolyser using a solid polymer electrolyte in the 1960s, the idea for PEM electrolysers were born. The catalyst is coated on both sides of the electrolyte, which acts as the anode and cathode and is often a proton-permeable membrane. Proton-permeable membrane (PPM), polymer electrolyte membrane (PEM), or rarely solid polymer electrolyte (SPE) electrolysis are terms used to describe this technology.

Multiple smaller electrolysers are joined in larger, more potent electrolysers to improve voltage and power production. The most effective electrolysers right now are PEM ones, which can achieve 85 % efficiency.

The electrolyser contains an electrolyte with an anode and a cathode during operation. The electrolyte (water) goes through oxidation when an electric voltage is supplied to the electrodes. At the anode, oxygen, hydrogen protons, and free electrons are liberated. While the protons travel through the proton exchange membrane to the cathode, where they combine with electrons to generate diatomic hydrogen, oxygen can be collected at the anode.

The PEM membrane enables high proton permeability, little gas mixing, adaptability across a broad power range (100 % of rated power), compact system design, and high-pressure operation. Its thinness (20-300 mm) is yet another positive trait. Typically, sulfonic acids, notably PFSA (perfluoro sulfonic acid) material, make up the membrane. Membranes made from PFSA material are also produced by other manufacturers. The membrane in the electrolyser becomes moist and acidic when water is added, allowing hydrogen protons (H^+ cations) to pass through while remaining impermeable to negative anions.

PEM electrolyzes provide a flexible and effective option for producing hydrogen, finding use in a variety of industries and advancing renewable energy technology.

3 Experiment

3.1 PEM Experiment

3.1.1 Equipment

<u>POWER SUPPLY UNIT</u>

The electrical energy required to run the PEM electrolyser is provided by the power supply unit employed in the experiment [figure 3.1]. It provides the system with a controlled and adjustable voltage, enabling the electrolyser to operate under the preferred operating conditions. For reliable measurements and analysis during the experiment, a steady and consistent electrical current flow is ensured by the power supply unit.

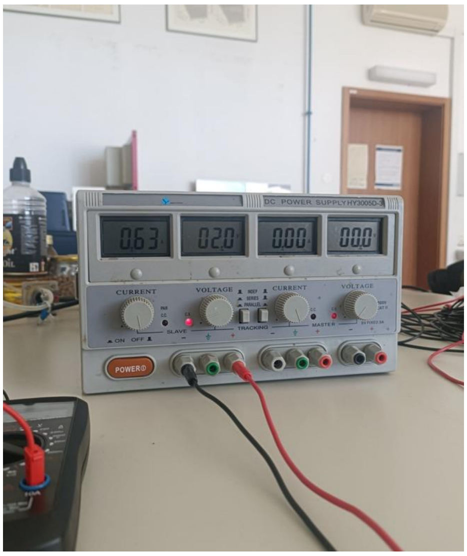

Figure 3.1: Power supply unit

MEASURING CIRCUIT WITH VARIABLE RESISTOR

In the PEM electrolyser experiment, the measurement circuit with a variable resistor is crucial [figure 3.2]. It enables for a wide range of resistance adjustment. At the electrolyser terminals, measurements of electric current and voltage are made for each resistance value. Due to the fuel cell and electrolyser's fluctuating internal resistance, the relationship between current and voltage is non-linear. The behaviour of the electrolyser can be deciphered by methodically altering resistance and examining the non-linear dependencies. For researching its features under various load levels, this knowledge is essential. Overall, a thorough evaluation of the PEM electrolyser's performance is made possible by the measuring circuit with the variable resistor.

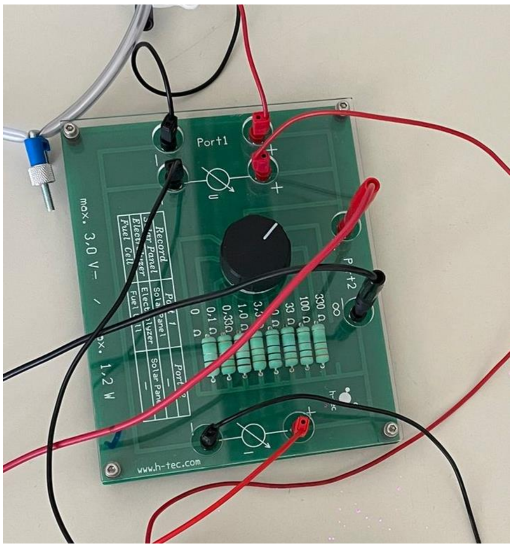

Figure 3.2: Variable resistor

MULTIMETERS

A voltage and current meter are also necessary for the measurements [figure 3.3]. Two multimeters, which we will set up differently, will be used.

Figure 3.3: Multimeters

RESERVOIR TANK AND PEM ELECTROLYZER

As was already explained, the electrolyser creates oxygen O_2 and hydrogen H_2 from water in a ratio of 1:2. The power of the electrolyser is 2 W. The tank is utilized to hold water, oxygen, or hydrogen [figure 3.4]. Water is present in a tank that has hydrogen or oxygen stored in it. This water acts as a seal for the tank as well as the medium from which we extract the different gases. 30 cm^3 is the volume.

