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MARKETABILITY ANALYSIS OF GREEN HYDROGEN PRODUCTION IN TÜRKİYE

M.Sc. Thesis by

Ayşen KÖSE

Department of Mechanical Engineering

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We have read the thesis entitled **"MARKETABILITY ANALYSIS OF GREEN HYDROGEN PRODUCTION IN TÜRKİYE"** completed by **AYŞEN KÖSE** under the supervision of **PROF. DR. SELAHATTİN ÇELİK** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Prof. Dr. Selahattin ÇELİK

Prof. Dr. Hasan ÖZCAN

Jury Member

Prof. Dr. Kamil ARSLAN

Jury Member

Prof. Dr. Sadettin ORHAN

Director

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MARKETABILITY ANALYSIS OF GREEN HYDROGEN PRODUCTION IN TÜRKİYE

ABSTRACT

Green hydrogen has a great importance not only for its potential to reduce carbon emissions but also for its role in sustainable energy production. Among the remarkable factors that will take Türkiye one step ahead in preparation for green hydrogen are its rich renewable energy resources such as wind, solar and geothermal. The marketability of green hydrogen in Türkiye is a very important factor for integration and long-term use. Marketability depends on the development and integration of renewable energy systems, advances in electrolyzer technologies, and the evaluation of both operating expenses (OPEX) and capital expenditures (CAPEX) for different electrolyzer systems. The most significant technology in green hydrogen production is the electrolyzer which has types of Anion Exchange Membrane (AEM), Polymer Exchange Membrane (PEM), and Solid Oxide Electrolysis Cell (SOEC). Evaluation of all these technologies, in terms of CAPEX and OPEX, has great importance in determining the economic feasibility of green hydrogen production in Türkiye. When looking at Türkiye from a green hydrogen perspective, high potential can be seen due to the diversity and abundance of renewable energy sources and strategic initiatives. Successful integration of advanced electrolyzer technologies into existing/planned renewable energy systems and CAPEX and OPEX minimization targets will be vital in realizing this potential. Increasing governmental support, developing international relations and constitute infrastructure will further strengthen Türkiye's position in the green hydrogen market.

Keywords: Green hydrogen, CAPEX, OPEX, electrolyzer, market analysis, sustainability

TÜRKİYE'DE YEŞİL HİDROJEN ÜRETİMİNİN PAZARLANABİLİRLİK ANALİZİ

ÖZ

Yeşil hidrojen, sadece karbon salınımını azaltma potansiyeli değil, aynı zamanda sürdürülebilir enerji üretimindeki rolü açısından büyük önem taşımaktadır. Türkiye'nin yeşil hidrojen hazırlığında bir adım öne çıkmasını sağlayacak dikkate değer faktörlerden biri, rüzgar, güneş ve jeotermal gibi zengin yenilenebilir enerji kaynaklarına sahip olmasıdır. Türkiye'de yeşil hidrojenin pazarlanabilirliği, entegrasyon ve uzun vadeli kullanım açısından oldukça önemli bir faktördür. Pazarlanabilirlik, yenilenebilir enerji sistemlerinin geliştirilmesine ve entegrasyonuna, elektrolizör teknolojilerindeki ilerlemelere ve farklı elektrolizör sistemleri için işletme giderleri (OPEX) ve sermaye harcamaları (CAPEX) değerlendirmelerine bağlıdır. Yeşil hidrojen üretimindeki en önemli teknoloji, Anion Exchange Membrane (AEM), Polymer Exchange Membrane (PEM) ve Solid Oxide Electrolysis Cell (SOEC) türleri bulunan elektrolizördür. Bu teknolojilerin CAPEX ve OPEX açısından değerlendirilmesi, Türkiye'de yeşil hidrojen üretiminin ekonomik uygulanabilirliğini belirlemede büyük önem taşımaktadır. Türkiye'yi yeşil hidrojen perspektifinden incelediğimizde, yenilenebilir enerji kaynaklarının çeşitliliği ve bolluğu ile stratejik girişimler nedeniyle yüksek bir potansiyel görülmektedir. Gelişmiş elektrolizör teknolojilerinin mevcut/planlı yenilenebilir enerji sistemlerine başarılı bir şekilde entegrasyonu ve CAPEX ile OPEX minimizasyon hedefleri, bu potansiyelin gerçekleştirilmesinde kritik rol oynayacaktır. Artan devlet desteği, uluslararası ilişkilerin geliştirilmesi ve altyapı oluşturulması, Türkiye'nin yeşil hidrojen pazarındaki konumunu daha da güçlendirecektir.

Anahtar Kelimeler: Yeşil hidrojen, CAPEX, OPEX, elektrolizör, pazar analizi, sürdürülebilirlik

CONTENTS

NOMENCLATURE

Roman Letter Symbols

A Area (cm^2)

F Faraday constant ($C.mol^{-1}$)

FE Faraday efficiency

J Constant operating current density(A/cm^2)

M Molecular weight of H_2

m Total amount of hydrogen (kg)

N Number of electrons

T The daily running time of the factory (hour)

V Voltage range

Roman Letter Symbols

η Efficiency

Subscripts

AEM	Anion Exchange Membran Water Electrolysis
AWE	Alkaline Water Electrolysis
CAPEX	Capital expenditure
LCOH	Levelized cost of hydrogen
OPEX	Operational expenditure
PEM	Proton Exchange Membran Water Electrolysis
SOEC	Solide Oxide Water Electrolysis
IC	Initial Cost

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CHAPTER 1

1. INTRODUCTION

Energy consumption is a constant global phenomenon, essential to fulfilling humanity's primary needs. However, numerous global challenges stem from these energy demands. Thus, there is a critical need for a worldwide focus on energy production and the exploration of novel methods. Presently, global energy production relies heavily on fossil fuels, hydroelectricity, and nuclear resources. In Türkiye, fossil fuels dominate the energy landscape, underscoring the necessity to expand energy capacity and discover alternative sources. Nevertheless, interest in renewable energy sources has markedly surged in Türkiye recently and is anticipated to grow further [1].

