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ÚSTAV JAZYKŮ

NON-TRADITIONAL ALTERNATIVES OF ELECTRICITY GENERATION

NETRADIČNÍ ZDROJE VÝROBY ELEKTRICKÉ ENERGIE (REŠERŠE)

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4) Fuel cells
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6) Conclusion

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Abstract

In recent years, the global demand for clean energy has increased significantly, driving efforts on shifting energy generation toward renewable energy sources to minimize carbon dioxide emissions. This thesis investigates some of the non-traditional alternatives of electricity generation. It begins with a study focus on the alternative energy sources from the sea, continues with potential lower orbit energy generation, and then explores the geothermal energy and fuel cells. The paper also includes a measured V-I characteristic of a proton exchange membrane fuel cell (PEMFC) and an evaluation of electrolyser efficiency. Some of the topics described in this thesis are well-known, but they are not utilized in the commercial sector for various reasons. One of them is economic inefficiency. Nevertheless, these promising non-traditional alternatives of electric energy generation offer promising potential for sustainable electricity generation for years to come.

Keywords

Tidal powerplant, Solar energy, Geothermal energy, Electrolyser, Fuel cell, Hydrogen, Electric energy

Abstrakt

V posledních letech výrazně vzrostla poptávka po čisté energii, přičemž je pozornost soustředěna převážně na přesun výroby energie směrem k obnovitelným zdrojům, aby se minimalizovala úroveň oxidu uhličitého. K omezení emisí, CO_2 jsou zapotřebí nové techniky a technologie pro získávání elektrické energie. Tato práce zkoumá a shrnuje některé netradiční alternativy výroby elektrické energie. V úvodu se zaměřuje na alternativní energetické zdroje z moře, pokračuje výrobou energie na nižší oběžné dráze a poté se věnuje geotermální energii a palivovým článkům. V této práci dále zahrnuje naměřenou voltampérovou charakteristiku palivového článku s protonovým výměnným membránovým článkem (PEMFC) a měření účinnosti elektrolyzéru. Některá témata popsaná v této práci jsou dobře známá, avšak z různých důvodů nejsou využívána v komerčním sektoru – jedním z nich je ekonomická neefektivita, a některé technologie se stále nacházejí v rané fázi vývoje. Přesto je v práci popsáno mnoho slibných netradičních alternativ výroby elektrické energie, které mají velký potenciál do budoucna.

Klíčová slova

Přílivová elektrárna, Solární energie, Geotermální energie, Elektrolyzér, Palivový článek, Vodík, Elektrická energie

Rozšířený abstrakt

V posledních letech stále roste poptávka po udržitelné energii. Z důvodu snížení uhlíkové stopy by mělo v příštích letech dojít k přesunu z neobnovitelných zdrojů elektrické energie na ty obnovitelné za účelem minimalizování produkce CO_2. K dosažení tohoto cíle bude zapotřebí vyvinout nové, nebo upravit stávající technologie, pro získávání té elektrické.

Tato práce se zabývá netradičními zdroji výroby elektrické energie. Cílem bylo popsat a prozkoumat netradiční zdroje elektrické energie, proniknout do jejich základů a zjistit jaké výhody, nebo komplikace, představují pro implementaci do elektrické sítě. Kromě toho tato práce obsahuje měření V-I charakteristiky palivového článku a měření efektivity elektrolyzérů. Zkoumání současných trendů ve světě výroby elektrické energie navíc poskytuje výhled do budoucnosti pro obor energetiky.

První kapitola se zaměřuje na obnovitelné a neobnovitelné zdroje elektrické energie. Z netradičních zdrojů popisuje uhlí, jadernou energii, zemní plyn, ropu a geotermální energii. Z geotermálních zdrojů se zabývá geotermální energií, solární energií, energií větru, energií vody a biomasy.

Druhá kapitola pojednává o některých alternativních zdrojích výroby elektrické energie z moří a oceánu, na zemské oběžné dráze a také o ostatních netradičních zdrojích. Věnuje se jejich historii, způsobu přeměny elektrické energie a uvádí některé příklady, kde se tato technologie využívá k dodávkám elektřiny do elektrické sítě. U zdrojů z moří a oceánů je hlavně popsána problematika přílivových hrází a přílivových turbín, které využívají jevů, které se odehrávají jak na mořské hladině, tak mořském dně. Dále je popsán způsob, který by mohl být využit jako alternativní zdroj elektrické energie na oběžné dráze. A jako poslední v této kapitole byla popsána geotermální energie, zejména způsoby, kterými probíhá přeměna geotermální energie na tu elektrickou.

Třetí kapitola se věnuje klasifikaci a způsobům, kterým lze obstarat vodík. Jedná se o poněkud komplikovanou problematiku, která zahrnuje výrobu vodíku pomocí parního reformingu nebo třeba parciální oxidace. Rovněž se také zabývá tím, jak lze využít elektrolýzy vody za účelem jejího rozkladu a obstarání vodíku. Dále jsou v kapitole obsaženy některé chemické reakce, které probíhají ať už při elektrolýze vody, parním reformingu, nebo parciální oxidaci. Všechny tyto procesy, jsou způsoby, jak vodu rozložit na vodík a kyslík. Parní reforming a parciální oxidace se využívá hlavně u jaderných elektráren. Elektrolýza vody se využívá spíš v laboratorním prostředí stejně jako rozklad vody za pomocí elektrolyzéru.

Čtvrtá kapitola popisuje palivové články a uvádí jejich nejvýznamnější typy. Podrobněji jsou popsány palivové články s alkalickým elektrolytem a Palivové články s polymerní membránou, a to zejména jejich historie, kde se využívají a jakým způsobem vyrábí elektrickou energii. Dále je uvedeno mobilní využití palivových článků s polymerní membránou. Byly popsány chemické reakce jak na katodě, tak anodě u palivového článku s polymerní membránou. Pro lepší pochopení celé problematiky byly vytvořeny schéma, jak pro článek s alkalickým elektrolytem, tak pro palivový článek s

polymerní membránou. Do obou schémat byly obsaženy chemické reakce, které v článku probíhají.

Pátá kapitola prostřednictvím dvou měření zkoumá výkon palivového článku pracujícího s rozdílným odporem a také výpočet efektivity elektrolyzéru. Byla přiložena fotografie celé měřené laboratorní úlohy a byly popsány přístroje, pomocí kterých bylo měření prováděno. Pro lepší pochopení problematiky zapojení byly vytvořeny, blokové schéma obou zapojení Toto měření poskytnulo cenné informace ohledně celého procesu, jak elektrolyzér rozkládá vodu na vodík a kyslík a také jak probíhá výroba elektrické energie pomocí palivového článku. Měření byly provedena na Fakultě elektrotechniky a komunikačních technologií za dohledu Ing. Lukáše Radila, Ph. D.

Pro provedení měření bylo zapotřebí dvou multimetrů, programovatelného zdroje napětí, odporové dekády, sady čítající deset palivových článků a elektrolyzéru. Při měření palivového článku byl změřen jeho výstupní proud a výstupní napětí. Z těchto dvou údajů byl poté vypočítán celkový výkon sady palivových článků. Při měření elektrolyzéru byl změřen čas, za kterou rozloží destilovanou vodu při rozdílných napětích. Proud byl změřen pomocí dvou provedených měření, které byly poté zprůměrovány. Také bylo do tabulky zaznamenáno napětí vycházející ze zdroje a napětí pod kterým elektrolyzér opravdu pracoval. Výsledky byly pro přehlednost zaznamenány pomocí tabulek a prezentovány za pomocí grafů.

Měření vykazuje hodnoty, které jsou v souladu s typickými hodnotami jak u výkonu článků s polymerní membránou, tak u výpočtu efektivity elektrolyzéru. Aby však bylo možné naplno využít elektrolýzy vody i v komerčním sektoru, bude zapotřebí dalšího vývoje v tomto oboru. Ovšem palivové články s polymerní membránou v kombinaci s elektrolyzérem, představuje technologii, která má veliký potenciál do budoucna.

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Author's Declaration

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Topic:	*Non-traditional alternatives of electricity generation*

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the project and listed in the comprehensive bibliography at the end of the project.

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Brno, May 28, 2025 --------------------------------------
author's signature

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1. INTRODUCTION

In today's world, nations require astonishing amounts of electric energy for many different purposes, such as transportation, manufacturing, cooling, and heating. Energy requirements continue to increase every year. Non-renewable power plants produce most of the electric energy but also a lot of greenhouse gases and carbon dioxide. Demand for green electric energy production is one of the central problems of the 21st century. Non-traditional alternatives were chosen on relatively well-researched topics and because of their potential for years to come.

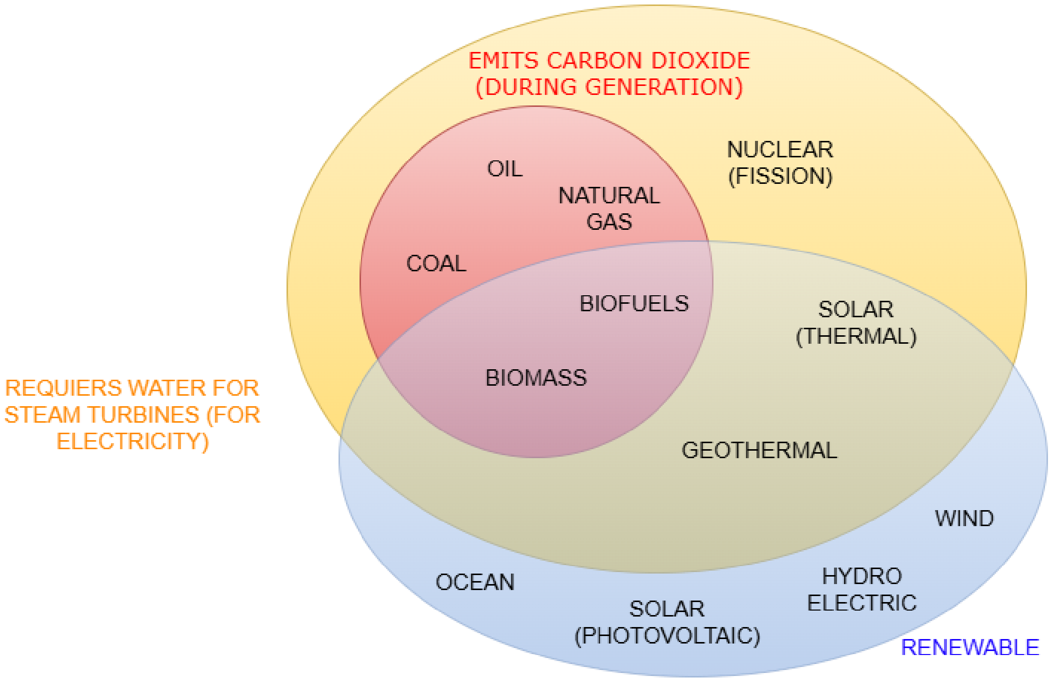

Figure 1 Distribution of Electrical Energy

1.1 Energy Sources

Sources of energy can be defined as those that can supply a sufficient amount of energy in an appropriate form over an extended period of time. The most significant sources of energy (excluding human and animal power) are geothermal sources, nuclear sources, natural gas, coal, hydropower, biomass, wind and solar sources. Primary energy sources can be further classified into two other groups: non-renewable and renewable energy sources. The introduction part of this Bachelor thesis will briefly summarize these types of energy.[1]

1.2 Non-Renewable Energy Sources

Energy from sources that have limited supplies will run out or not be restored in our lifetimes. These energy sources are stored underground in the form of gas or in the liquid or solid state. Oil, natural gas, and coal are called fossil fuels, which have been formed from the remains of prehistoric plants and animals. Nuclear energy is also a type of non-renewable energy but does not belong to the fossil fuels category. [1] [2]

Fossil fuels are a valuable source of energy that is inexpensive to extract and found worldwide. However, when burned, fossil fuels produce many harmful gases, which lead to pollution.[2]

1.2.1 Coal

Coal is a non-renewable energy source that has been formed during the last 475 million years. Coal is mainly composed of carbon and hydrocarbons with high energy density, which is released through burning. Based on the amounts of carbon contained and produced heat energy, coal is classified into four main categories (Anthracite, Bituminous, Sub-bituminous, and Lignite). Both Lignite and Bituminous are employed to generate electricity. Lignite is composed of carbon in 25-35%. Bituminous, on the other hand, contains 45-86% carbon with higher energy density than Lignite. Coal is mainly used in power plants and chemical industries. In 2021, coal-fired power powerplants generated over a third of all electricity worldwide.[1] [3]

1.2.2 Nuclear Energy

Nuclear energy is the energy released during nuclear reactions, especially fission or fusion.