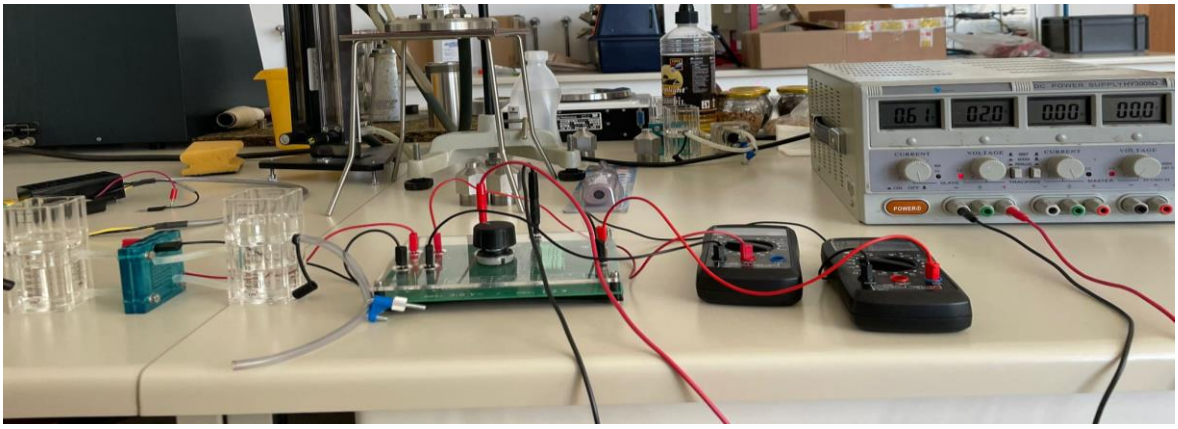

Figure 3.4: Reservoir tanks and PEM electrolyzer

3.1.2 Preparation and course of the experiment

The electrolyser and fuel cell were meticulously prepared before the experiment began. To reach the ideal humidity, a vital step entailed immersing the PEM membrane in distilled water. The efficient movement of electrons was made possible by this. The fuel cell and electrolyser's performance was directly impacted by how moist the membrane was, thus care was made to avoid either scenario.

The electrolyser was properly set up, a continuous water supply was offered, and the device was connected to a source of constant voltage. Two tanks were connected in the appropriate manner to make the creation of hydrogen and oxygen easier. A 2 V constant voltage source was used as opposed to a battery. The electrolysis reaction then started, producing hydrogen and oxygen as a by-product. The electrolyser's progress was observed, especially how much hydrogen and oxygen were produced. The gases were produced in a 2:1 ratio, as expected. This demonstrated that the electrolyser was set up and operated well.

To ensure optimal performance and consistency in the experiment, the resistance was set to an infinite value, allowing the electrolyser to receive the maximum voltage from the battery. This configuration aimed to enhance the efficiency of the electrolysis process and maintain stable conditions throughout the measurements.

Throughout the experiment, the production of hydrogen was closely monitored, recording the amount of hydrogen and the corresponding time intervals. By systematically adjusting the voltage, starting from 2 V and decreasing it incrementally by 0.1 V the relationship between voltage levels and the time required to produce 20 cm^3 of hydrogen gas was observed.

Each measurement was done several times to confirm its accuracy and dependability. I wanted to reduce any potential inaccuracies and take into consideration any variations or swings in the data, so the measurements were repeated various times. The consistency and repeatability of the data were evaluated by repeating the measurements. It provided a more robust dataset for drawing inferences and accurately comparing various voltage levels, as well as aiding in the identification of any anomalies or outliers.

3.1.3 Measurements

3.1: Measured and calculated data for the PEM analysis

Voltage (V)	Time (min)	Current (A)	Resistance (Ω)	Volume (cm^3)
1.98	1:58	1.26	∞	20
2.01	2:00	1.3		
2.04	2:01	1.24		
2.08	2:02	1.16		
2.09	2:05	1.15		
2.04	**2:012**	**1.22**		

Voltage (V)	Time (min)	Current (A)	Resistance (Ω)	Volume (cm^3)
1.92	2:42	0.95	∞	20
1.91	2:44	0.93		
1.91	2:45	0.91		
1.89	2:47	0.87		
1.9075	**2:445**	**0.915**		

Voltage (V)	Time (min)	Current (A)	Resistance (Ω)	Volume (cm^3)
1.79	4:00	0.65	∞	20
1.77	3:56	0.6		
1.81	3:30	0.69		
1.79	**3:48**	**0.646**		

Voltage (V)	Time (min)	Current (A)	Resistance (Ω)	Volume (cm^3)
1.68	7:30	0.36	∞	20
1.69	6:49	0.38		
1.73	5:05	0.49		
1.696	**6:28**	**0.41**		