With advancing technology and escalating global energy demands, investments in hydrogen technologies are poised to increase significantly in the coming years. Hydrogen is increasingly recognized as a crucial alternative energy carrier due to its high energy density and minimal environmental impact compared to fossil fuels. Its applications span diverse sectors including transportation, industry, renewable energy integration, and green chemical production. Moreover, enhancing production, storage, and utilization technologies for hydrogen will potentially open new export avenues for our country. This includes leveraging renewable energy sources, integrating hydrogen into existing natural gas infrastructure to reduce greenhouse gas emissions in heating, and tapping into domestic resources such as coal and boron [2].

Nevertheless, Türkiye possesses significant potential for green hydrogen production thanks to its abundant renewable energy resources and lower costs associated with installing renewable energy-based power plants compared to many developed nations. Consequently, it is anticipated that Türkiye will emerge as a formidable player in the global hydrogen market [2].

One of the paramount objectives countries worldwide are setting for the near future is to cleanse the planet of carbon and mitigate the impacts of climate change. Green hydrogen, derived from water electrolysis, stands as a crucial component in achieving these objectives by helping to decarbonize the planet [2, 3].

Recently, there has been increasing interest in large-scale production of green hydrogen through electrolysis, particularly for applications in renewable energy-powered power plants, as well as in transportation and industrial systems [2].

Investments directed towards these objectives in our country offer significant benefits in enhancing energy efficiency, advancing decarbonization efforts, and fostering long-term hydrogen exports. Overcoming the technological, economic, regulatory, and environmental challenges confronting the global hydrogen industry necessitates sustainable and supportive policies. It is critical to expand and diversify research and development funding, particularly in hydrogen technologies. Moreover, effective legislation and strategic planning will play pivotal roles in achieving these aims. These strategies are pivotal in accelerating the widespread adoption of hydrogen. Therefore, reducing our nation's dependence on foreign energy sources, harnessing our existing strengths to develop domestic electrolyzer and fuel cell technologies, promoting green hydrogen production, and integrating hydrogen across diverse sectors emerge as essential objectives [2].

In Chapter 2, the definition of basic energy and its importance worldwide are mentioned. It is mentioned how much of the basic energy demand worldwide can be met by energy production and inferences are made. The energy demands of countries and their perspectives on renewable energy are evaluated. The effects of sustainable energy on the world and its benefits are explained. Renewable energy types are defined and renewable energy rates in both Türkiye and the world are examined.

In Chapter 3, hydrogen definition, types and electrolyzer systems are investigated and inferences are made. Since green hydrogen is more reliable and environmentally friendly than other hydrogen types, research is conducted focusing on green hydrogen. The status of green hydrogen in the World and Türkiye is examined and the importance of green hydrogen is stated. In addition, water electrolysis systems are examined extensively and a comparison is made.

In Chapter 4, hydrogen is examined more through trade and marketing. The hydrogen and green hydrogen sector in the world and Türkiye is discussed. The number of studies on hydrogen and green hydrogen both globally and in Türkiye are examined and inferences are made. In addition, CAPEX, OPEX and LCOH etc. of water electrolysis systems are compared and efficiency calculations are mentioned. Cost calculations and equations in electrolysis systems are created and examined.

1.1 Literature Review

Villagra and Millet conducted a study about techno-economic analysis was made according to the high current densities of the PEM water electrolysis cell and the relationship between the high current densities of the PEM cell, cell voltage and hydrogen cost was examined. As a result, it was found that high current densities reduce capital expendature and hydrogen cost [1].

Vignisdottir presented a techno-economic analysis of the hydrogen produced by using hydroelectricity as a renewable energy source. As a result, it was found that the cost of hydrogen production decreases when the electricity is provided by renewable energy [2].

Matuteet al. studied a techno-economic analysis of green hydrogen produced by using photovoltaics in green hydrogen production facilities was made. Solar energy provided by photovoltaic systems was used as electrical energy and a significant decrease in the cost of hydrogen production was observed. With the study in this paper, a difference of 5 $/MWh in the PPA price can be up to 0.13 $/kg. Access to exemptions from the grid access tariff ATR definitely affects the electricity supply costs. In this case, reductions occur between 0.12 and 0.22 $/kg [3].

Nasser and Hassan studied the efficiency and potential of two types of electrolyzers operating at different temperatures. Using solar wind and waste heat energy, a techno-economic and environmental analysis was performed. According to this study, the advantage of waste heat systems came to the fore. This study shows that PV panels have lower values than wind turbines. The production varies from 0.0147 to 0.0166 kgH_2/kWh for PEM and 0.0282 to 0.0334 kgH_2/kWh for SOEC [4].

The study conducted by Reksten et al. examined the techno-economic analysis of PEM and AWE results. They revealed that the system area has a positive effect on the hydrogen cost. They also examined the cost impact of future Technologies. According to the cost model in the study, CAPEX is expected to decrease by 1-10 MW depending on the plant size. It is also thought that PEM and AEM systems will be less costly by 2030 [5].

Nami et al. studied the thermodynamic and techno-economic analysis of SOEC and AEM electrolyzer systems in green hydrogen production. Accordingly, they also presented cost calculations and thought that it would positively affect the cost of hydrogen production with capital expenditures. They also found that SOEC electrolyzer systems increase their efficiency when used in steam systems [6].

Gallardo et al., in Chile, performed a techno-economic analysis of AWE and PEM electrolysis systems using solar energy. They found that the total cost was low when electricity was provided by solar energy [7].

Li et al. investigated the chemical oxidation and electrocatalyst part of hydrogen production from water electrolysis and performed a techno-economic analysis by showing the CAPEX, OPEX and LCOH equations of the electrolysis cell. They found that to ensure environmentally friendly and sustainable hydrogen production, low-toxicity or non-toxic raw materials should be used in catalyst preparation to minimize pollution [8].