Every object in the universe is made up of atoms. Bonds that hold atoms together contain large amounts of energy. Nuclear energy is mainly utilized to produce electric energy. The fuel employed in the reactor is usually uranium 235(235U).[1]

With nuclear fusion, nuclei fuse together. With nuclear fission, nuclei of atoms split into two or more smaller nuclei while releasing energy in the form of heat and radiation. The released heat then warms the cooling agent to produce steam. Electric energy is generated with an electric generator connected to a turbine, transferring kinetic into electric energy. With nuclear fusion, the energy is released by combining smaller atoms to form larger ones.[1] [4]

1.2.3 Natural Gas

Compressed Natural Gas (CNG) is composed of simple hydrocarbon compounds, including ethane, pentane, and butane, but mostly, the CNG is made from methane. CNG (Liquid natural gas by applying high pressure) is applied as fuel in factories, cars, buses, and trucks. CNG is used in natural gas power plants to generate electricity by using it as fuel. All natural gas plants utilize a gas turbine with a stream of air. Burning natural gas releases significantly fewer emissions than coal and oil.[1] [4] [5] [6]

1.2.4 Oil (Petroleum)

Petroleum is a fossil fuel comprised of oil and natural gas. It is found either in a liquid (crude oil) or gaseous state (natural gas). Either way, it consists of different hydrocarbon molecules containing hydrogen and carbon. However, when electric energy is generated, burning gasoline releases hazardous gases and fumes into the air, which is harmful to the environment. Petroleum products account for 50-95% of commercial energy supplies, and they currently meet nearly all the energy demands of the transportation sector and mobile equipment [1] [2]

1.3 Renewable Energy Sources

Renewable energy sources such as hydropower, biomass, wind, solar, hydropower, and geothermal energy can be replenished naturally in a short period of time. Many countries are switching to renewable energy-based systems to lower the CO_2 emissions exhibited into the air. This part of the Thesis describes conventional renewable energy sources.[2]

In 2023, 40% of the world's electricity was generated by zero-carbon technologies.[7]

1.3.1 Geothermal Energy

Geothermal energy is heat located in the Lithosphere, which is also called the crust, and it is the most solid mantle.

Geothermal energy is an energy in the form of heat generated in the Earth's core and extracted from within the Earth's interior. To create electric energy, the heat is usually obtained from reservoirs of hot water at depths ranging from 3 to 10 km from where it is brought to the surface using wells. The extracted heat is mainly used for electricity generation and for heating and cooling of buildings.[1] [9]

1.3.2 Solar Energy

Solar energy is the most abundant source of energy. The amount of sunlight that reaches any spot on the Earth's surface differs because of its geographical location, time of day, season, local landscape, and local weather. Earth's surface receives the maximum possible energy when the Sun's rays are vertical. Electric energy is generated using solar technologies that capture the sunlight and transform it.[10] [11]

Two main technologies to convert sunlight into electricity are photovoltaic cells and solar thermal systems. Photovoltaic cells directly convert solar radiation into electrical energy with the use of semiconductor devices. Solar thermal systems convert solar energy into thermal energy in the form of steam, which is then employed to drive a turbo generator.[1] [11]

1.3.3 Wind Energy

Wind is a form of solar energy, and they are caused by the rotation of the Earth, uneven heating of the atmosphere received from the Sun, and also the ruggedness of the Earth's surface, which contributes to wind creation. Hot air rises, which reduces the atmospheric pressure of the Earth's atmosphere on the surface. Cooler air rushes to these areas to replace the hot air, which results in wind. Wind energy produces very little or no greenhouse gases.[12]

Wind turbines convert kinetic energy into mechanical power, which can be used to generate electricity. Wind machines are utilized to harness this energy in areas where the flow of wind is constant and can reach an average speed of only 22.5 kilometers per hour.[13]

1.3.4 Hydropower

Hydropower is a source of energy based on the natural water cycle. It is one of the most reliable and mature renewable power generation technologies available. However, the worldwide electricity generation using hydropower is declining. Hydropower is flexible and capable of responding to demand fluctuation in minutes. With the utilization of a reservoir, electricity can be stored for weeks or even months. The power can be stored to meet system peaks or demand decoupled from inflows. Reservoir levels can be increased for the time of low sunlight or wind covering the electric energy generation of these two electricity sources.[14] [8]

1.3.5 Biomass

Biomass is a renewable source of energy that is obtained mainly from the byproducts of the wood industry and agricultural crops, animal manure, and human sewage. Biomass exists in one form in plants and can be transferred through the food chain to animal bodies and their wastes. With the process called combustion, this waste then releases the carbon dioxide stored in the plant material. The energy in biomass is released as heat when burned. The advantage of Biomass electric energy generation is that the same equipment can be applied to produce electricity in already existing power plants that burn fossil fuels. The use of biomass could provide an alternative source of energy to coal, petroleum, or natural gas. Fossil fuels, as well as burning biomass, release carbon dioxide (CO_2). However, when these plants are grown, a nearly equivalent amount of CO_2 is captured through photosynthesis.[1] [15]

2. ALTERNATIVE ENERGY SOURCES (FROM SEA AND OCEAN, LOWER ORBIT AND OTHER ALTERNATIVE SOURCES)

2.1 Tidal Barrage

2.1.1 Introduction

Tidal energy is issued from the interaction between the Earth and celestial bodies. Marine and wave currents originate from the wind blowing on the ocean’s surface. Kinetic energy is extracted from the vertical and horizontal movement of the tides. The most dominant techniques that can be used to harness the kinetic energy of waves and currents are the tidal barrages and tidal stream turbines.[16]

2.1.2 History

For thousands of years, humans have been harnessing water to grind wheat into flour. While Greeks employed water wheels to grind grain, Egyptians used water screws for irrigation during the third century B.C. In the mid-1700s, French hydraulic engineer Bernard Forest de Bélidor wrote the groundbreaking Architecture Hydraulique, which started the evolution of the modern hydropower turbine as we know it today.[17]

The first commercial installation of an alternating current hydropower plant in the U.S. was constructed at the Redlands Power Plant in California in 1893. This powerplant utilized a three-phase power generator and Pelton water wheels for consistent power delivery.[17]

2.1.3 Tidal Power Plant Energy Generation Principle

When the tide comes to the shore, it can be trapped behind barrages with water passages guiding the water to a place where the tidal motion starts to move the turbine blades. The generated kinetic energy of these blades can then be used to drive a generator to create electricity like in a hydroelectric powerplant. The tidal means of generation utilizes the Moons and the Sun’s gravitational pull on the oceans. Tidal energy relies on the rise and fall of the tides. When the tide comes, the water flows into the basin, keeping the sluice gates open. Then, the sluice gates close until the desired difference between the sea water level and the water level in the basin is achieved. The sluice gates then open, with water flowing onto a turbine, creating electric energy.[18] [19]

The tidal barrage is a wall consisting of tidal turbines. Sluice gates are situated on both sides of the barrage, separating the turbine when needed. The sluice gates are used to control the difference between the water level in the ocean and the water level in the basin. Tidal barrages operate in three modes: an ebb mode, a flood mode, and a two-way generation mode.[18] [19]

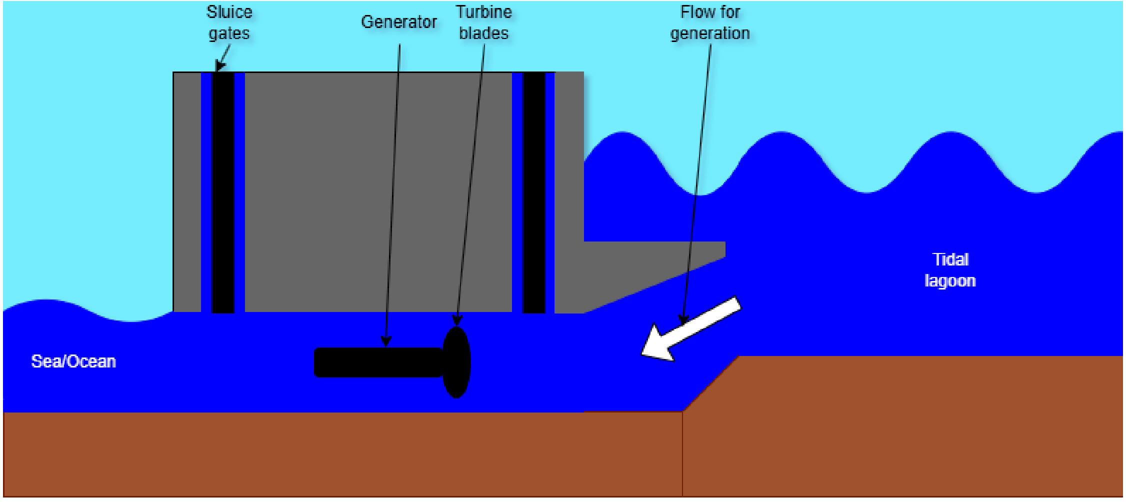

Figure 2 Tidal Barrage/Lagoon [52]

2.1.4 Sihwa Tidal Power Plant

Sihwa tidal power plant is located on the west coast of South Korea. This powerplant utilizes the Tidal barrage system to trap high tide and then generate electricity using the Ebb generation method. The reason why this power plant was built was to generate electricity and to improve the water quality inside the lake. The basin area is 43 km^2.[20] [21]

2.2 Tidal Stream Turbine Electric Energy Generation

Tidal streams are horizontal movements of tides that possess a considerable amount of kinetic energy. It is one of the natural potentials that comes from the gravitational influence of the Moon and the Sun on ocean waters. Tidal stream plants exploit the kinetic energy by installing tidal turbines on the bottom of the ocean where these strong currents occur. They are very similar to wind turbines.[18]

Usually, a tidal stream turbine comprises several blades mounted on a rotor, gearbox, and generator. The generator turns on as the hub starts to rotate due to the hydrodynamic effect of moving water. The generated electric energy is then transmitted to land using cables.[19]

2.2.1 Parts of Tidal Stream Turbine and Types of Structures

The rotor, gearbox, and generator are mounted onto a structure that can withstand harsh environmental loading. Water is denser than air, which is the most significant advantage in comparison between tidal energy generation and wind energy generation. The mode of operation in a tidal farm depends on the type of turbine deployed to generate electricity. The turbines used for this kind of electricity generation are still in development. Some tidal stream farms are operational and located near the United Kingdom. The two most common types of turbines are horizontal and vertical.[18] [19]

The simplest and most popular are Horizontal axis turbines, also known as axial flow water turbines. Vertical axis turbines, also known as crossflow water turbines, rotate on the horizontal axis and are independent of the stream direction. The advantage of this type of electricity generation is that the environmental impact is almost non-existent because their installation requires minimum land use.[18] [19]

We recognize three types of support structures: gravity structure, piled structure, and floating structure. The piled structure is placed on the seafloor and connected to it using steel or concrete beams. The gravity structure is a large mass of concrete that sits on the seabed with the turbine embedded in it. The floating structure is attached to the seafloor using a chain or wire. The turbine is connected facing downward and pointing towards the vertical beam. The beam is then attached to a floating structure.[22]

2.3 Conclusion

One of the main drawbacks of tidal barrage energy generation is the expensive construction and its effects on water quality and ocean life. With ever-increasing demands on the reduction of greenhouse gases and Carbon dioxide levels, tidal energy can play an important role in worldwide electricity generation.

Tidal stream turbines are still in the early stage of development with issues like underwater installation, maintenance, and electricity transmission. However, in comparison with the tidal barrage, tidal stream turbines have a much lesser impact on the environment, which is an important advantage over the tidal barrage way of creating electric energy.

2.4 Solar Energy

2.4.1 Introduction

Solar energy is a renewable source of energy that comes from the sunlight. Solar energy can even be considered inexhaustible. However, solar power makes minimal contribution to the power grid in comparison with other sources of energy. In today's world, much more emphasis is given to sustainability, renewability, and overall reduction of carbon dioxide footprint. Therefore, a transition to more sustainable energy sources is required. One of the many possible options is solar energy.[23]

2.4.2 History

Passive solar is the term that describes a suite of technologies, which converts the energy from the Sun directly, usually for heating and cooling. This happens without the need for any mechanical or electrical devices. Many ancient Indian and Greek houses were built in a way so that the interiors of the buildings could absorb the maximum amount of sunlight during the coldest days of the year.[23]

Photovoltaic technology began when Alexandre-Edmond Becquerel worked in the laboratory with his father. They observed that some materials could generate electric current when exposed to light. The first actual solar cell was created by Charles Fritts in 1883, with only 1% of the incident light converted into electricity.[23]

A crucial theoretical breakthrough occurred in 1905 when Albert Einstein partially explained the photovoltaic effect, the phenomenon responsible for the generation of electricity by a solar cell. The first photovoltaic cells capable of producing significant amounts of electricity were made almost 50 years later, in 1954.[23]

2.4.3 Photovoltaics

A photovoltaic cell converts the incoming sunlight directly into electricity. Photovoltaic technology has the potential to create more electric power than other competing technologies. Many laboratories around the world aim to reduce the price and improve the efficiency of photovoltaic cells for this matter. One problem with photovoltaic technology is that it is a very costly technology to produce. Therefore, it is vital that the sunlight is converted into electricity as efficiently as possible and as often as possible.[23]

2.5 Thermoelectric Generator

2.5.1 Introduction

In every power generation and industrial process, thermal energy is generated as a byproduct of the process. The Thermodynamic laws play a significant role in the amount of useful power that can be extracted. The need to reduce energy consumption and pollutant emissions led to many developments in waste heat recovery with thermoelectric devices.