Voltage (V)	Time (min)	Current (A)	Resistance (Ω)	Volume (cm^3)
1.62	12:00	0.21	∞	20
1.61	12:46	0.19		
1.615	**12:23**	**0.20**		

Voltage (V)	Time (min)	Current (A)	Resistance (Ω)	Volume (cm^3)
1.53	∞	0,04	∞	20
1.53	∞	**0,04**		

3.2 Wind turbine experiment

3.2.1 Equipment

WIND TURBINE

The Rutland 504 [figure 3.5] wind turbine is a specific type of turbine widely used in renewable energy applications. It is known for its compact design and efficiency in harnessing wind power. This particular model is commonly employed in small-scale wind energy systems, making it suitable for our experimental setup.

Figure 3.5: Wind turbine

WIND TUNNEL

The wind tunnel itself is a closed chamber equipped with a fan or blower system that generates airflow [figure 3.6]. By adjusting the frequency of the fan or altering the speed of rotation, we were able to control the airflow velocity within the tunnel. This variability was crucial in accurately simulating real-world wind conditions and evaluating the turbine's response at various wind speeds.

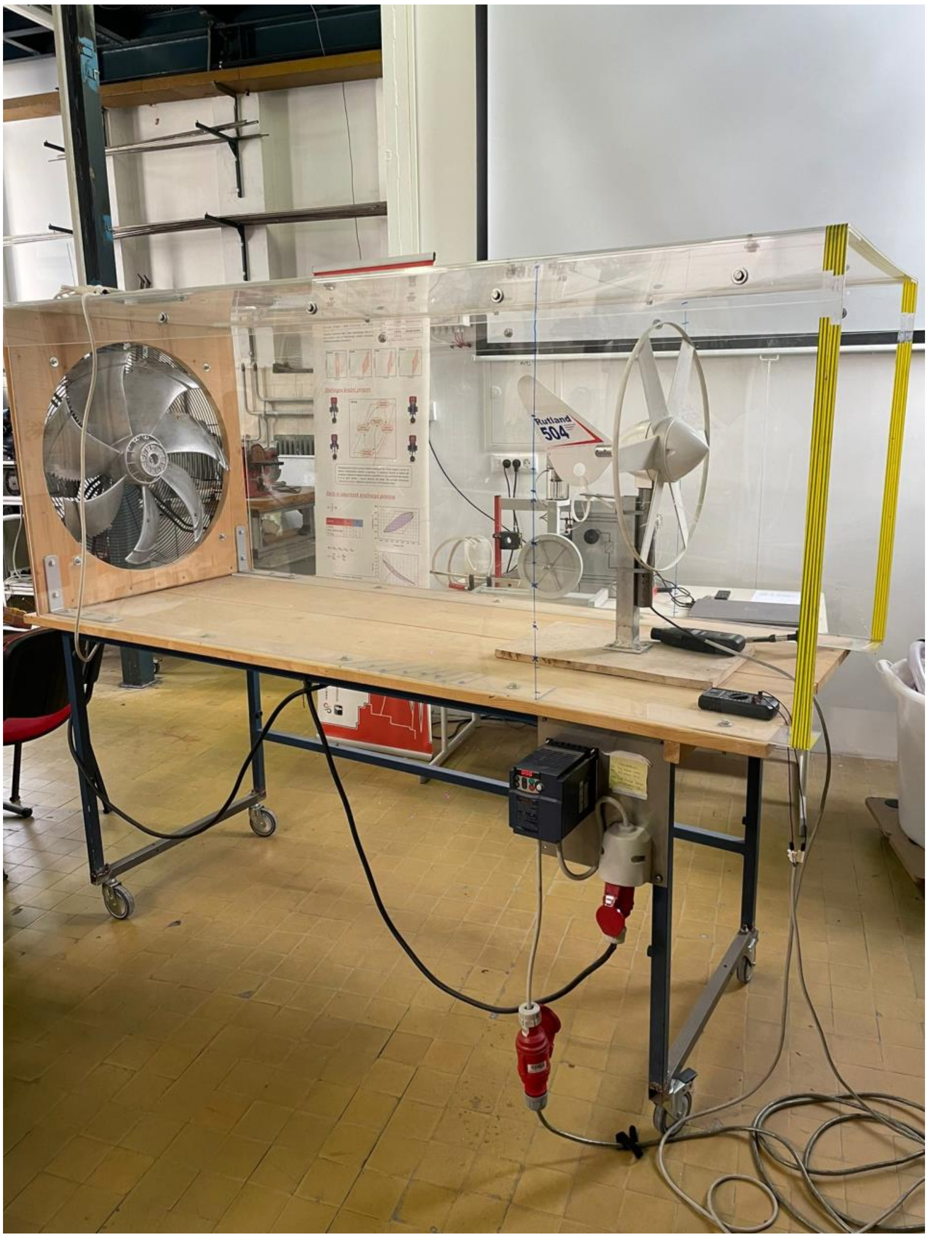

Figure 3.6: Wind tunnel

MULTIMETERS

A voltage and current meter are also necessary for the measurements. Two multimeters, which we will set up differently, will be used [figure 3.3].