Shin et al., especially focusing on AWE and PEM systems, examined the performance of electrolysis systems operating at low temperatures and investigated their compatibility and efficiency with renewable energy. Considering wind and solar energy, CAPEX, OPEX and LCOH analysis were performed for both energies and cost calculations were made. It was determined that the hydrogen cost of the AWE system with wind energy was lower [9].

Ginsberg et al. studied the PEM electrolyzer system and made its techno-economic analysis. They studied the effects of the characteristics such as area, fluid density, cell voltage in the electrolyzer system on the hydrogen cost [10].

Kadıoğlu, S. et al. conducted the use of energy resources and highlighted the significance of sustainable energy. They concluded that technological advancements are necessary for the development of alternative energy sources In recent years, importance should be given to the development of alternative energy sources, which have been shown to contribute significantly to the solution of environmental problems caused by energy and, in particular, to reduce the consumption of fossil fuels [11].

The Ministry of Energy conducted a hydrogen technology roadmap study that outlines the necessary path for Türkiye in the field of hydrogen technology and presents a future plan [12].

Zulfhazli et al. conducted A study on technological and economic evaluation of hydrogen production methods. In this way, they presented a systematic examination of the hydrogen economy [13].

El-Shafie et al. conducted an overview of hydrogen production technologies, covering various production methods. According to this study, ammonia separation using catalyst was found to be more efficient than separation method without catalyst [14].

Statista provides data on global primary energy consumption from 2000 to 2022 [15].

Statista presents data on primary energy consumption by country for the year 2022 [16].

Aydoğdu, Ç. conducted an evaluation of renewable energy and energy efficiency supports and their impacts in Türkiye. They have also revealed that with the increase in support in Türkiye, fossil fuel usage will decrease, and a systematic effort will lead to a greater shift towards sustainable energy sources [17].

The IRENA, renewable energy capacity report provides data on renewable energy capacity and provides information on global renewable energy capacity [18].

Saha et al. conducted a comprehensive review of the technical, social, environmental, and economic parameters for integrated renewable energy systems. They found that integrated renewable energy systems are the optimal electrification option for standalone applications. Hybrid control is found to be the best option for robust control in integrated energy systems with the advantage of master and slave controller [19].

Zaim et al. conducted an analysis of the current status of geothermal energy plants in Türkiye. As of the end of 2016, the total installed capacity of our country reached 78,497.4 MW, gross electrical energy demand increased by approximately % 4.7compared to the previous year and reached 278.3 billion kWh, and peak power demand was 44,733.9 MW. While a total of 273.4 billion kWh was produced, 6.4 billion kWh was imported, and 1.4 billion kWh of the total electrical energy supplied was exported [20].

IRENA, wıth ıts report on geothermal, provides information on geothermal energy technologies. It provides data on the advantages and applications of geothermal energy [21].

In their report on Hydrogen Production for Water, IRENA examined the supply and consumption of water for clean and sustainable hydrogen production. Accordingly, they discussed the applications of water electrolysis systems [22].

IRENA, with its report on creating a global hydrogen market certification to enable trade, Discusses the development of a global hydrogen market certification to facilitate international trade [23].

IRENA, presents outlook for hydrogen in each G7 member, including analyses of technology, costs, strategy and stated policy support for each country, and presents recommendations for accelerating global hydrogen trade [24].

IRENA, analyzed the compatibility of hydrogen with renewable energy sources and its impact on technology [25].

IRENA, with this report, presents a number of solutions for smart electrification of renewable energy end-use sectors [26].

IRENA conducted energy production cost research with this report. They revealed that despite the increase in material and equipment prices, interest in renewable energy continues [27].

The joint report by IRENA and the World Trade Organization (WTO) presents their review of green hydrogen trade and sets out the future policy elements of green hydrogen. International trade cooperation has found that it is important to ensure sustainable market growth and promote technology development and innovation [28].

With this report, IRENA presents its annual employment analysis and foresees the need to develop various policies to increase employment. By 2050, IRENA's Transformation Energy Scenario projects a total of 100 million jobs in the energy sector, with 42 million in renewable energy, 21 million in energy efficiency and around 15 million in power grid and energy flexibility, with the remainder in traditional technologies. This figure is %62 larger than the Planned Energy Scenario, which matches governments' current plans [29].

Clean Air Task Force assesses the current status of solid oxide electrolysis technology, including its advancements, challenges, and potential applications in the field of energy conversion and storage. They found that with an external heat source to generate steam, SOECs achieved 20 percent electrical efficiency [30].

Hydrogen Europe presents the future importance of hydrogen, the determination of strategies in line with increasing demands, and the analysis of hydrogen's impact on the ecosystem. Clean hydrogen production pipeline projects are expected to grow, incentives are needed for decarbonization [31].

Deloitte economic analysis indicates that green hydrogen will play an important role in achieving net zero targets by 2050. It offers strategic ways to overcome fossil fuels and current problems. Emerging green hydrogen market to redraw the global energy and resource map as early as 2030, creating a $1.4 trillion a year market by 2050 [32].

According to the IEA report, despite technological developments such as heavy transport industry, they emphasize the importance of zero-emission energy production. They also emphasize the importance of emission values in existing structures [33].

Energy Efficiency 2023 is the IEA's analysis of global developments in energy efficiency markets and policies. It examines the latest trends in energy demand and efficiency-related investment and technology. This report enables more rapid deployment of efficient technologies and contributes to the expected peak in fossil fuel demand in the coming years [34].

According to the Nationaler Wasserstoffrat report, the fields of application of hydrogen were examined and economic evaluations were made by examining hydrogen production and demand. This report therefore not only provides a technology-specific perspective on hydrogen, but also integrates it into the overall energy, climate and industrial policy framework [35].