The earliest observations were made by studying the thermoelectric phenomenon with the proposition of the first thermoelectric pile. Nevertheless, it was only after Thomson's studies on thermodynamics and Rayleigh's suggestions to exploit the Seebeck effect that the first thermoelectric generators saw the light of day. This technology evolved from unreliable to very sophisticated.[25]

2.5.2 The Working Principle of Thermoelectric Materials

Thermoelectric modules deploys thermoelectric materials to harvest energy. Thermoelectric modules are solid-state devices made of thermoelectric couples. The thermoelectric couple is made from p-type and n-type semiconductor elements, which are electrically connected in series and parallel for thermal purposes. When a temperature difference is present at the p-n junction, the charge carriers diffuse from the hot side to the cold side, where a voltage is generated. This phenomenon is called the Seebeck effect.[26]

Special thermoelectric materials are then utilized to convert the heat to electricity. Bismuth telluride is one of the most common materials used as a thermoelectric material due to the high figures of merit.[26]

2.5.3 Design of the Thermoelectric Generators

The main goal of the design is to ensure that the electric power obtained from the waste heat flow is bigger than the possible energy losses that are caused by the system. Some of the aspects that are evaluated when designing a thermoelectric generator are the heat source, the hot side heat exchanger, and the efficiency in converting heat that actually reaches the device.[26]

Two main heat exchanger designs are a flat-shape heat exchanger and a hexagonal heat-exchanger. The flat shape heat-exchanger is more suitable for limited space applications so that it can be used in cars and buses. The hexagonal heat exchanger has a more even hot surface temperature in the modules at the same distance downstream of the gas inlet. This temperature is almost twice as big with the use of the flat-shape heat exchanger.[26]

2.5.4 Applications of Thermoelectric Generator from Solar Array Arcing

Solar power serves as a traditional form of electric power generation in satellites. Solar cells are separated by an 800 µm wide gap. In this gap, the surrounding plasma, the surface insulator, and the conductor form a junction where the arcing phenomenon is observed. The entire system is welded between two one-millimeter-long strips of alumina substrate. The results of the study show that a primary arc of 0.2 A for 4 µs arc duration can yield 0.117µJ. Although the generated energy seems small if we consider multiple thermoelectric generators working together, such power generated can play an important role in low-power space exploration applications.[27]

2.5.5 Conclusion

Solar energy, in its current state, still has a long way to go to fully take advantage of its potential with problems like making photovoltaic cells more efficient and reducing the overall price. The thermoelectric generator would be a great addition to the solar systems for wasted heat energy electricity generation on satellites and other space stations. However, with further advancements in technology and making photovoltaic cells more efficient, the future is bright for solar energy.

2.6 Geothermal Energy

2.6.1 Introduction

Geothermal energy is characterised as a renewable source of electric energy. This energy is used sustainably, which means that the production system can produce electricity over long periods of time. The source of geothermal energy is the heat stored under the surface of planet Earth.

The geothermal power plants worldwide comprised to 15.4 GW of generated electric energy, with countries like Indonesia, the Philippines, and Kenya significantly scaling up their geothermal energy output in recent years.[28]

2.6.2 History

Geothermal energy is one of the oldest types of power used by humans. The first attempt to harness this energy came with the Industrial Revolution in the 19th century. Francesco de Larderello tried to extract boric acid from volcanic mud in 1827. The town of Larderello, in which this experiment took place, is home to the world’s largest geothermal dry steam field and geothermal powerplant, with an installed capacity of over 800 MW. One of the biggest challenges that geothermal energy has faced is the high price of drilling wells to reach the dry steam or wet vapor.[29]

The 21st century marks a new era for geothermal energy. With more concern regarding sustainability, climate change, and Carbon dioxide production, geothermal energy is gaining recognition for its reliability and renewability. With the right investments and policy frameworks, geothermal energy can become a cornerstone of the future green energy landscape.[29]

2.6.3 The Principle of Geothermal Electric Energy

The working process involves the use of steam to produce electricity. The steam is collected from the hot water sources below the Earth's surface. The collected steam is brought up to the Earth's surface using wells and pipes, which causes the rotation of the turbine, which activates the generator for electricity production. Examples of geothermal energy sources are steam vents, hot springs, mud pots, and hot water released through geysers.[24]

2.6.4 Vapor-Dominated Geothermal Energy System

The simplest type used to harness geothermal energy is called a vapor-dominated system. These systems are deployed on vapor-dominated sites. They are more effective than the other types of geothermal power plant systems. However, sites that are vapor-dominant are rare. Boreholes have to bring only very dry steam, not wet steam or liquid water.[24]

As the steam comes from the well to the turbine, it carries particles of dirt that must be removed. After the dirt is removed, the pressurized steam flows through a valve to the turbine. The steam drives the turbine, which drives the generator, and electricity flows to the power grid. The condenser then converts the vapor into water, which is injected back into the well.[24]

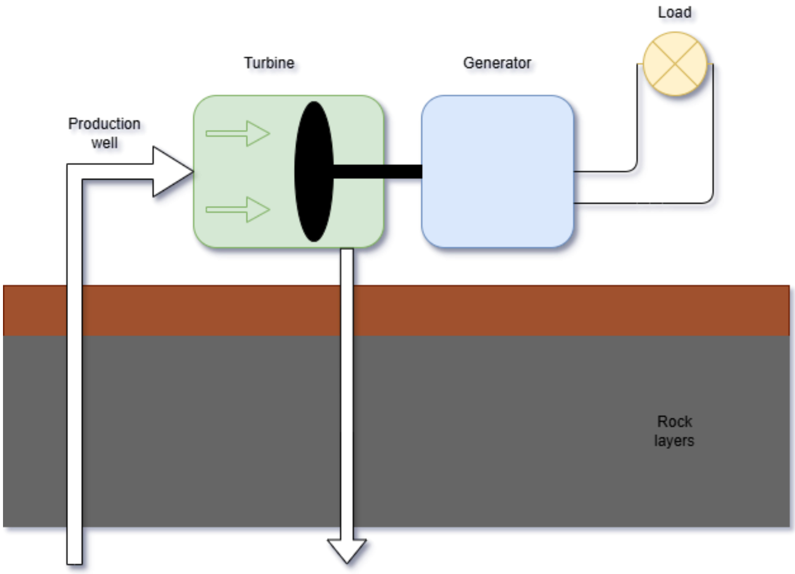

Figure 3 Vapor-Dominated Geothermal System [24]

2.6.5 Hot-Water System (Flash System)

Flash systems are a more common type of geothermal power energy systems. This type pumps hot, liquid water from thermal reservoirs instead of vapor. The water sometimes exceeds the boiling point twice, but because the pressure drop beneath the Earth's surface is much higher than the one at the surface, the water remains in a liquid state. As the water is brought to the surface, the pressure begins to drop, and the water begins to boil, not all, but some of it turns into steam. Also, the turbine needs to turn the water into steam. Therefore, a "flash tank" device is deployed to allow more of the liquid to change into steam. Meanwhile, the non-vaporized water is pumped back into the injection well. The steam then drives the turbine-generator combo, as in the previous example. The steam from the turbine is then condensed, and some of it is injected back into the reservoir, which completes the cycle of this method.[25]

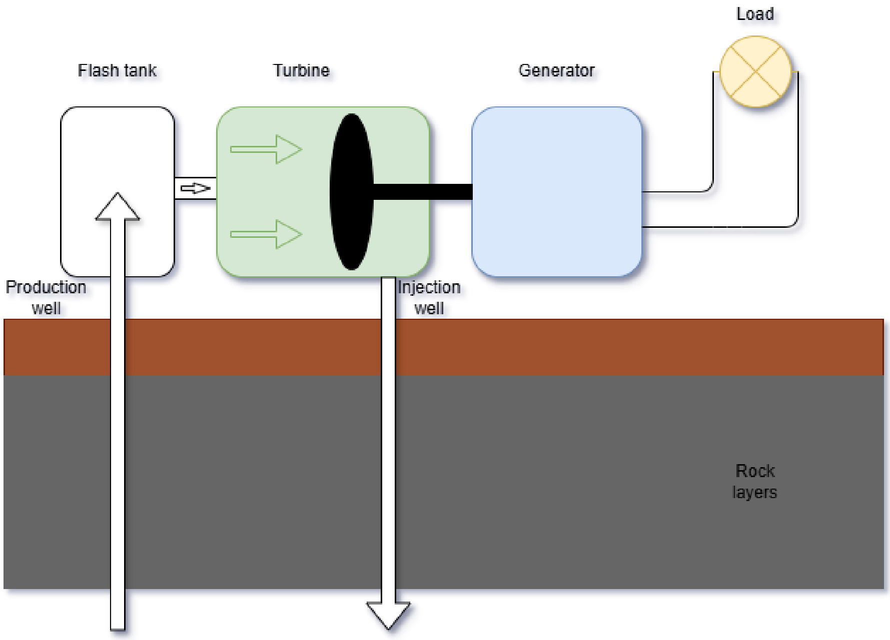

Figure 4 Hot-Water System [24]

2.6.6 Binary Cycle Power Plant (Moderate-Temperature System)

A binary system uses two independent loops, each carrying a different fluid. One of the loops contains hot water produced from the well. This fluid enters the heat exchanger, transferring some thermal energy to the working fluid in the second loop. The water then returns to the underground with the injection well, where it is reheated. The working fluid absorbs the heat from the first loop and changes into a gaseous phase. The right choice of working fluid is crucial to the efficiency of the design. The fluid choice differs from system to system. Some systems deploy water because it is abundant and inexpensive; others may deploy ammonia, carbon dioxide, helium, or other liquids and gases.[24]

This type is deployed to boreholes where the water is hot but not hot enough to form large amounts of steam. The lower-temperature water is unsuitable for driving a turbine because, in a conventional powerplant, the steam delivered has a reasonably high pressure, which is not the case in this scenario. The system, therefore, deploys the so-called binary system, which uses two fluid-containing circuits, one circuit with hot water and another circuit carrying the working fluid. This technology is employed at the Casa Diablo geothermal field in California.[24]

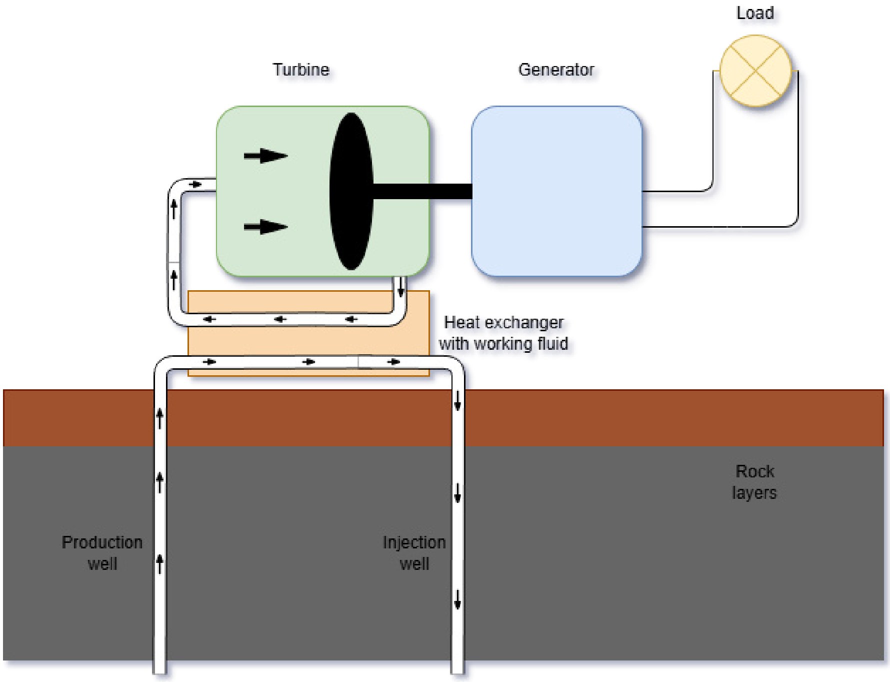

Figure 5 Moderate-Temperature System [24]

2.6.7 The Geysers

The Geysers is the world's largest geothermal field, with over 18 geothermal power plants, drawing steam from more than 350 wells. The powerplant is in the Mayacamas Mountains, north of San Francisco, California. The power plants from this region provide electricity to Sonoma, Lake, Mendocino, Marin, and Napa counties. Unlike most geothermal resources, the Geysers is a dry steam field that uses the vapor-dominant system to create electric energy. Geysers produce about 20% of California's renewable energy, which is about 1 590 MW.[30]

2.6.8 Conclusion

Geothermal energy is already in big use all over the world; however, in the Czech Republic, this way of creating electric energy is still in the very early stages. Therefore, I chose to include this as a non-traditional way to create electric energy. Geothermal energy is reliable, and it does not produce any greenhouse gases or create a carbon dioxide footprint.