TACHOMETER

The tachometer plays a significant role in the experimental setup as it allows us to accurately measure the rotational speed or revolutions per minute (RPM) of the wind turbine [figure 3.7]. By employing a laser and a detector positioned on one of the turbine blades, the tachometer detects the passing of the blade and records the number of rotations.

Figure 3.7: Tachometer

DIGITAL ANEMOMETER

The use of a digital anemometer in our experiment was crucial for obtaining accurate and reliable wind speed measurements [figure 3.8]. The digital display allowed us to quickly and easily read and record the wind speed data. This real-time information enabled us to monitor and analyse the varying wind speeds throughout the experiment.

Figure 3.8: Digital anemometer

RESISTOR BOX

By adjusting the resistance, we can simulate different loads that the wind turbine would encounter in real-world applications [figure 3.9]. This enables us to find the optimal load at which the turbine operates most efficiently.

Figure 3.9: Resistor box

3.2.2 Preparations and course of the experiment

During the wind turbine experiment, careful preparations were made to ensure accurate measurements. One crucial aspect was determining the optimal set load for maximum power generation. To accomplish this, voltage and current were measured for different load values, enabling the identification of the load resistance that resulted in the highest power output [table 3.2].

Once the optimal load resistance was determined, it was set using a variable resistor box. This ensured that the wind turbine operated at its peak power output for subsequent measurements. With the equipment in place, various parameters were measured at different fan frequencies to evaluate the turbine's performance under varying conditions.

To assess the performance of the wind turbine, measurements were taken of air speed, voltage, and current. An accurate digital anemometer was utilized to measure the air speed, providing precise readings essential for subsequent calculations. the impact of turbulent flows on air speed measurements was considered. To account for this, air speed measurements with the digital anemometer were taken at various positions around the turbine.

By measuring the air speed at different locations, the influence of turbulent flows on the wind turbine's performance could be better understood. Turbulent flows can disrupt the smooth and uniform wind flow, leading to variations in air speed. By capturing air speed readings at multiple positions, a more comprehensive picture of the wind conditions affecting the turbine was obtained [table 3.3].

The experiment involved calculating both kinetic (1) and wind power. By considering air density and turbine diameter, the kinetic power of the wind was determined using the formula that incorporates these factors and the cube of the wind speed. Additionally, wind power was calculated by multiplying the kinetic power by the turbine's capture area.

$$P_{max.kin} = \frac{1}{2} \cdot \frac{\pi \cdot D^2}{4} \cdot \rho \cdot v^3 \, , \tag{1}$$

$$P_{elect.} = U \cdot I \, , \tag{2}$$

Voltage and current measurements were obtained for each fan frequency, enabling the determination of turbine power by multiplying these values. The efficiency of the turbine was evaluated by dividing the turbine power (2) by the wind power, revealing the proportion of captured wind energy converted into electrical power.

Through these meticulous steps, the wind turbine's performance was evaluated comprehensively. The experimental setup allowed for the accurate measurement of parameters such as air speed, voltage, and current. Subsequent calculations involving kinetic and wind power, as well as turbine power and efficiency, provided valuable insights into the turbine's ability to convert wind energy into electrical power and optimize its performance for specific wind conditions.

3.2.3 Measurements

Table 3.2: Measured and calculated data for determine optimal load

Resistance (Ω)	Voltage (V)	Current (A)	Power (W)	Rot.Freq (Hz)
0.1	0.038	0.31	0.027	60
0.47	0.2	0.33	0.066	
1	0.372	0.31	0.11532	
3.3	1.22	0.35	0.427	
10	4.79	0.47	2.251	
33	9.79	0.27	2.64	
100	12.78	0.12	1.53	
330	15.1	0.04	0.604	
3000	46.42	0.015	0.246	

Values measured for internal and external turbine diameters:

R_{ext} **= 27 cm** R_{int} **= 7.5 cm**

Table 3.3: Measured and calculated data for obtaining kinetic and electrical Power

Speed (m/s)		Voltage (V)	Current (A)	Power (W)	Rot.Freq (Hz)
1.7	1.375	2.1	0.06	0.126	20
1.3					
1					
1.5					
2.4	2	4.3	0.13	0.559	30
1.3					
2.3					
2					
2.5	2.825	6.8	0.2	1.36	40
2.8					
2.7					
3.3					
2.9	3.38	9.2	0.27	2.489	50
3.5					
3.2					
2.95					
4.35	3.96	11.7	0.34	3.978	60
3.9					
3.9					
3.7					

3.3 Coupling PEM and Wind turbine

3.3.1 Preparations and course of the experiment

When coupling the wind turbine with the PEM electrolyser, it posed a challenge to precisely control the wind speed within the desired voltage range of 1.5-2V. Due to the inherent variability of wind conditions, it was difficult to consistently achieve the target voltage. To address this issue, a different approach was taken. The highest rotational frequency and wind speed were selected, which ensured that the generated voltage would be on the higher end of the range. Subsequently, the voltage was regulated using the power supply while monitoring the time and current required to produce a specific volume of hydrogen. This approach allowed for a more controlled and accurate measurement of the electrolyser's performance, compensating for the limitations in directly adjusting the wind speed. By employing this methodology, the experiment could still assess the efficiency and operational characteristics of the wind turbine and its coupling with the PEM electrolyser, albeit through an alternative means of controlling the input voltage.