The EFI Foundation report addressed hydrogen demands. Global energy resources and strategies were addressed, and an economic analysis of hydrogen was provided. This report aims to address the information gap between stakeholders interested in the development of hydrogen technologies and the future growth of clean hydrogen markets in various regions. By providing stakeholders with access to relevant and up-to-date information, this report seeks to enhance their understanding of the hydrogen industry, enabling them to make informed decisions. A deeper understanding of market dynamics, technological advancements, and regulatory frameworks will empower these stakeholders to actively contribute to the development of the hydrogen market and the formation of demand, fostering a more robust and sustainable clean energy ecosystem [36].

Department for Business, Energy İndustrial Strategies presents levelised cost estimates for hydrogen production technologies, detailing methodology, data and assumptions. The aim of this paper is to help policy makers, industry and researchers better understand the economics of hydrogen production and how it could play a role in the UK’s wider energy strategy and climate targets [37].

The Hydrogen Council report examines North America’s hydrogen plans and analyzes the hydrogen economy. The Hydrogen Insights 2023 report aims to provide a comprehensive understanding of the status and potential of the hydrogen sector for those ranging from governments and policymakers to industry leaders and investors, and outline ways to increase hydrogen production and use globally in the future [38].

The IEA’s report, A Roadmap for a Net Zero Global Energy Sector by 2050, analysed hydrogen strategies and plans to 2050 and examined the impact of global net zero emissions. The IEA’s ‘Net Zero by 2050’ report aims to provide a practical, data-driven framework for achieving a sustainable, low-carbon future and highlights the need for a global transition to renewable energy [39].

The IEA’s Net Zero Roadmap: A Global Path to the 1.5°C Target report charts the global impact of net zero emissions and examines the 1.5°C temperature target and sets out what needs to be done in the global energy sector in 10 years [40].

In this report, IEA examined the renewable energy market and analyzed the renewable energy situation in 2020 and 2021 during the Covid-19 outbreak. This report serves as a guide going forward, highlighting the continuing momentum in renewable energy deployment and the steps needed to scale up this transformation over the next few years, particularly as countries strive to meet their climate goals and energy transition objectives [41].

This report from the IEA explores the key challenges of renewable energy in electricity, heating and transport technologies and analyses developments in the sector up to 2028 [42].

The European Commission states that it is necessary to set green energy targets, and to take action for this, it is necessary to set green energy targets between 2030 and 2050 [43].

The Breakthrough Agenda Report 2023 is an annual collaboration between the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA) and the United Nations High-Level Champions on Climate Change, which has shown support for global greenhouse gas emissions reductions. In addition to support, they have highlighted the need for cooperation on financial, technical assistance and market creation to meet international climate goals [44].

The Role of Carbon Credits in Scaling Up Innovative Clean Energy Technologies report aims to achieve a zero-emission future, mentioning low-emission hydrogen, the adoption of sustainable aviation technologies, and the promotion of carbon credits. The report calls for robust policy and international cooperation to harness the full potential of carbon credit systems to plan for a future of clean and renewable energy and drive the global energy transition [45].

In progress towards the sustainable development goals report, United Nation focuses on sustainable energy developments and sets targets. The reports' conclusions generally highlight the importance of policy changes, cooperation and reforms at the international level for a more sustainable world [46].

The U.S. National Clean Hydrogen Strategy and Roadmap report discussed the potential and importance of hydrogen, highlighted the importance of clean hydrogen in decarbonization, and stated that the U.S. could contribute to the hydrogen economy with clean hydrogen. The report aims to reduce hydrogen production costs and, in particular, to make the costs of green hydrogen competitive [47].

According to a report published by the World Economic Forum, hydrogen is a promising solution for decarbonizing hard-to-electrify sectors, and China has included it in its latest national development strategy. The report proposes a roadmap for China’s green hydrogen development, defined by six key barriers and targets related to cost, infrastructure, market demand, technology and evolution, and cooperation [48].

In this report, the IEA provides a global benchmark for tracking capital flows in the energy sector, examining how investors assess risks and opportunities in fuel and electricity supply, critical minerals, efficiency, research and development, and energy financing, as well as their cost policies [49].

The World Energy Outlook 2023 provides in-depth analysis and strategic insights into every aspect of the global energy system. Against a backdrop of geopolitical tensions and fragile energy markets, this year’s report explores how structural shifts in economies and energy use are changing how the world meets rising energy demand [50].

CHAPTER 2

2. IMPORTANCE OF ENERGY AND ENERGY SYSTEMS

Today, energy is one of our most critical needs, with consumption continually rising and expected to increase further. The escalating energy demand, driven by rapid population growth, increased traffic density, urbanization, and industrialization, has led to many environmental challenges that continue to expand in scale.

In recent years, environmental issues have increasingly come to the forefront in our country. Despite its indispensable role in modern life, the energy sector is also a significant contributor to environmental problems during the production, transmission, and consumption stages. A substantial portion of pollutants and greenhouse gases emitted into the atmosphere originates from energy production, consumption, and its lifecycle. Globally, energy production relies heavily on fossil fuel thermal power plants, hydroelectric facilities, and nuclear power plants. In Türkiye, where fossil fuels like oil, coal, and natural gas are extensively used, there is a pressing need to enhance efficiency in their utilization while expanding into new energy sources. This approach aims to mitigate the negative impacts of energy dependence on foreign resources. Achieving energy savings without compromising production levels and welfare is essential for fostering a stronger, more competitive economy and promoting a cleaner environment. Industrial activities contribute annually to the release of millions of tons of carbon dioxide, sulfur compounds, lead, and other toxic chemicals into the atmosphere. Despite the known risks posed to humans and the environment by these emissions, the global demand for abundant and affordable energy continues to rise steadily [11, 12].

Energy is essential for meeting human needs and ensuring future sustainability across sectors such as industry, housing, and transportation. While energy sources deliver indispensable benefits to our lives, their production, distribution, transportation, and consumption stages also contribute significantly to large-scale environmental pollution [11, 12].