3. CLASSIFICATION AND USE OF HYDROGEN

3.1 Introduction

Hydrogen is the most common element in the universe and is very abundant. Hydrogen’s most significant consumer is arguably the Sun, which consumes over 600 million tons of it each second. One of hydrogen's drawbacks is that, unlike oil, hydrogen is not found in large reservoirs on Earth. Hydrogen is bound with other elements in molecules; therefore, it must be extracted so it can be utilized for fuel cells or combustion. Hydrogen can be perceived as a sustainable, non-polluting source of power that can be used in many applications. This can increase our energy diversity and can help us to become more independent of hydrocarbon-based fuels. The two essential ways of hydrogen production are the production using the water splitting method and production involving fossil fuels.[31]

3.2 Water Decomposition

With the utilization of water splitting, the three main decompositions are utilized: electrolytic decomposition, thermal decomposition, and decomposition using radiation.

3.2.1 Water Electrolysis

Water electrolysis is a well-known electrochemical process in which hydrogen gas (H_2) is produced by splitting water (H_2O) into its constituent elements of hydrogen and oxygen using an electric current. The water molecules are split into hydrogen and oxygen ions with the help of an electric current, which passes through the water. Water is decomposed with the use of an electrolyser, and hydrogen ions (H^+) are drawn to the cathode as the current runs through the electrolyte solution. The most well-known electrolytes are Sodium hydroxide and Potassium hydroxide. In order to produce the hydrogen gas, hydrogen ions interact with the cathode's electrons. Meanwhile, anode electrons are joined by the oxygen ions (O^{2-}), which are drawn to anode. Nine liters of water and around 50 kWh in electrolyser working with 70% efficiency are needed to produce 1 kg of hydrogen.[32] [33]

Chemical reactions on the electrodes are therefore:

$$2H_2 + 2e = H_2 + 2OH^- \tag{3.21}$$

$$2OH^- = \frac{1}{2}O_2 + H_2O + 2e \tag{3.22}$$

This method is also environmentally friendly because no toxic gases are emitted during the process, but the electricity must come from renewable energy sources. Some of the method's difficulties are the need for highly pure water and the need for relatively high amounts of electricity to generate hydrogen.[32]], [[34]

3.2.2 Proton Exchange Membrane (PEM) Electrolyser

With the use of water electrolysis, a PEM Electrolysis is deployed to decompose water into hydrogen and oxygen. The first PEM electrolyser was produced by General Electric in 1966. The reactions and basic theory taking place at the electrodes are the same for electrolysers as well as for fuel cells; with the electrolyser, the reactions are reversed.[35]

Reaction at the anode:

$$4H^{+} + 4e^{-} \rightarrow 2H_2 \tag{3.23}$$

Reaction at the cathode:

$$2H_2O \rightarrow O_2 + 4H^{+} + 2e^{-} \tag{3.24}$$

Most industrial electrolysers employ an alkaline electrolyte; however, the use of PEM electrolysers has been gaining popularity in recent years.[35]

The basic structure of the PEM electrolysers is the same as the PEMFC, although the electrodes have different requirements. The success and popularity of PEM electrolysers consists of the fact that many problems surrounding the working process of PEMFCs do not apply. Those advantages are depicted in the following sentences. As for the cooling of the system of the electrolyser, the water is supplied to the cathode, and it can be pumped around the cell to lower the heat of the whole system. Water management is also much simpler than in the case of PEMFC because the positive cathode must be flooded with water. PEM electrolysers can also operate at higher current densities; ohmic losses limit the maximum achievable current densities with the use of a thin membrane capable of good proton conductivity.[35] [39]

In recent years, the high-pressure PEM electrolyser has been in development because when hydrogen pressure of 12-20 MPa can be achieved, the use of a gas compressor is not needed because it can be both inefficient and expensive for maintenance.[35]

3.2.3 Thermal Decomposition of Water

With the utilization of high-temperature decomposition, water can be decomposed into hydrogen and oxygen. The high-temperature thermal decomposition of water is performed at the temperature of around 4000 ºC. The semi-permeable membrane was deployed for the separation of individual temperature-cracking elements. For future implementation, the use of a High Temperature Gas Cooled Reactor (HTGR) was considered.[33]

According to [46], The High Temperature Gas Cooled Reactor is: “A Uranium-fueled, graphite-moderated, gas-cooled nuclear reactor design concept capable of producing very high core outlet temperatures.”

Water can also be decomposed with low-temperature water decomposition, which typically happens within 1000 ºC, and during this process, the step decomposition methods are utilized. The process is called the Thermochemical cycle.[33]

3.2.4 The Use of Radiation for Water Decomposition

The radiation utilized for the water decomposition is solar radiation, intense Roentgen radiation, and ionizing radiation. If the only utilized radiation was solar radiation, then the real accumulated primary energy is enormous.

In the following chemical reactions, an example of homogeneous photocatalysis is expressed. While under the influence of sunlight, the redox process takes place, and then the thermal decomposition happens when the sunlight is no longer present. The solution is decomposed into hydrogen with the sunlight passing through the bath. The decomposition into oxygen occurs while the backplate is heated with the sunlight.[33]

$$\mathrm{Ce^{4+}} + \frac{1}{\mathrm{2H_2O}} + \mathrm{hv} = \mathrm{Ce^{3+}} + 1/2\mathrm{O_2} + \mathrm{H^+} \tag{3.25}$$

$$\mathrm{Ce^{3+}} + \mathrm{H_2O} = \mathrm{Ce^{4+}} + \frac{1}{\mathrm{2H_2}} + \mathrm{OH^-} \tag{3.26}$$

$$\mathrm{H^+} + \mathrm{OH^-} = \mathrm{H_2O} \tag{3.27}$$

3.3 Production Utilizing Fossil Fuels

3.3.1 Steam Reforming

Steam reforming is utilized for large-scale hydrogen production. It is a well-developed technology that is utilized for mass production of hydrogen. This process is also the most efficient one, with the most significant hydrogen production and the lowest operating costs.

Valuable data for system design provided by [36] "The respective basic reforming reactions for methane and a generic hydrocarbon C_nH_m are:”

$$\mathrm{CH_4} + \mathrm{H_2O} \rightarrow \mathrm{CO} + \mathrm{3H_2} \tag{3.31}$$

$$\mathrm{C_nH_m} + \mathrm{nH_2O} \rightarrow \mathrm{CO} + \left(\frac{\mathrm{m}}{2} + \mathrm{n}\right)\mathrm{H_2} \tag{3.32}$$

$$\mathrm{CO} + \mathrm{H_2O} \rightarrow \mathrm{CO_2} + \mathrm{H_2} \tag{3.33}$$

“The reforming reactions and the associated WGS reaction is usually conducted over a supported nickel catalyst at an elevated temperature, typically above 500ºC.”

The overall product of these two equations comprises CO, CO2, and H2. These two main products are followed by unconverted CH4 and steam. Higher temperatures favor the formation of H2 because of the fact that the first two reactions are usually highly endothermic and need a constant supply of heat to drive them.[36] [40]

3.3.2 Partial Oxidation

Provides an alternative solution to steam reforming for hydrogen production. Partial Oxidation is typically carried out at high temperatures ranging from 1200 - 1500ºC. The chemical part of the process also does not require a catalyst, and hydrocarbons, such as heavy gas oils, resid, and coal, can be used as feed. [36] [40]

According to [36]: "Methane and other hydrocarbons may be converted to syngas and hence hydrogen for fuel cells by "partial oxidation."

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \tag{3.34}$$

Most hydrogen plants are steam reformers. Partial Oxidation is chosen in times when steam reforming is not economically viable, or there is no access to low-molecular-weight feeds, such as natural gas. One advantage of this process over the catalytic processes is that the sulfur compounds could be removed at the later stage of the process if the hydrogen is used to supply a fuel-cell stack. The disadvantage is the need for complex gas cleaning, oxygen, and high temperatures for the chemical process to be conducted.[36] [40]

3.4 Use of hydrogen

3.4.1 Fuel cell Plants Operating with Steam Reforming or Natural Gas

A fuel cell plant is a facility working with some type of the previously mentioned methods of generating hydrogen. The preferred option to further harness the generated hydrogen in Proton exchange membrane fuel cells (PEMFC) and Phosphoric acid fuel cells (PAFC) is to deploy the steam reforming method. The reason for this combination is the overall efficiency of the whole working system. This technology has been in use for many years, mainly in facilities between 50 kW and several MW.[36]

The chemical processes, such as desulfurization and steam reforming, happen at different temperatures.

The following paragraph describes the requirements for steam reforming to take place.

The dry fuel gas must be heated to approximately 300ºC, which is done prior to the Hydrodesulfurization. Also, the gas and steam are heated to 600ºC or higher before the steam reforming process. The reformer product (gas) is then cooled to about 400ºC for the high-temperature Water-Gas shift reaction. The gas is then cooled even more for the low-temperature Water-Gas shift reaction. Lastly, the temperature is adjusted before the gas enters the CO removal step or is fed directly into the fuel cell.[36]

As the temperature changes indicate, in similar fuel cell systems, some gases have to be heated, and others cooled. In many cases, the process of heating and cooling is combined with the utilization of heat exchangers. In addition, steam reforming also demands high-temperature heat. This problem can be solved by burning the anode exhaust gas, which may prove advantageous.[36]

4. FUEL CELLS

4.1.1 Introduction

Electrochemical energy production is designed to be more sustainable and environmentally friendly as an alternative energy source for the future. Systems utilizing electrochemical energy storage also include fuel cells, which will be discussed in the following chapter.

4.1.2 History

Fuel Cells have been known to science for more than 150 years. Wiliam Nicholson and Anthony Carlisle, two British scientists, described the electrolysis process in 1800. The process is using electricity to decompose water into hydrogen and oxygen. Michael Faraday then conducted experiments from which the two fundamental Laws of Electrolysis were derived. The first fuel cells were invented by William Grove in 1838.[41]

The first commercially deployed fuel cell was the hydrogen-oxygen fuel cell invented by Francis Thomas Bacon in 1932. Fuel cells have been harnessed by NASA, since the 1960s in its space programs. The alkaline fuel cell was used to generate power for satellites and space capsules.[41]

Since then, fuel cells have been used in many other industries and applications.