To assess the performance of the coupled system, various voltage values were controlled and measured. The time required for each set voltage to produce 20 cm^3 of hydrogen gas was recorded, along with the corresponding current [table 3.4]. This data allowed for the evaluation of the system's efficiency and the characterization of its response to different voltage inputs. By focusing on the time taken to produce a specific volume of hydrogen gas, the experiment aimed to understand the electrolyser's performance under varying wind conditions. The recorded current values provided additional insights into the electrochemical processes occurring within the PEM electrolyser.

The experiment involved systematically varying the voltage settings, capturing the time and current data for each condition. This approach allowed for the determination of the optimal voltage inputs that would yield efficient hydrogen gas production. Additionally, it provided valuable information on the system's responsiveness to different voltage levels and its overall energy conversion efficiency.

3.3.2 Measurements

Table 3.4: Measured and calculated data for obtaining coupled efficiency

Voltage (V)	**Current (A)**	**Time (min)**	**Resistance (Ω)**	**Volume (cm^3)**
1.82	0.65	4:52	∞	20
1.72	0.47	6:00		
1.65	0.30	9:00		
1.60	0.17	17:00		

4 Results and discussion

4.1 PEM results and discussion

In terms of the effectiveness of hydrogen production, the PEM experiment produced substantial results. We gathered important information about the electrolyser's performance by adjusting the voltage settings and timing how long it took to create 20 cm^3 of hydrogen. The findings identified an ideal range of voltages that enabled better output rates with quicker electrolysis periods [figure 4.1].

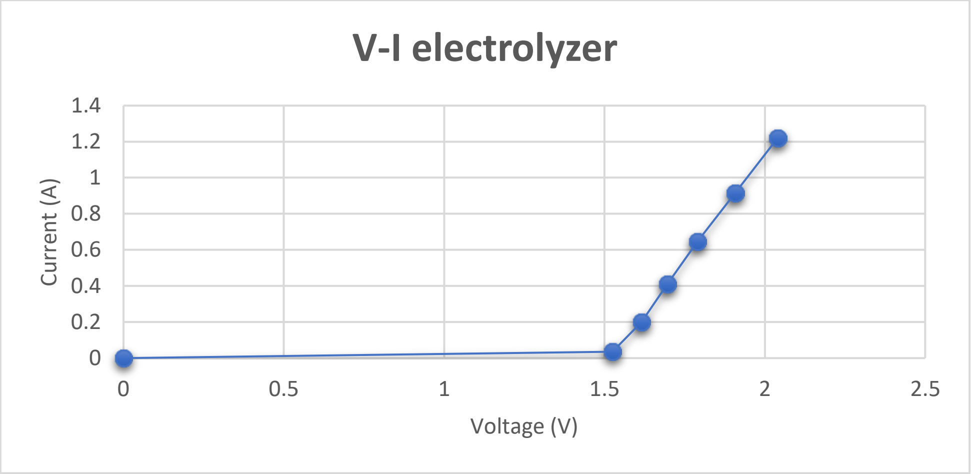

Figure 4.1: Comparison measured values for PEM electrolyser

In addition, the PEM electrolyser's effectiveness was evaluated by comparing the amount of hydrogen produced to the electrical energy input. The experiment showed a high efficiency in producing hydrogen gas from electrical energy, underlining the promise of PEM electrolysis as a reliable and effective approach for producing hydrogen.

In the PEM electrolyser experiment, the efficiency was calculated for the highest voltage (3), considering that it resulted in faster hydrogen production. However, it was observed that the highest voltage did not necessarily correspond to the best efficiency. This discrepancy indicates that there exists an optimal operating point where the electrolyser achieves maximum efficiency, even if it may not produce hydrogen as quickly. By analysing the data obtained at different voltage levels, it was possible to identify the voltage at which the electrolyser exhibited the highest efficiency, highlighting the importance of selecting the appropriate operating conditions to optimize energy conversion in the system [figure 4.2].