Before the mid-19th century, the predominant energy source worldwide was wood. Coal emerged as the primary global energy source throughout the 19th century. With a significant increase in the global population, energy consumption escalated rapidly, leading the world to shift towards petroleum as a more viable alternative to coal. However, petroleum fuels have since faced environmental challenges, prompting a shift towards natural gas. Natural gas offers cleaner combustion, higher efficiency, and lighter environmental impact. Its distribution via extensive pipeline networks is less obtrusive compared to fuel oil. Today, natural gas has become the preferred choice for electricity generation, alongside the increasing contribution of renewable energy sources to global power production [14].

2.1 Global Energy Demand: Current Trends and Future Projections

The world population is increasing with widespread urbanization. As seen in Figure 2.1, over the past nearly twenty-five years, this population growth has resulted in a significant increase in energy consumption worldwide. Energy use varies greatly between countries; As seen in Figure 2.2, China is the leader in consumption rates due to its large population. Another major energy consumer that follows closely is the United States. The rapid depletion of fossil fuels has spurred intense research and development efforts aimed at finding new alternative sources and improving the efficiency of existing fossil fuel use. In recent years there has been a significant shift towards renewable energy sources, reflecting the global trend towards sustainability. As a result, renewable energy consumption is increasing. In particular, the fact that buildings account for %51 of total energy consumption emphasizes the importance of energy use in the built environment. As global energy needs continue to evolve, the Earth's energy landscape is undergoing a transformation towards more sustainable energy production and consumption [14, 15, 16].

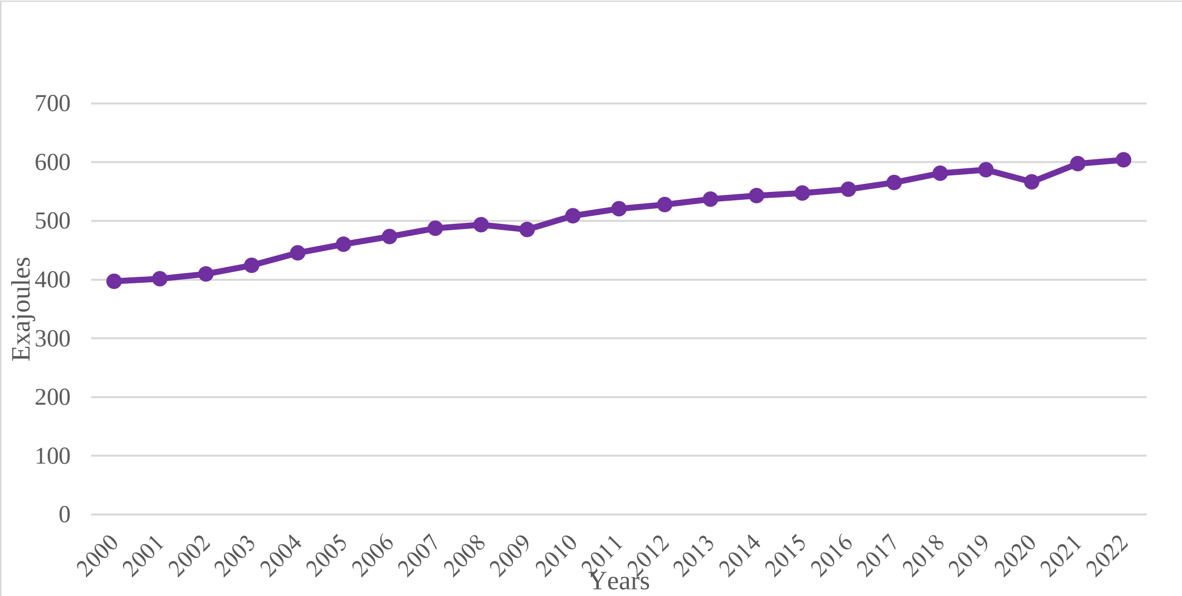
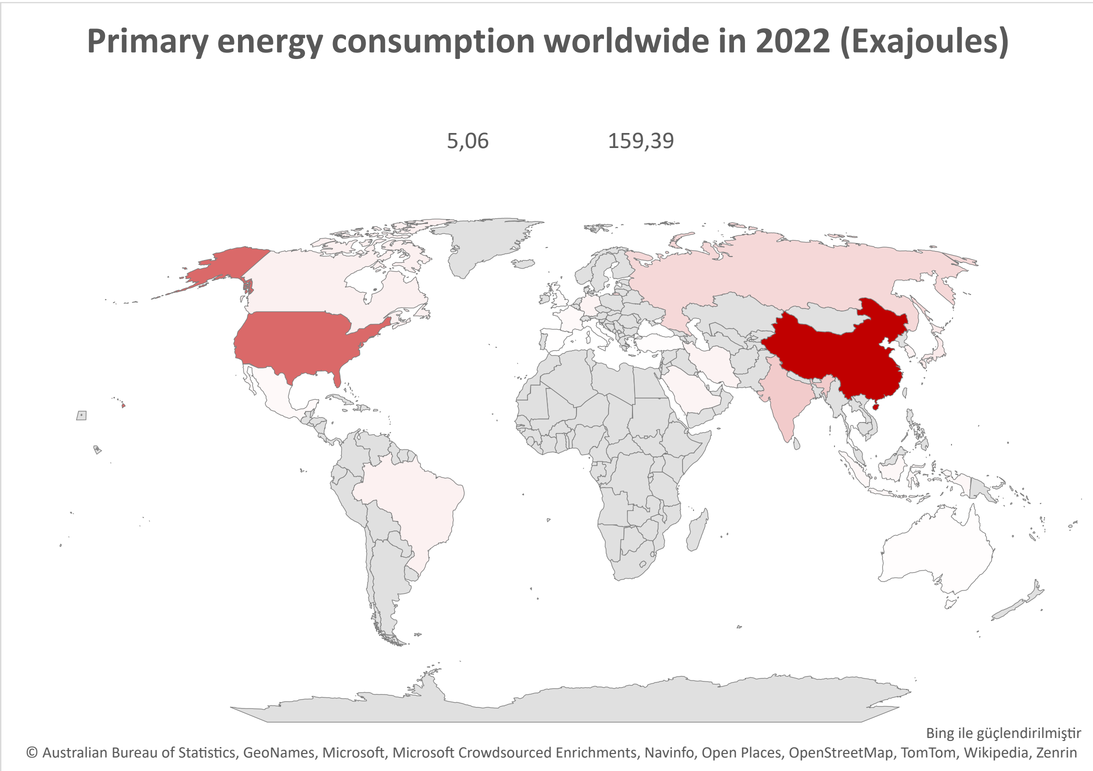