4.1.3 The Fuel Cell Principle

Fuel cells convert chemical energy residing in a fuel into electrical energy on demand. Fuel cells consist of two electrodes in contact with an electrolyte solution. Energy-providing processes happen at the phase boundary of the electrode/electrolyte interface, where electron and ion transport are separated. In fuel cells, electrical energy is generated by the conversion of chemical energy through a redox reaction at the anode and cathode. Fuel cells operate only as long as the energy is supplied, like internal combustion engines. After the fuel runs out, the fuel cell tank is refilled with fuel. The fuel of choice is mainly hydrogen, but methanol, gasoline, or natural gas can also be used.[42]

4.1.4 Types of Fuel Cells

- Alkaline electrolyte (AFC)
- Proton-exchange membrane (PEMFC)
- Direct methanol (DMFC)
- Phosphoric acid (PAFC)
- Solid oxide (SOFC)
- Molten carbonate (MCFC)

4.1.5 Alkaline Electrolyte (AFC)

The Alkaline fuel cell is one of the oldest fuel cell types. This type of electrode was mainly developed by NASA for the Apollo missions. They are still harnessed to this day, only the original AFC’s updated versions. The used electrolyte is based on potassium hydroxide. Alkaline fuel cells reach higher cell voltages because the hydrogen and oxygen kinetics are more facile in alkaline than acid electrolytes. This fact allows to use the non-noble metal catalysts as the fuel for electrode. On the other hand, the oxygen electrodes deploy the silver and spinel-type oxides with iron phthalocyanines and other porphyrins as catalysts. The alkaline fuel cell is mainly deployed on the Earth’s orbit because of the requirement for pure fuels and the need to lower the Carbon dioxide levels for longer life. Both electrodes are manufactured with a layer of platinum catalyst on carbon support and binder that is backed by a wet-proofed Teflon bonded carbon layer to control the wetting of the electrodes by the electrolyte and thus the location of the three-phase boundary. Before being catalysed, the carbons are treated to remove active entities on the surface. The Alkaline electrolyte operates at up to 1 A/cm^2 at 0.7 V. [42]

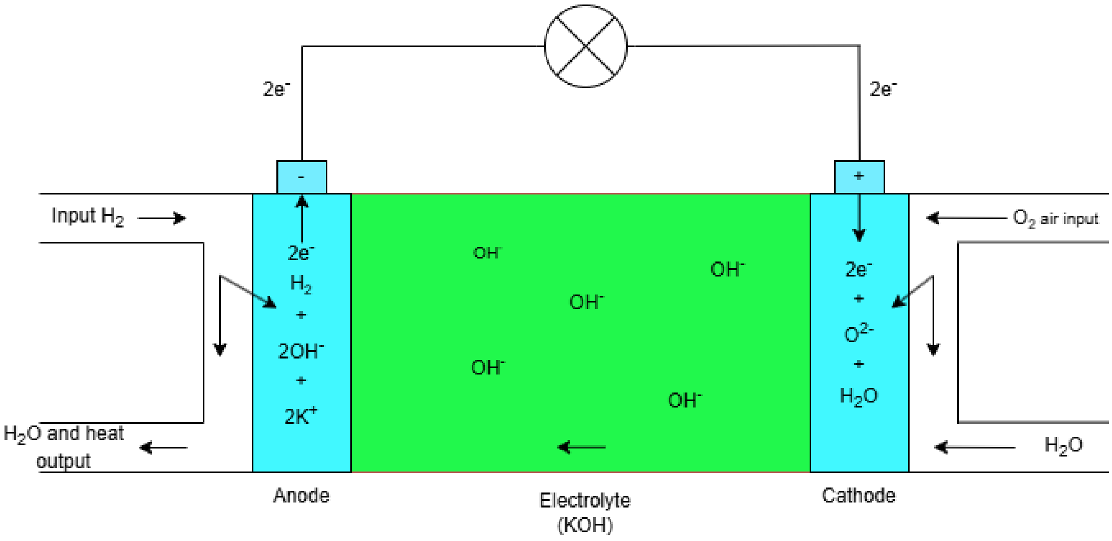

Figure 6 Alkaline Electrolyte Fuel Cell [53]

4.1.6 Proton-Exchange Membrane Fuel Cell (PEMFC)

The PEMFC was mainly developed for the Gemini space vehicle. PEMFC utilizes two porous electrodes and a solid electrolyte for the membrane electrode assembly (MEA). The MEA is formed of carbon cloth or a gas diffusion layer, a dispersed catalyst layer, and a membrane. The electrodes are formed on a thin layer on each side of a proton-conducting polymer membrane, used as an electrolyte. The electrolyte consists of a solid polymer PTFE backbone with a perfluorinated side chain that ends with a sulfonic acid group. Platinum is usually deployed as a catalyst due to its better catalytic properties. The solvated protons are mobile within the polymer and provide electrolyte conductivity. The membrane has low permeability to oxygen and hydrogen to maintain high coulombic efficiency.[42] [43]

According to [43], the chemical reactions on anode and cathode are as follows:

Anode:

$$H_2(g) \rightarrow 2H^+ + 2e^- \tag{4.11}$$

Cathode:

$$\left(\frac{1}{2}\right) O_2(g) + 2H^+ + 2e^- \rightarrow H_2O(1) \tag{4.12}$$

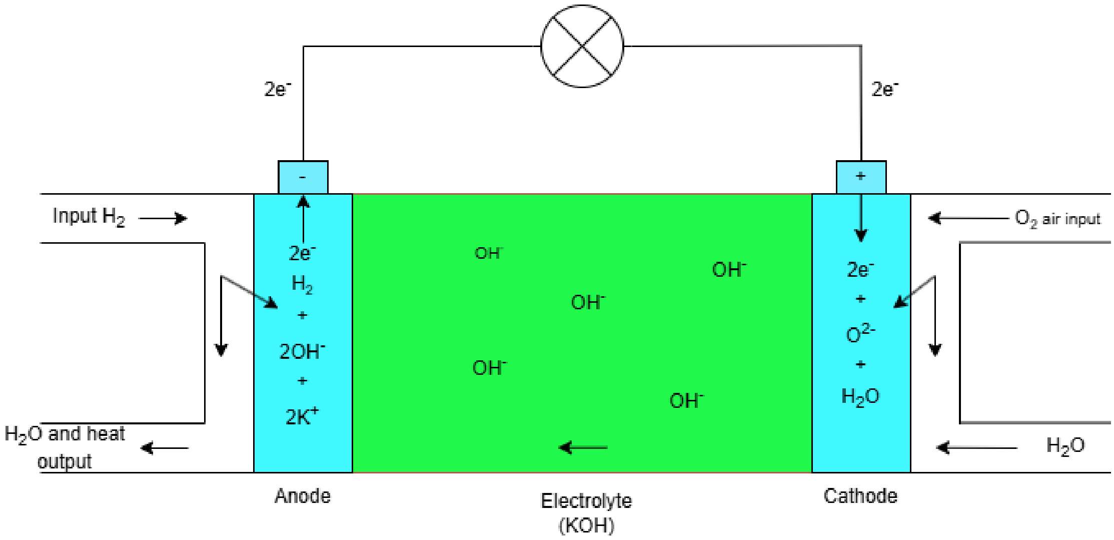

Figure 7 Proton Membrane Exchange Fuel Cell [53]

The metal that is used for both electrodes is platinum, with the greatest catalytic activity. The usage of 28 mg of platinum was required for each electrode in the early days of development. However, this changed to below 0.2 mg. Many have believed, and some still believe to this day, that the reason for the high price of the PEMFC was the amount of platinum used. After the reduction of the used platinum, the overall performance of the PEMFC has increased.[37]

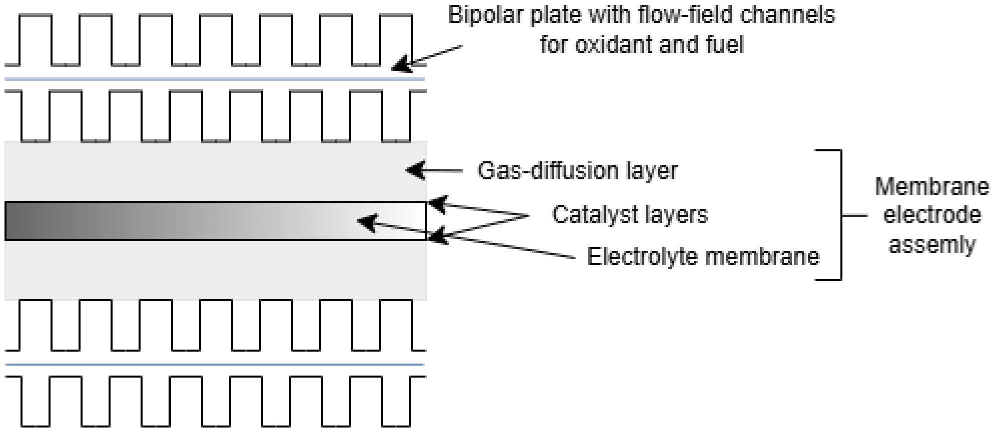

Figure 8 Basic structure of a low-temperature PEMFC with a simple configuration of bipolar plate [37]

Figure 8 shows the MEA with Bipolar plates. The catalyst layers are situated in between the electrolyte membrane and porous Gas Diffusion Layers (GDL). The GDL is also in direct contact with the bipolar flow-field plate.[37]

4.1.7 Proton-Exchange Membrane Fuel Cell Application in Cars

Transportation is the most promising application of the PEMFCs. The success of the PEMFC in this field might be the most important factor to provide an incentive for expanding their application to other fields. The development of a fuel cell vehicle requires a fuel-cell system in on-board integration installment complemented by electric energy storage devices, with a suitable energy management system.[44]

4.1.8 Proton-Exchange Membrane Fuel Cell Application in Buses

The power output of the fuel cell system used in the studies conducted on the bus was 50kW. Compressed hydrogen was used as a fuel, and oxygen was used as ambient air. The heart of the bus contained two PEMFC stacks (105 cells). During the tests, the bus was loaded with external weight. The test shows that a fuel cell system with a nominal power output of approximately 35-50kW is adequate for a full-size (12m) hybrid electric city bus, even with an additional air conditioning system.[44]

4.1.9 Conclusion

It has been described how fuel cells work with provided examples of more common fuel cell types. It is also worth mentioning, that the uncertainties of the measurement were not evaluated. Some information about the history and the development of the fuel cell as we know it today was described. In the end, research on how the Proton exchange membrane fuel cell could supply electricity for cars and buses was discussed.

5. MEASUREMENT OF ELECTROLYZE AND PEM FUEL CELL

5.1 Measurement of PEMFC (Proton-Exchange Membrane Fuel Cell)

The Measurement of proton-exchange membrane fuel cell was carried out on H-TEC fuel cell stack 10. The measurement was carried out to observe how the power output changes under different loads of resistance.

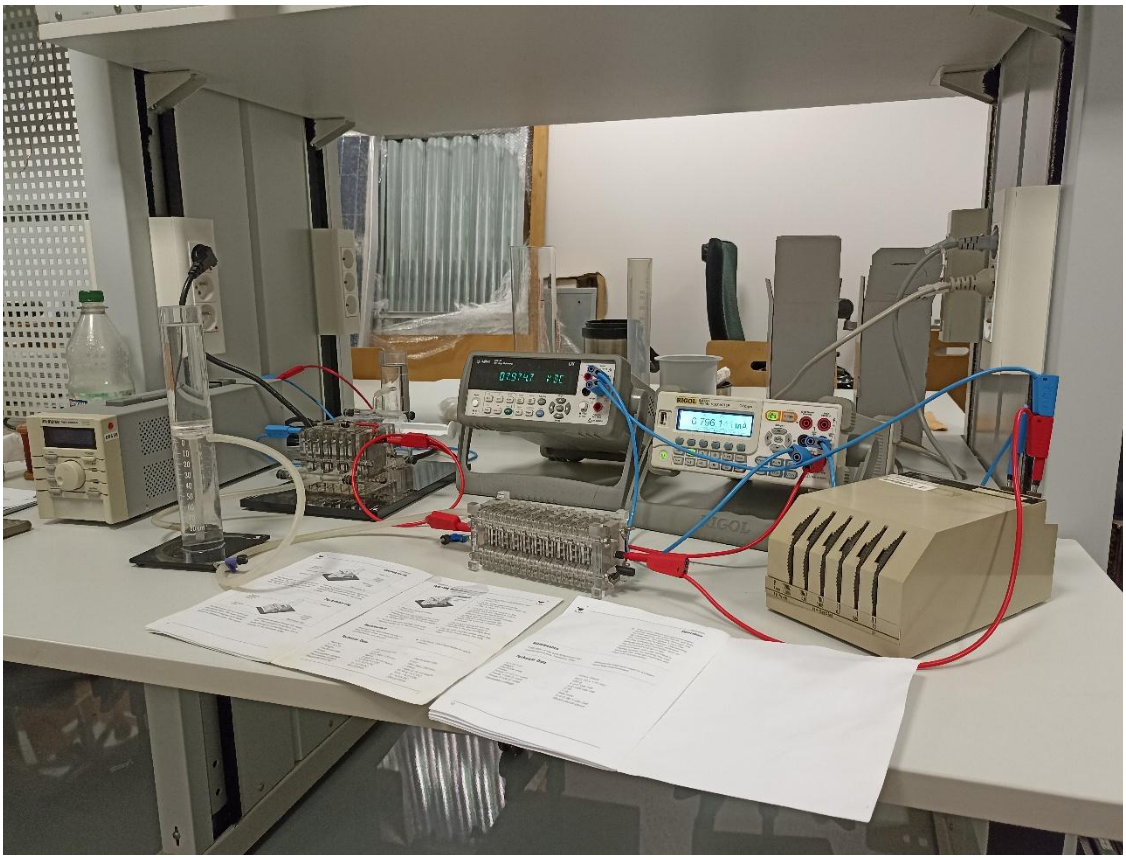

Figure 9 Measurement of the Fuel Cell and Electrolyser

5.1.1 Instruments Used for the Measurement

- DC power supply: Programmable Power Supply GW Instek PSH – 6006A
- Electrolyser: Electrolyser 230
- Fuel Cell stack: H-tec PEMFC 10-fuel cell stack
- Resistance Decade Box: Resistance Decade Box L110
- Amperemeter: Rigol DM3061 DIGITAL MULTIMETER
- Voltmeter: Agilent 34410A

5.1.2 Programmable Power Supply GW Instek PSH – 6006A

According to the user manual provided with the power supply, the PSH series are modular-type programmable switching power supplies designed for a broad range of applications. The output of the power supply is 360W. The power supply can handle a voltage output of 60 V and a current output of 6 A. The accuracy of the voltage output is $\leq 0.05\% + 25$ mV (rating ≤ 36V) and $\leq 0.05\% + 50$ mV (rating < 36V).[51]

5.1.3 Electrolyser 230

According to the user manual provided with the Electrolyser 230, it uses electricity and water to react according to the formula $2H_2O \rightarrow 2H_2+O_2$. The generated gases are collected in storage tanks, which are then forwarded to the fuel cell stack if and when required.