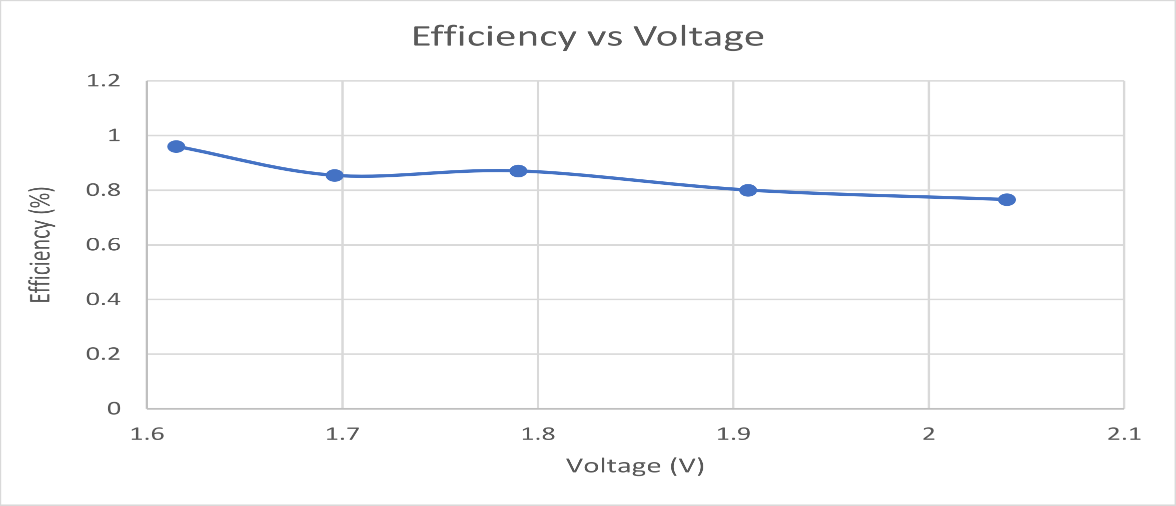

Figure 4.2: Efficiency optimization with voltage

$$\eta = \frac{V \cdot H}{U \cdot I \cdot t} = 0.76\,, \tag{3}$$

Where H is the calorific value for hydrogen 11.523 MJ/m^3. Where V is the volume of hydrogen produced and U, I, t stands for the voltage, current, and time measured to produced that volume of hydrogen.

The experiment also shed light on the electrolyser's sensitivity to changing voltages and how that affected hydrogen production [figure 4.3]. This knowledge is essential for maximizing the performance of PEM electrolysers and their effectiveness in real-world applications.

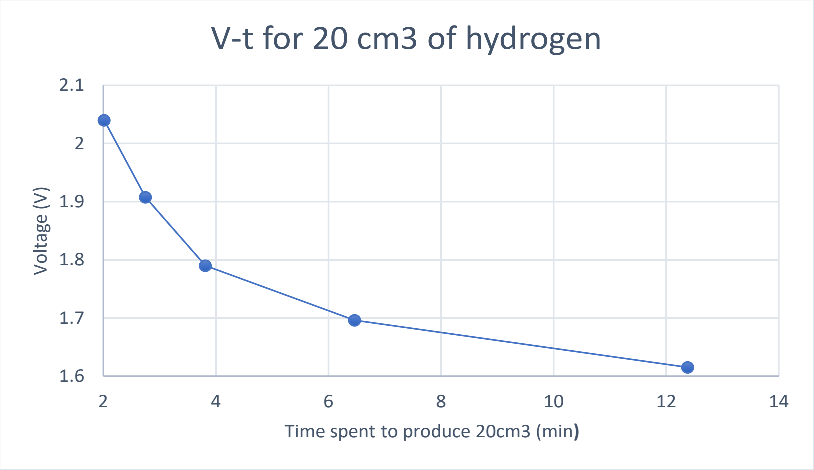

Figure 4.3: Time needed to produce 20 cm^3 of Hydrogen

The PEM experiment's overall findings demonstrated this technology's capacity to produce hydrogen with great efficiency and highlighted its promise as a clean energy alternative. The research supports the creation of sustainable energy systems and advances methods for producing hydrogen.

4.2 Wind turbine results

The following graph shows the results of the experiment [figure 4.4], which showed that the highest power was generated at a load of 33 ohms. This illustrates the ideal load for the wind turbine quite clearly. We then calculated our wind turbine's efficiency using this ideal load.