Figure 2.1 Primary energy consumption Worldwide [15]



China	United Sta	India	Russia	Japan	Canada	Brazil	South Kore	Germany	Iran	Saudi Arab	Indonesia	Mexico	France	United Kin	Turkey	Italy	Australia	Spain	Thailand
159,39	95,91	36,44	28,89	17,84	14,14	13,41	12,71	12,3	12,16	11,5	9,77	8,73	8,39	7,31	7,01	6,14	5,98	5,76	5,06

Figure 2.2 Primary energy consumption worldwide in 2022 by country [16]

To mitigate the effects of climate change, there is a global shift towards alternative and renewable energy sources, moving away from fossil fuels. Annual global investments of approximately $300 billion in renewable energy have contributed to a reduction in global carbon dioxide emissions. However, further exploration of renewable resources is necessary for them to fully replace the still dominant consumption of fossil fuels. Many countries are formulating strategies to reduce energy dependency and transition to cleaner energy sources, focusing on more efficient use of renewable resources. Consequently, there is a trend towards reducing or even phasing out fossil fuels, implementing financial support mechanisms, and emphasizing research and development (R&D) efforts. The detailed consideration of cost implications, application methods, and economic impacts is crucial in advancing these initiatives. Given the multifaceted nature of renewable energy and its continual evolution through new technologies, each country must assess its unique resources and conduct comprehensive studies. Agricultural products are increasingly recognized alongside natural resources such as wind, solar, sea, and geothermal as viable renewable energy sources. As global attention on renewable resources grows, so too does renewable energy capacity worldwide. This development can be examined in Figure 2.3. Continued efforts by countries in this direction will further enhance renewable energy capabilities. Notably, technological advancements play a pivotal role, with developed countries leading the way in renewable energy innovation and deployment [17, 18].

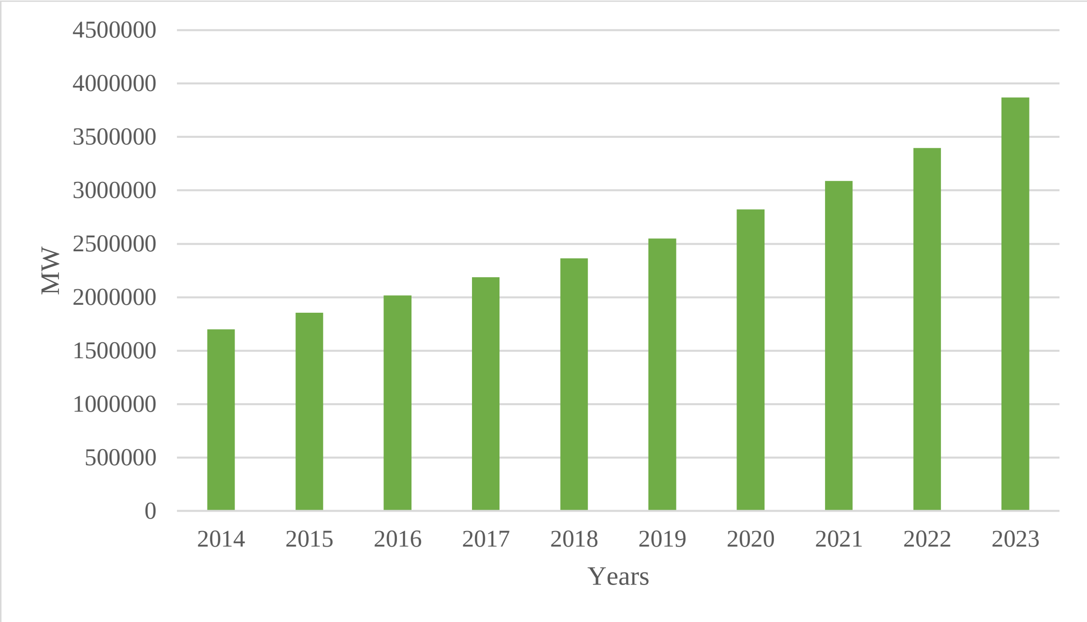


Figure 2.3 Total renewable energy capacity Worldwide [18]

2.2 Renewable Energy Sources

Energy plays a pivotal role in the overall development of a country. It is indispensable across various sectors including domestic use, commercial industries, and agriculture. Broadly, energy sources are categorized into non-renewable, such as coal, crude oil, and natural gas, and renewable, encompassing solar, wind, biomass, biogas, and small hydropower. Traditional sources like fossil fuels, nuclear, and hydrogen have long been foundational in meeting energy demands. However, the extraction of fossil fuels has escalated due to rising global demand and rapid industrialization, leading to challenges like resource depletion and environmental degradation. Presently, fossil fuels satisfy approximately 66% of global energy needs but come at a cost, contributing significantly to global warming and climate change through emissions of CO_2, CO, and other pollutants harmful to the environment [19].

Energy production from renewable sources offers numerous advantages compared to traditional sources. Renewable energy can be harnessed without causing harm to the environment, making it a sustainable choice. Moreover, these resources replenish naturally at a rate comparable to or faster than their consumption rate. This dual benefit not only supports ecological balance but also ensures long-term availability of energy without compromising future needs [19].