The Electrolyser comprises of 7 cells. One cell of the electrolyser has an electrode area of 4 cm^2 for one cell. The permissible operating voltage ranges from 0 V to 14 V. The Permissible operating current ranges from 0 A to 4.4 A. The Rated power consumption of the electrolyser is approximately 56 W. The Electrolyser can produce approximately 230 cm3/min of H2 at the rated power output and approximately 115 cm3/min of O_2 at the rated power output. The permissible operating pressure ranges from 0 mbar to 20 mbar.[50]

5.1.4 Fuel Cell Stack

The modular fuel cell stack was developed and assembled by the H-TEC company. Singular fuel cells can be removed or added to the assembly. The measurement was conducted on a fuel cell stack comprising 10 fuel cells. The voltage can be measured on each cell separately.

According to the data in the user manual, the fuel cell stack has an electrode area of 3 cm^2 for one cell. The power output per cell can reach 200 mW and 2 W for all 10 cells. The generated voltage output is stated (0.4-0.96) V per cell Short-circuit-proof. Therefore, the voltage output for the whole fuel cell stack should range from 4 V to 9.6 V. The permitted operating pressure is from 0 to 20 mbar.[49]

5.1.5 Decade Resistance Box

The decade resistance box is deployed to insert a resistive element into the circuit. The decade resistance box works with a range from 1 MΩ to 0 Ω. The error of the decade box with 10x and 100x with a max error of around 0.18%. The x1000 and above stand with a max error of 0.04%

5.1.6 Rigol DM3061 Digital Multi Meter

According to the data in the manual provided with the multimeter, the accuracy specifications for DC measured current with a range of 1.0 A, Test current, or Burden Voltage of < 0.6 V. The accuracy specifications for DC measured current with range of 1.0 A and 90-day accuracy is 0.065+0.030 with ± 5 ºC from the calibration temperature. [48]

5.1.7 Agilent 34410A Digital Multi Meter

According to the data in the corresponding user manual, the accuracy specifications for DC measured voltage with range of 10 V and 90-day accuracy is 0.0020+0.0005 with ± 5 ºC from the calibration temperature.[47]

5.1.8 The Assembly

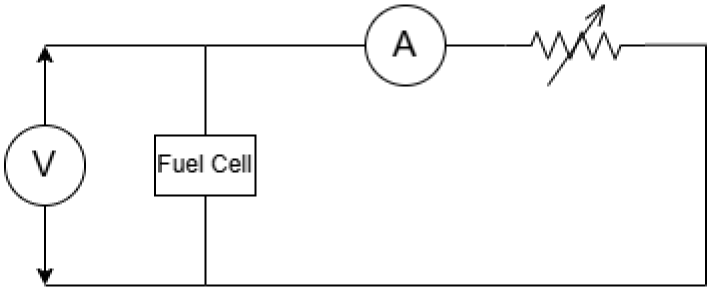

Figure 10: Block Scheme of the Fuel Cell Measurement

According to Figure 10, the fuel cell stack is used in this circuit as a source of electric energy. To measure the voltage on the output of the fuel cell stack, a voltmeter was added to the circuit, connected in parallel with the fuel cell stack. The ammeter is connected in series and measures the output current of the fuel cell stack under the influence of the resistance decade box. The resistance decade box, which is represented as the variable resistor in the block diagram, is used in the circuit to change the resistance load acting on the fuel cell.

This way, it is possible to observe how the output voltage and current change under the influence of the resistance load.

The distilled water is stored in the electrolyser's water storage tank, which is connected via a tube to the electrolyser. The electrolyser is deployed to decompose the distilled water into the hydrogen and oxygen.

Water reacts in the electrolyser under the influence of electrical energy according to the following formula:

$$2H_2O = 2H_2 + O_2 \tag{5.11}$$

This process takes place in the MEA (membrane electrode assembly). The MEA consists of the cathode, the anode, and a special polymer membrane (PEM), which is permeable to protons, but for the protons, the PEM presents a type of barrier.

H-TEC‘s Fuel Cell Stack 10 is a modular fuel cell stack that is used to change hydrogen into electrical energy. Hydrogen gas is oxidized within a fuel cell. In the process of oxidization, the chemical energy stored in the hydrogen gas is converted directly to electrical energy.

From the measured Voltage [V] and Current [I], Power [P] was calculated using the formula (5.12):

$$P = V \cdot I \tag{5.12}$$

5.1.9 Obtained Results

Table 1: Measured and Calculated Results of the Measurement

V (V)	I (mA)	P (W)	R (Ω)
8,040	0,000	0,00000	-
8,030	0,080	0,00064	100000
8,030	0,090	0,00072	90000
8,020	0,100	0,00080	80000
8,020	0,114	0,00091	70000
8,010	0,133	0,00107	60000
8,000	0,159	0,00127	50000
7,990	0,199	0,00159	40000
7,960	0,265	0,00211	30000
7,920	0,390	0,00309	20000
7,840	0,782	0,00613	10000
7,820	0,860	0,00673	9000
7,800	0,970	0,00757	8000
7,780	1,110	0,00864	7000
7,750	1,290	0,01000	6000
7,710	1,540	0,01187	5000
7,650	1,910	0,01461	4000
7,570	2,520	0,01908	3000
7,450	3,707	0,02762	2000
7,190	7,100	0,05105	1000
7,150	7,840	0,05606	900
7,100	8,740	0,06205	800
7,040	9,890	0,06963	700
6,970	11,400	0,07946	600
6,880	13,450	0,09254	500
6,760	16,420	0,11100	400
6,560	21,740	0,14261	300
6,260	31,030	0,19425	200
5,600	55,230	0,30929	100
5,500	60,210	0,33116	90
5,380	66,110	0,35567	80
5,270	73,140	0,38545	70
5,110	82,770	0,42295	60
4,880	95,030	0,46375	50
4,650	110,650	0,51452	40
4,290	136,010	0,58348	30
3,740	175,300	0,65562	20
2,560	250,000	0,64000	10
2,480	265,700	0,65894	9
2,360	280,300	0,66151	8
1,910	330,200	0,63068	7
1,850	300,100	0,55519	6
1,610	301,300	0,48509	5
1,600	384,500	0,61520	4
1,370	410,200	0,56197	3
1,030	465,200	0,47916	2
0,650	504,000	0,32760	1
0,410	590,041	0,24192	0,5
0,100	604,000	0,06040	0

At the beginning of the measurement, no resistance was applied. The resistance was then gradually decreased from 1 MΩ down to 0 MΩ.

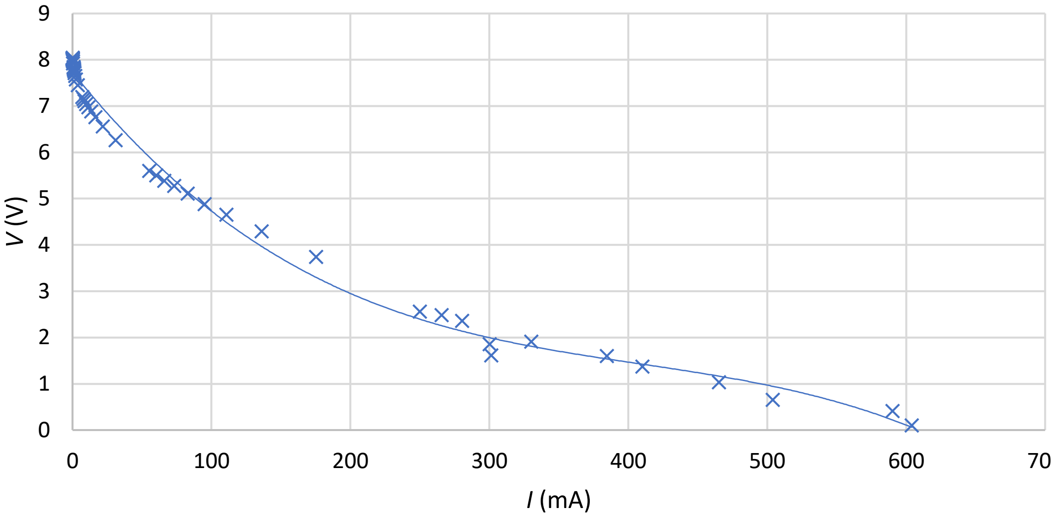

Figure 11: V-I Characteristic of the Fuel Cell Stack

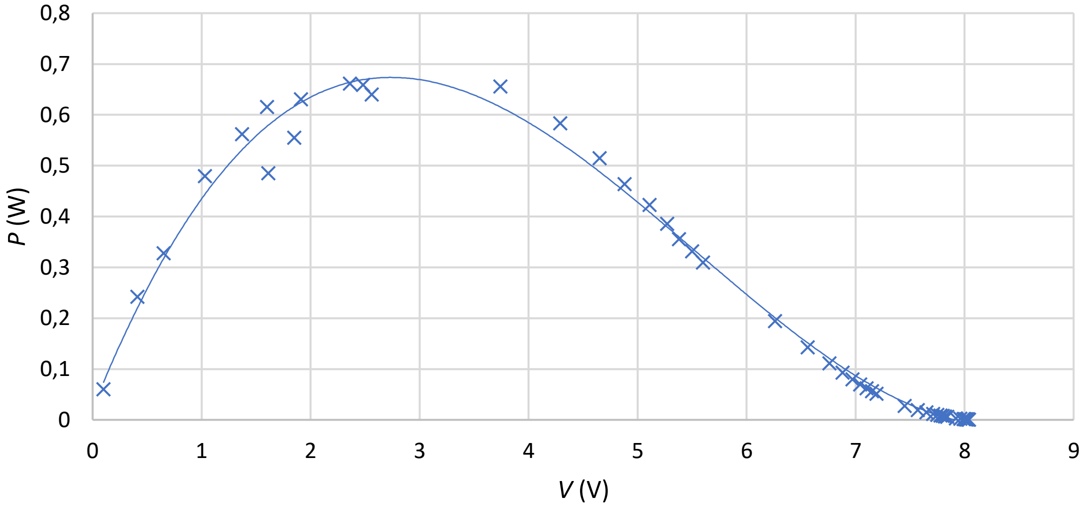

Figure 12: P-V Characteristic of the Fuel Cell Stack

Both Figures 11 and 12 correspond to a typical graph exhibited by a fuel cell. When resistance decreases, the current increases while the voltage is still not significantly reduced, which results in a greater power output. The highest power is measured under the load of 2.36V, more precisely 0.66W, which corresponds to the ideal working point of the fuel cell. Under these conditions, the fuel cell has the highest power output until the power starts to drop. The fuel cell reaches optimal working conditions between 2.5 V and 4 V; with higher voltage loads, the power output decreases due to voltage losses.

The characteristic shape of the V-I characteristic and P-V characteristic shown in Figures 11 and 12 is affected by four major irreversibilities.

Activation losses represent how fast the reaction happens on the surface of the electrodes. Some part of the voltage is lost because it is needed to drive the chemical reaction in order to move the electrons from or to the electrode. The result of the activation loss is highly non-linear voltage.[38]

Ohmic losses represent the resistance to the flow of electrons through the electrode material. Ohmic losses also indicate the resistance to the flow of ions through the electrolyte. [38]

Internal currents and fuel crossover is a voltage loss that happens when a smaller than desired amount of fuel passes through the electrolyte from the anode to the cathode and also from electron conduction through the electrolyte. The electrolyte should only transport ions through the cell in an ideal scenario. [38]

Concentration or mass-transport losses occur due to changes in the concentration of the reactants at the electrode surfaces as the fuel is consumed. [38]

5.1.10 Conclusion

The generated voltage from the fuel cell stack is in the range of 4V and 9.6V for the whole stack. However, with the power output provided by the manufacturer of 2 W exhibited by 10 cells, the measured power output achieved by the fuel cell stack is 0.66 W, which is nowhere near the tabular value provided by the manufacturer. On the other hand, the conducted measurement exhibits typical characteristics of PEMFC. The optimal working conditions were achieved with the voltage load of 2.63 V and a current of 280 mA, which is typical for PEMFC.