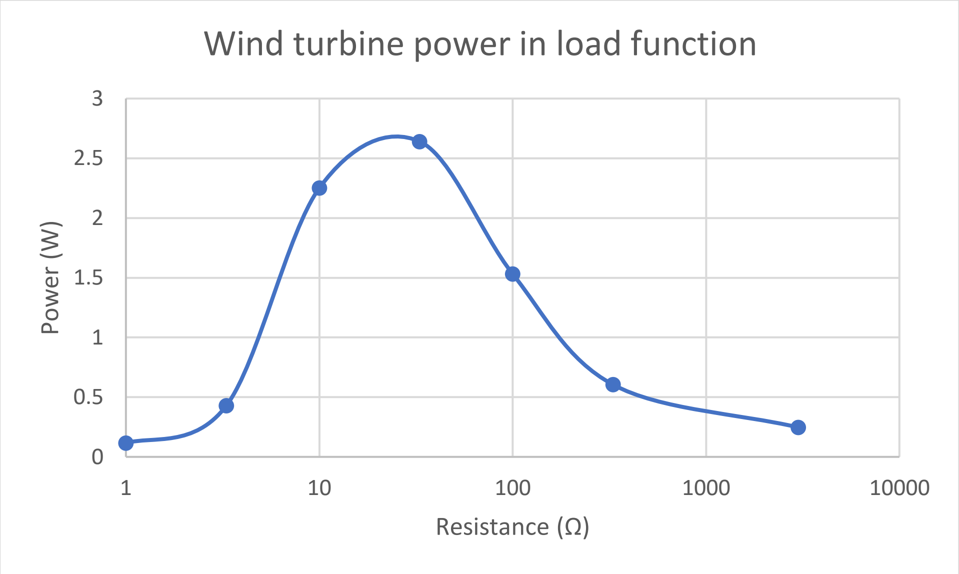

Figure 4.4: Optimal load comparison

We were able to determine the efficiency of our wind turbine by examining the data collected at the ideal load. The efficiency is a measure of how effectively a wind turbine converts wind energy into electrical electricity [table 4.1].

Table 4.1: Obtained efficiency values

Speed (m/s) *v*	**Wind Power (W) P_{kin}**	**Turbine Power (W) *P***	**Efficiency (%)**
1.375	0.312	0.126	41.6
2	1.20	0.559	46.5
2.825	2.705	1.36	50.2
3.38	4.633	2.484	53.4
3.96	7.45	3.978	53.2

The experiment's execution yielded astonishing outcomes. Our wind turbine demonstrated an amazing efficiency of 53.4 % at greater wind speeds, which is noticeably high and is close to the theoretical maximum. This demonstrates the outstanding efficiency with which our wind turbine captures wind energy.

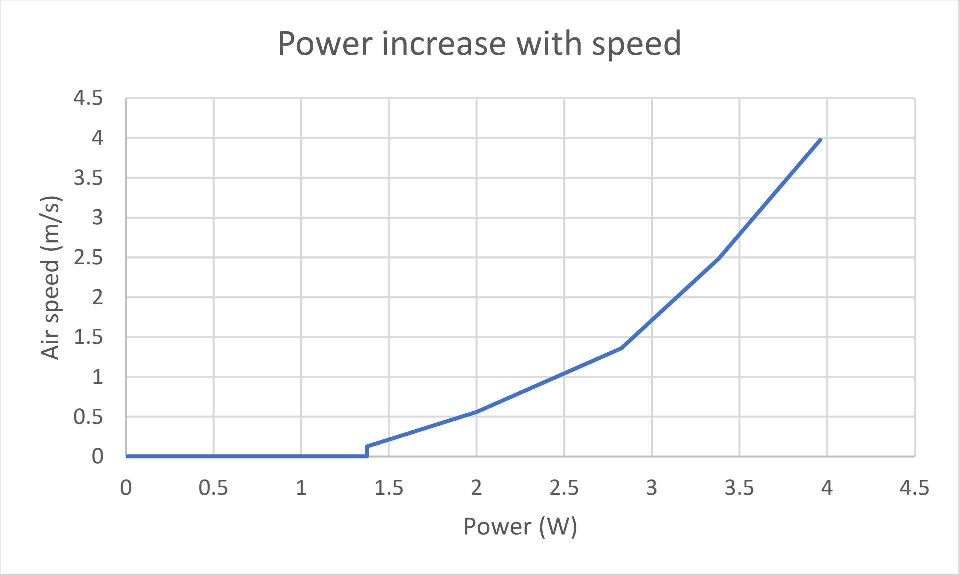

Figure 4.5: Power increase with speed comparison

It is significant to highlight that, despite our impressive efficiency, we were unable to operate the turbine to its full potential [figure 4.5]. This restriction was attributable to the wind tunnel's capacity limitations. However, the achieved efficiency is a clear demonstration of the turbine's ability to efficiently transform wind power into electrical energy.

These results demonstrate the considerable advancements made in enhancing the functionality of our wind turbine. The great efficiency attained illustrates its promise as a dependable and long-lasting solution for the production of renewable energy. In order to completely release the turbine's potential, additional research and development efforts can concentrate on overcoming the constraints provided by the wind tunnel capacity.

4.3 Coupling PEM and wind turbine results

The results from combining wind power and the electrolyser have shed important light on how these two technologies interact. Compared to the solitary electrolyser experiment, it did take longer to create hydrogen, but the efficiency was discovered to be incredibly high – around 71.8 % (it was calculated for the higher voltage the same as in the PEM experiment). This result can be due to our purposeful emphasis on system optimization to guarantee maximum voltage delivery to the electrolyser. We sought to maximize efficiency by designing an efficient load that constrained the wind turbine's output. As a result, the experiment's lower current values are consistent with our predictions of a better efficiency curve at lower current levels [figure 4.6].