2.2.1 Geothermal Energy

A geothermal resource refers to hot water and steam with temperatures consistently exceeding the regional atmospheric average, often containing a diverse array of minerals, salts, and gases due to accumulated heat from varying depths beneath the earth's surface. Geothermal energy harnesses these resources effectively, playing a significant role in electricity generation, heating, and drying processes. As one of the foremost renewable energy sources, its utilization is steadily growing worldwide, spurred by intensified research into renewable energy alternatives. As a result, global installations of geothermal-based energy continue to increase steadily over time, as seen in Figure 2.4 [20, 21].

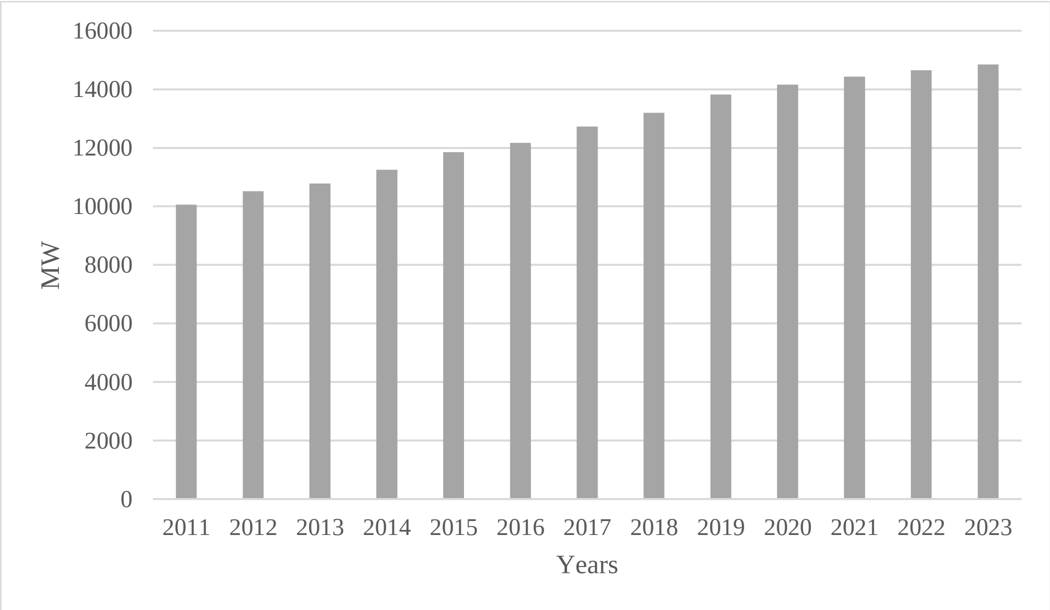


Figure 2.4 Installed power for geothermal energy in the World [21]

Many studies examining Türkiye's total installed power reveal a notable absence of geothermal energy utilization, alongside investigations into its environmental impacts [20].

As widely recognized, geothermal energy represents an economically viable means of tapping into the heat stored within accessible depths of the earth's crust. Türkiye boasts significant geothermal potential, with identified capacities of 31,100 MW for heat generation and 4,500 MW for electricity production. Economically feasible geothermal reservoirs typically occur between temperatures of 40 to 80 degrees Celsius, located in permeable rocks beneath impermeable layers at depths of less than 3,000 meters. Notably, 90% of Türkiye's geothermal fields are suitable for heating applications [11].

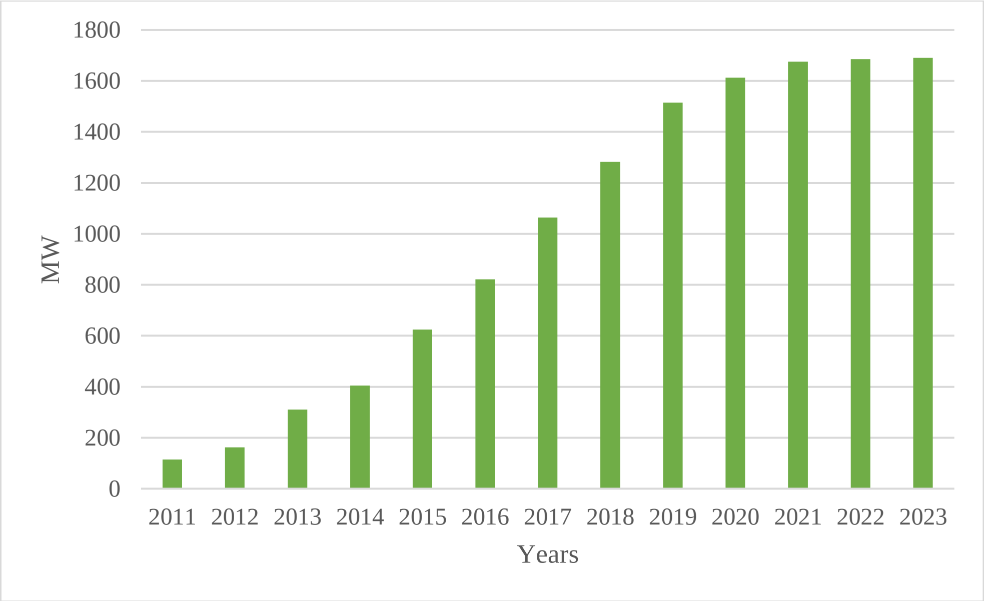


Figure 2.5 Installed power for geothermal energy in Türkiye [21, 52]

Türkiye boasts nearly 1000 natural hot water sources suitable for electricity generation. The country's geothermal energy potential is estimated at 610 MW for electricity production and a substantial 31,500 MW for heating purposes. By the end of 2023, Türkiye had successfully developed a geothermal power plant capacity of up to 1691 MW, with the majority of this capacity operational and ready for use. This situation can be observed in Figure 2.5. Consequently, efforts are underway to maximize the utilization of Türkiye's entire geothermal electricity generation capacity [51,52].