5.2 Measurement of the Electrolyser

Polymer membrane electrolyser is a device utilized to create hydrogen for fuel cells which is done in an environmentally conscious manner. Water reacts in the electrolyser under the influence of electric energy. The chemical reaction that takes place in electrolyser when working:

$$2H_2O = 2H_2 + O_2 \tag{5.21}$$

This chemical reaction occurs in the MEA (membrane electrode assembly). The MEA consists of the cathode, the anode, and PEM (polymer membrane). The PEM is permeable to protons, but electrons cannot pass through.

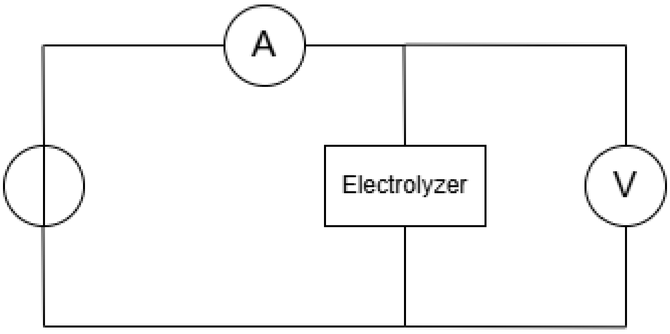

Figure 13: Block Scheme of the Electrolyser Measurement

The scheme of the measurement of the electrolyser efficiency. The PSU is utilized to supply a DC voltage into the circuit. Ammeter is connected in series and measures the current output of the electrolyser. The voltmeter is connected in parallel and measures the voltage output of the electrolyser.

Table 2: Measured and Calculated Values of the Electrolyser

t (s)	V_N (V)	V_R (V)	I_1 (A)	I_2 (A)	I (A)	η (%)
210	11	10.92	0.468	0.442	0.455	98.917
67	12	11.7	1.37	1.33	1.35	97.528
38	13	12.52	2.381	2.325	2.353	92.196
26	14	13.3	3.47	3.36	3.415	87.399

Where:

t – time needed to pump $80cm^3$ of hydrogen

V_N – Nominal voltage set on the modular power supply

V_R – Actual voltage measured with the use of a voltmeter

I_1 – Current measured during the first measurement

I_2 – Current measured during the second measurement

I – The average current calculated from I_1 and I_2

The measurement was conducted using the same equipment as stated in the section 5.1. The voltage load was set on the programmable PSU, and then the process started. With the use of a stopwatch, the total time needed to pump 80 cm^3 of hydrogen under the voltage was measured. During the measurement, the actual voltage that reached the electrolyser was measured. The current generated by the electrolyser was measured twice, then the average was calculated. The higher the current, the faster the decomposition of water is, thus resulting in faster decomposition of water.

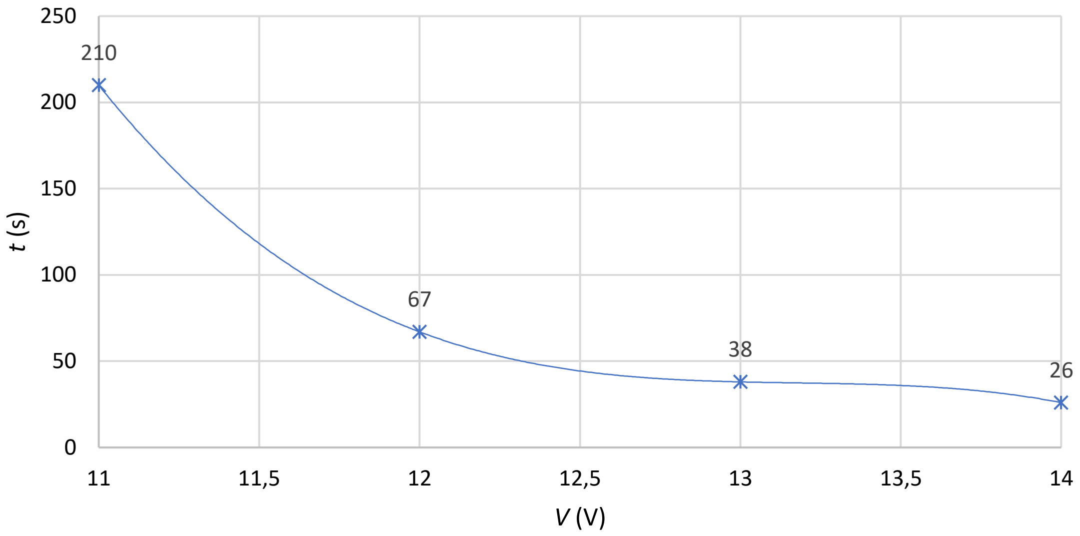

Figure 14: Time Needed to Obtain 80 cm^3 With Different Loads of Voltage

Figure 14 shows that as the voltage load increases, the time needed to pump 80 cm^3 of hydrogen shortens. The difference between the time isn’t that significant from 12-14 V. However, this is not the case with 11 V, where we can observe 143 second difference between 11 V and 12 V.

The formula for energy efficiency of the electrolyser calculation is:

$$\eta_{energy} = \frac{E_{Hydrogen}}{E_{electric}} = \frac{V_{H_2} \cdot c_P \cdot H_{HHV}}{\mathrm{V} \cdot \mathrm{I} \cdot t} \tag{5.22}$$

$$\eta_{energy} = \frac{8 \cdot 10^{-5} \cdot 1.0087 \cdot 12.745 \cdot 10^6}{10{,}91 \cdot 0{,}47 \cdot 190}$$

Where:

V_{H_2} – Quantity of hydrogen produced in (m^3)

c_P – pressure correction coefficient

H_{HHV} – HHV Caloric value of hydrogen = 12.706 · 10^6 Jm^{-3}

V_R – Voltage in volts (V)

I – Current in amperes (A)

t – Time in seconds (s)

The pressure correction coefficient c_P was calculated for the height of the 9 cm water slope. To calculate the hydrostatic pressure of the water slope, the following equation was used:

$$P = \rho \cdot g \cdot h \tag{5.23}$$

$$P = 1000 \cdot 9.81 \cdot 0.09 \approx 883\ Pa$$

Where:

ρ – 1000 kg/m^3

g – 9.81 m/s^2

h – 0.09 m

ρ stands for the water density deployed for the experiment, g is the agreed-upon value used for the standard gravity, and h is the height of the electrolysers water slope. The resulting value is in Pascal. This pressure represents the pressure of water used in the electrolyser above the atmospheric pressure.

The pressure in the electrolyser and the atmospheric pressure were summed up using the equation (5.24).

$$P_2 = P_1 + P \tag{5.24}$$

$$P_2 = 101.325 + 883 = 102.208\ Pa$$

With the Ideal gas law equation, the volume has been increased by 0.87%. This parameter was calculated using the equations (5.25) and (5.26):

The classical ideal gas law equation:

$$pV = n \cdot R \cdot T \tag{5.25}$$

We assume that V and T in the equation are the same, therefore:

$$\frac{n_2}{n_1} = \frac{P_2}{P_1} \tag{5.26}$$

$$\frac{n_2}{n_1} = \frac{102.208}{101.325} \approx 1.0087$$

$$1.0087 - 1 = 0.0087 \approx 0.87\%$$

The calculated value indicates that the pressure generated by the 9 cm high water slope in the electrolyser is approximately 883 Pa above the atmospheric pressure. The overall pressure is approximately 102.208 Pa. With the use of the ideal gas law equation, the result indicates an increase of about 0.87% in comparison with the original state.

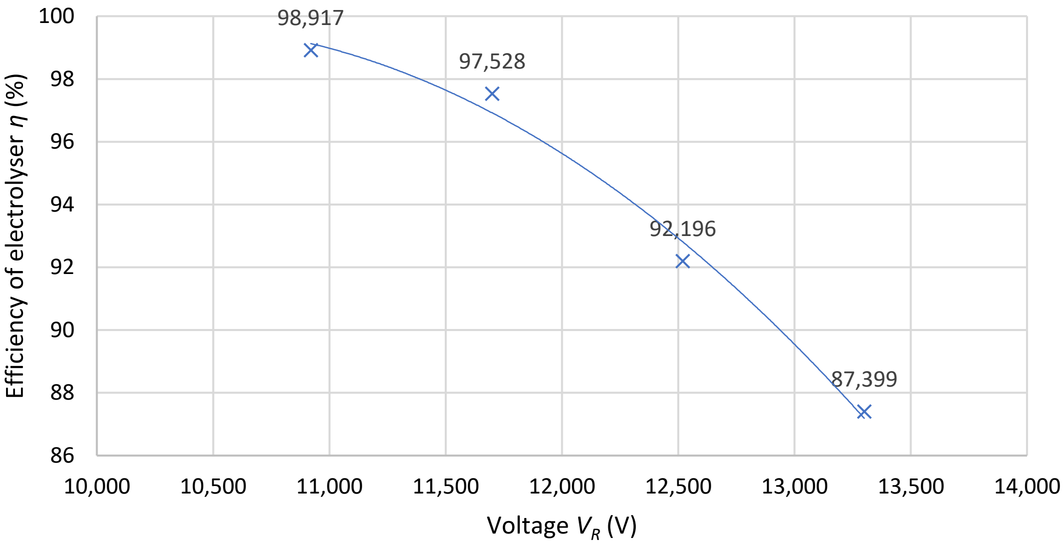

Figure 15: The Calculated Efficiency of the Electrolyser

Figure 15 shows the energy efficiency of the electrolyser working with different voltage loads. From the first measurement of 11V, the calculated efficiency is 98.9%. This means that the most optimal voltage load for the highest efficiency was measured under 11V, more precisely, under 10,91V. The efficiency decreased with the rising current and voltage load. It is also worth mentioning that under 11V, the system was the most efficient, with 98.9%. However, the time needed to pump 80 cm^3 of hydrogen was the slowest, at 210 seconds. Under 14V, the time needed for the electrolyser to pump the 80 cm3 of hydrogen was the fastest, at 26 seconds. However, the efficiency decreased by approximately 11% to 87%, compared with the measurement done for the 11 V voltage load.

Voltage losses follow the same pattern as those taking place in the fuel cells described in Chapter 5.1.9. The only difference is that there is no issue of fuel crossover in the electrolyser.[35]

According to [45], The properties of water electrolysis emitted by PEM electrolyser are: High current densities, Compact system design and Quick Response, Greater hydrogen production rate with High purity of gases (99.99%), Higher energy efficiency (80-90%), High dynamic operation. Under the voltage loads of 11 V and 12 V, the measured results indicate above-standard values of electrolyser efficiency. The uncertainty of the measurement was neglected.

5.2.1 Conclusion

The time needed to pump the 80 cm^3 of hydrogen by the electrolyser working with different voltage loads was measured during the experiment. The current of the electrolyser was also measured. From the measured values, the efficiency of the electrolyser was calculated. The obtained results have been displayed using tables and graphs. When compared with information about the water electrolysis from [45], the results indicate standard to above standard values. The uncertainties of the measurement were not evaluated.

6. CONCLUSION

The Non-traditional alternatives of electricity generation are presented in a formal and comprehensive form. Both renewable and non-renewable energy sources were described, mainly the non-traditional alternatives from the Sea, Earth's orbit, and other unconventional sources of electric energy were presented from the historical standpoint and also means of operation.

Geothermal energy is well known source of electric energy, however in The Czech Republic, it is still in the early stages of development, therefore I decided to include it in this thesis. For the Practical assignment of this thesis, the voltage and current output of the fuel cell stack was measured to calculate its power output. Efficiency of the electrolyser used to decompose water into hydrogen and oxygen was calculated. The calculated and measured values from the experiments are displayed in graphs and tables

One of the most impactful energy carriers for reducing carbon dioxide emissions is hydrogen.

The most commercially used way to obtain hydrogen is Steam reforming and Partial Oxidation. But water can also be decomposed into hydrogen and oxygen using water electrolysis, which is the more unconventional way. The created hydrogen can then be used as a fuel for PEMFC to create electric energy.

The utilization of PEMFC can contribute to decreasing the levels of carbon dioxide exhibited in the Earth's atmosphere. The only untapped products of the PEMFC are oxygen and heat, which makes this way of storing or creating electric energy a very sustainable and emission-free process if the hydrogen is created using water electrolysis.

Due to the greenhouse gas emissions and high levels of Carbon dioxide in the Earth's atmosphere, a change should be made so the CO_2 levels start to decrease. Some of the described ways to generate electric energy are ready to be implemented into the power grid. However, other ways of electricity generation still require advancements in the given field. With rising demand for green electric energy, now more than ever before, a need for alternative renewable electricity sources is nearly at an all-time high. The described ways to obtain electric energy can have a significant impact on decreasing the levels of CO_2 in the Earth's atmosphere for years to come.