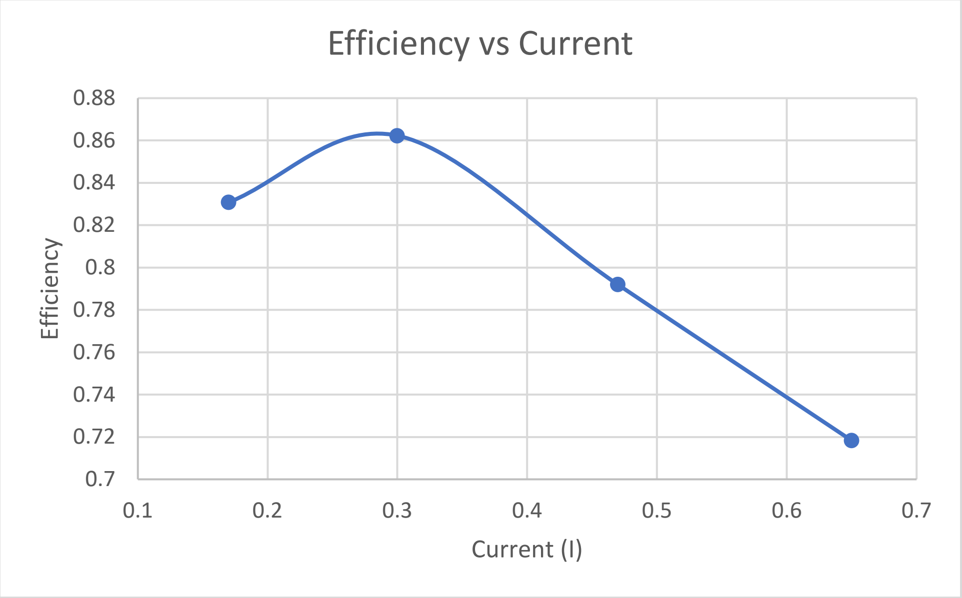

Figure 4.6: Efficiency vs Current

The linked system's durability and adaptability are demonstrated by the fact that it was still able to operate at a high level of efficiency despite the prolonged hydrogen generation time. The significance of system optimization and the delicate balance needed between electrolysis and wind power generation are both highlighted by this finding. It also highlights the necessity to think about the system's total efficiency rather than only concentrating on optimizing power production. We have learned a lot about the trade-offs involved in obtaining maximum efficiency in coupled energy systems by examining the interaction between wind power and the electrolyser.

Our research also highlights the need of locating the greatest efficiency point, which may not always correspond to the highest power output. This fact calls into question the widely held belief that a system's peak efficiency is represented by its maximum power. Instead, it emphasizes how crucial it is to identify the sweet spot where efficiency is maximized while balancing all of the relevant factors.

This result emphasizes the potential of combining hydrogen production and wind energy technology to produce sustainable and effective energy conversion. The development of large-scale renewable energy systems through additional study and system improvement could pave the way for a more environmentally friendly future.

5 Conclusions

In conclusion, this thesis was successful in achieving its stated goals, which included detailing the characteristics of the experimental system used and explaining it. The creation of an experimental matrix served as a clear direction for the methodical conduct of the investigation. To ensure proper data collection, measurements were carried out in accordance with the defined experimental strategy.

We have learned a lot from our experiments with the coupling of PEM electrolysers and wind turbines for hydrogen production. Even if the results are encouraging, it's crucial to recognize the difficulties and constraints that were experienced.

One significant challenge we faced was the limitation in our air tunnel, which prevented us from reaching the nominal capacities of the wind turbine. This restriction hindered our ability to fully explore the turbine's maximum potential and gather comprehensive data on its performance. To address this limitation, future experiments could be conducted in larger-scale wind tunnels or real-world settings to obtain more accurate and representative results. Additionally, we encountered difficulties in controlling and maintaining the optimal load for the wind turbine. The turbine's power output proved to be too powerful at its optimal load, making it challenging to control the voltage within the desired range. This limitation necessitated the use of an infinite load, which impacted the controllability and precision of our measurements. Overcoming this challenge would require the development of advanced control systems or load management strategies to ensure optimal performance under varying conditions.

Additionally, compared to the independent PEM electrolyser, the connected system's hydrogen production time was significantly longer. Future study may find success by looking into ways to improve reaction kinetics and boost output rates without sacrificing effectiveness. These results emphasize the significance of determining the best efficiency point rather than focusing only on maximum power and the necessity of balancing the performance of individual components within a coupled system.

Despite these difficulties, our research highlights the viability and potential of combining PEM electrolysers and wind turbines for the generation of clean energy. The great efficiencies attained by these technologies show that they are capable of assisting in the transition to sustainable energy. We can realize the full potential of these systems for clean hydrogen generation and renewable energy use by addressing the restrictions and further enhancing the integration and operation of these systems.

Suggestions for further work

Looking ahead, future work in this field should focus on refining the experimental setup and exploring strategies to enhance efficiency and overcome limitations, such as the constraints imposed by the experimental apparatus. Moreover, investigating the scalability and practical implementation of the coupled system in real-world scenarios would be beneficial.

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