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SYMBOLS AND ABBREVIATIONS

Abbreviations:

B.C.	Before Christ
U.S.	United States of America
km^2	square kilometres
MW	Megawatt
m	Meter
NASA	National Aeronautics and Space Administration
µm	Micrometre
A	Ampere
µs	Microseconds
µJ	Microjoule
GW	Gigawatt
km	Kilometre
AFC	Alkaline electrolyte fuel cell
PEMFC	Proton-exchange membrane fuel cell
DMFC	Direct methanol fuel cell
PAFC	Phosphoric acid
SOFC	Solid oxide fuel cell
MCFC	Molten-carbonate fuel cell
A/cm^2	Ampere per square centimeter
CNG	Compressed Natural Gas
H_2	Hydrogen
H^+	Hydrogen ions
O_2	Oxygen
kWh	Kilowatt-hour
PEM	Proton Exchange Membrane
MPa	Megapascal
HTGR	High Temperature Gas Cooled Reactor
kW	Kilowatt
MEA	Membrane Electrode Assembly
PTFE	Polytetrafluoroethylene
GDL	Gas Diffusion Layers
DC	Direct Current
W	Watt
mW	Milliwatt
V	Volt
mV	Millivolt
cm3/min	Cubic Centimetres per Minute

mbar	millibar
MΩ	Megaohm
PSU	Power Supply Unit
Pa	Pascal
cm^3	Cubic Centimetres

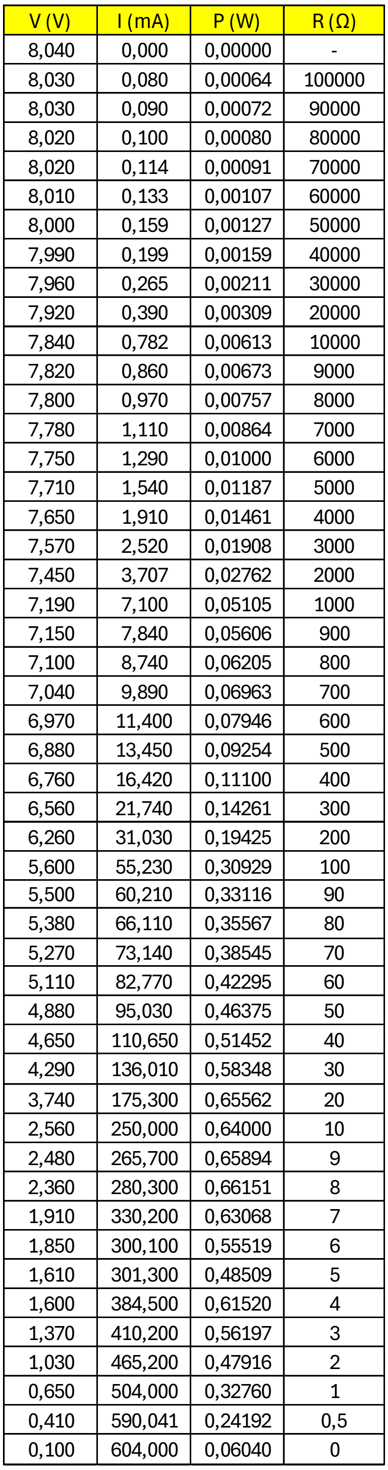
Symbols:

U	voltage	(V)
I	current	(A)
R	*resistance*	(Ω)
P	power	(W)
t	time	(s)
V_N	nominal voltage	(V)
V_R	actual voltage	(V)
η	efficiency	*(%)*
V_{H_2}	quantity of hydrogen	(m^3)
c_P	pressure correction coefficient	()
H_{HHV}	Caloric value of hydrogen	(Jm^{-3})
ρ	Water density	(kg/m^3)
g	Standard gravity value	(m/s^2)
h	height of the water slope	(m)
P	pressure of water in electrolyzer	(Pa)
P_1	atmospheric pressure	(Pa)
P_2	calculated pressure	(Pa)
n	amount of substance	(mol)
R	universal gas constant	J/(mol*K)
T	temperature	(K)

LIST OF APPENDICES

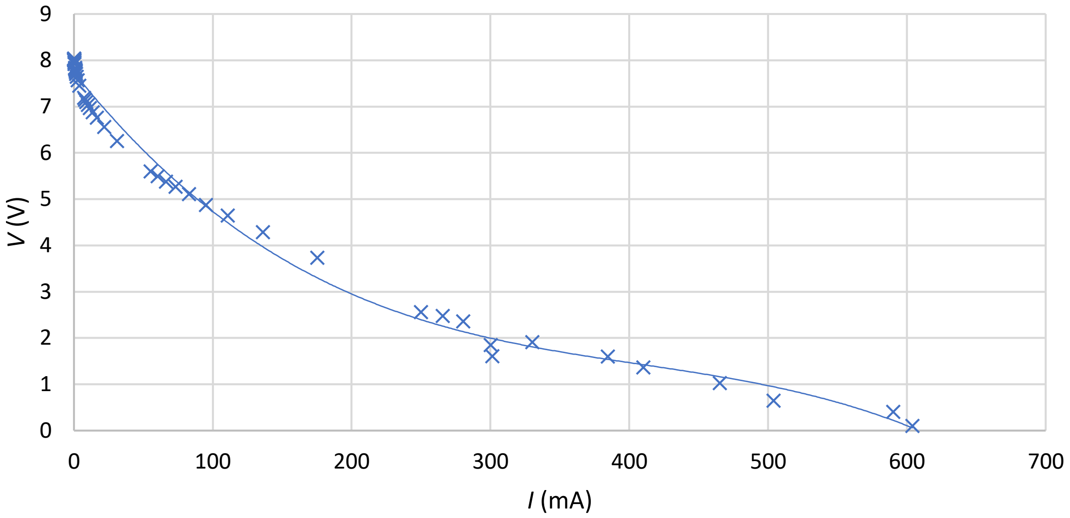
Appendix A - Measured And Calculated Values of The PEMFC Stack

A.1 Table of Measured and Calculated Values

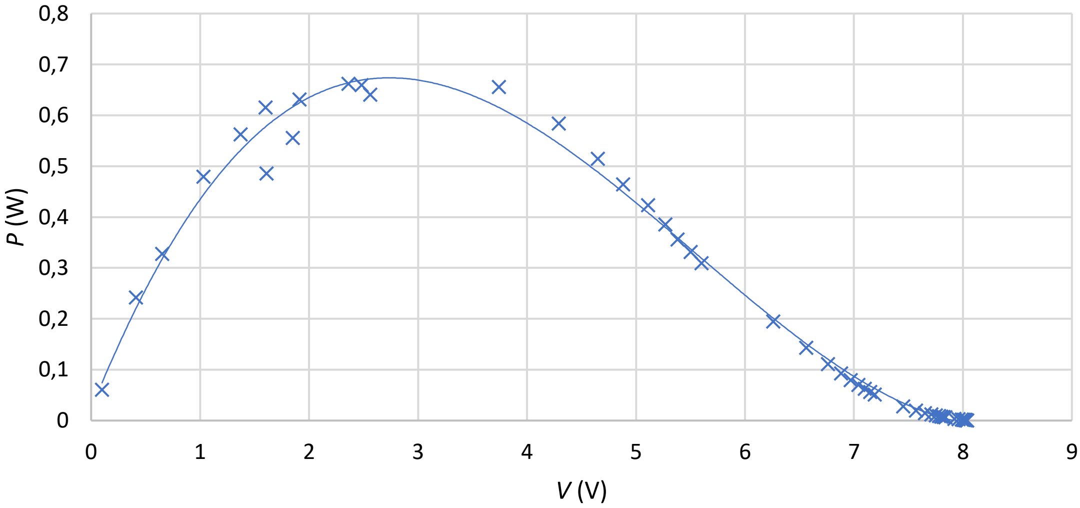


V (V)	I (mA)	P (W)	R (Ω)
8,040	0,000	0,00000	-
8,030	0,080	0,00064	100000
8,030	0,090	0,00072	90000
8,020	0,100	0,00080	80000
8,020	0,114	0,00091	70000
8,010	0,133	0,00107	60000
8,000	0,159	0,00127	50000
7,990	0,199	0,00159	40000
7,960	0,265	0,00211	30000
7,920	0,390	0,00309	20000
7,840	0,782	0,00613	10000
7,820	0,860	0,00673	9000
7,800	0,970	0,00757	8000
7,780	1,110	0,00864	7000
7,750	1,290	0,01000	6000
7,710	1,540	0,01187	5000
7,650	1,910	0,01461	4000
7,570	2,520	0,01908	3000
7,450	3,707	0,02762	2000
7,190	7,100	0,05105	1000
7,150	7,840	0,05606	900
7,100	8,740	0,06205	800
7,040	9,890	0,06963	700
6,970	11,400	0,07946	600
6,880	13,450	0,09254	500
6,760	16,420	0,11100	400
6,560	21,740	0,14261	300
6,260	31,030	0,19425	200
5,600	55,230	0,30929	100
5,500	60,210	0,33116	90
5,380	66,110	0,35567	80
5,270	73,140	0,38545	70
5,110	82,770	0,42295	60
4,880	95,030	0,46375	50
4,650	110,650	0,51452	40
4,290	136,010	0,58348	30
3,740	175,300	0,65562	20
2,560	250,000	0,64000	10
2,480	265,700	0,65894	9
2,360	280,300	0,66151	8
1,910	330,200	0,63068	7
1,850	300,100	0,55519	6
1,610	301,300	0,48509	5
1,600	384,500	0,61520	4
1,370	410,200	0,56197	3
1,030	465,200	0,47916	2
0,650	504,000	0,32760	1
0,410	590,041	0,24192	0,5
0,100	604,000	0,06040	0

A.2 V-I Characteristics of The PEMFC Stack



A.3 P-V Characteristics of The PEMFC Stack



A.4 Table of Measuring Instruments and Power Supply

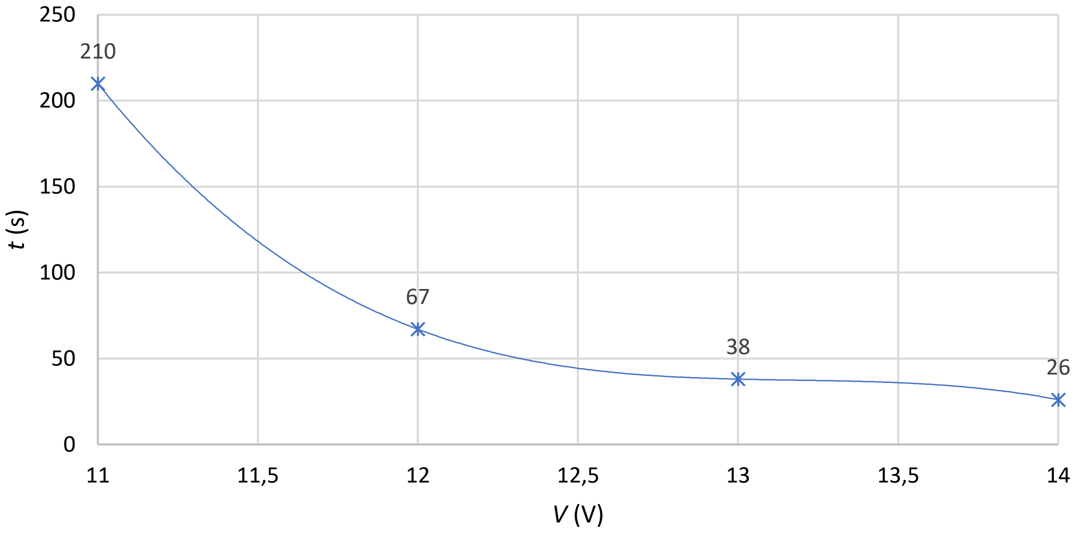
Instrument	Producer	Model	Registration number
Voltmeter	Agilent	34410A	SAP:001000191102-0000
Amperemeter	Rigol	DM 3061	SAP:001000215033-0000
Power supply	GW Instek	PSH-606A	SAP:001000243317-0000
Resistance decade box	-	-	SAP:001000032846-0000

Appendix B - Measured and Calculated Values of The Electrolyser

B.1 Table of Measured and Calculated Values of The Electrolyser

t (s)	V_N (V)	V_R (V)	I_1 (A)	I_2 (A)	I (A)	η (%)
210	11	10.92	0.468	0.442	0.455	98.917
67	12	11.7	1.37	1.33	1.35	97.528
38	13	12.52	2.381	2.325	2.353	92.196
26	14	13.3	3.47	3.36	3.415	87.399

B.2 The Time Needed to Obtain 80 cm^3 of Hydrogen With Different Loads of Voltage



B.3 Calculated Efficiency of The Electrolyser