2.2.2 Wind Energy

Wind energy originates from the disparate heating of the Earth's surfaces by solar radiation. Varied heating of the seas and atmosphere creates pressure differentials, prompting air movement from areas of high to low pressure, commonly known as wind. This wind energy can be harnessed to produce mechanical or electrical energy. Mechanical energy derived from wind is often employed for tasks like home and agricultural irrigation. Moreover, Wind Power Plants are dedicated facilities designed to convert wind energy into electrical power on a larger scale [51].

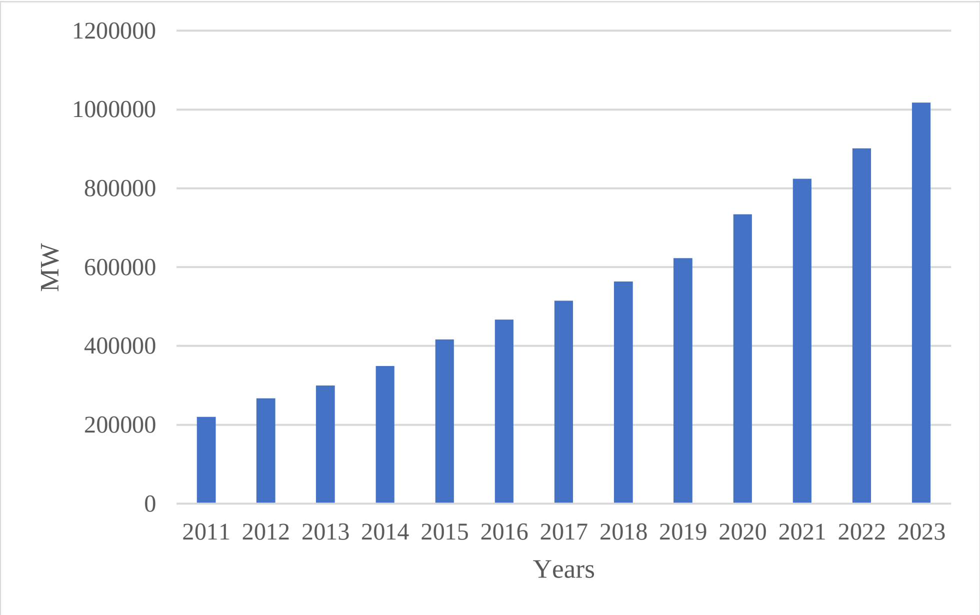


Figure 2.6 Installed power for wind energy in the World [53]

Today, the dwindling availability of fossil resources and the escalating global energy demand underscore the growing significance of renewable energy sources. Wind power, in particular, plays a crucial role as a clean and sustainable energy option. Factors such as wind speed and direction are pivotal in assessing and forecasting the performance of wind power plants. Moreover, wind energy stands out for its substantial potential to generate electricity efficiently and cleanly. As seen in Figure 2.6, in recent years there has been a significant increase in the adoption of wind energy worldwide, with installed capacity increasing by approximately 800,000 MW since 2011. Wind energy installations are cost-effective, requiring minimal infrastructure compared to solar panels, and entail lower maintenance and repair expenses, reducing dependence on foreign resources. The future expansion of wind energy hinges on robust support from local governments to harness its full potential and promote widespread adoption across various regions [53, 55].

Wind energy stands out as one of the fastest-developing renewable energy sources from a technical standpoint among emerging energy technologies. Globally, wind turbines contribute over 4000 MW of energy production. Türkiye, with an average wind speed of 2.5 m/sec and a wind power density of 24 W/m, currently utilizes this energy primarily for limited applications such as certain water pumps, with significant untapped potential otherwise [11, 55].

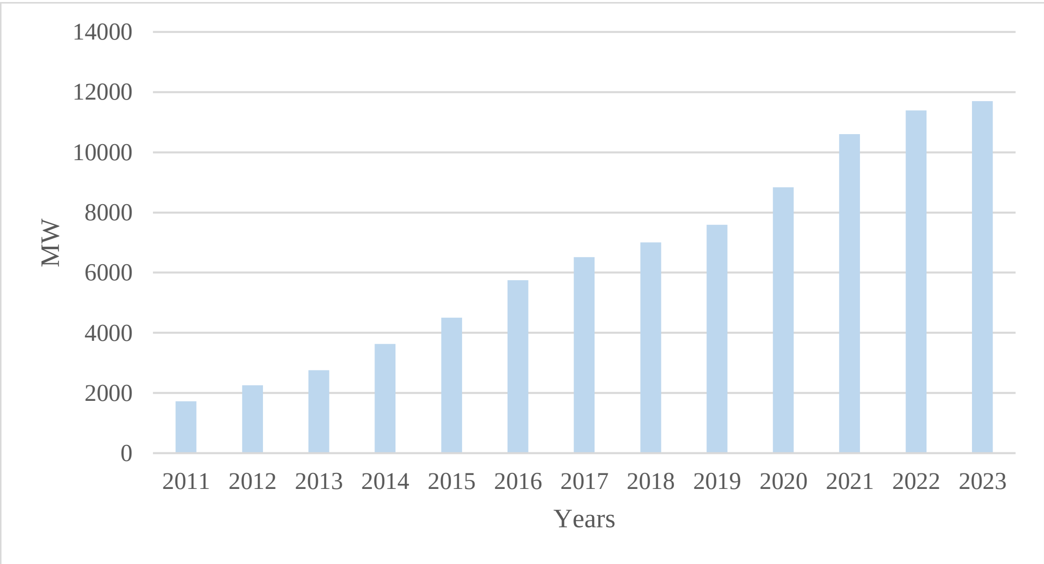


Figure 2.7 Installed power for wind energy in Türkiye [53, 54]

When the interest in wind energy in Türkiye is examined, it can be seen in Figure 2.7 that our installed power capacity in wind-rich regions continues to grow steadily. As of today, our installed capacity has reached 11,697 MW [54].

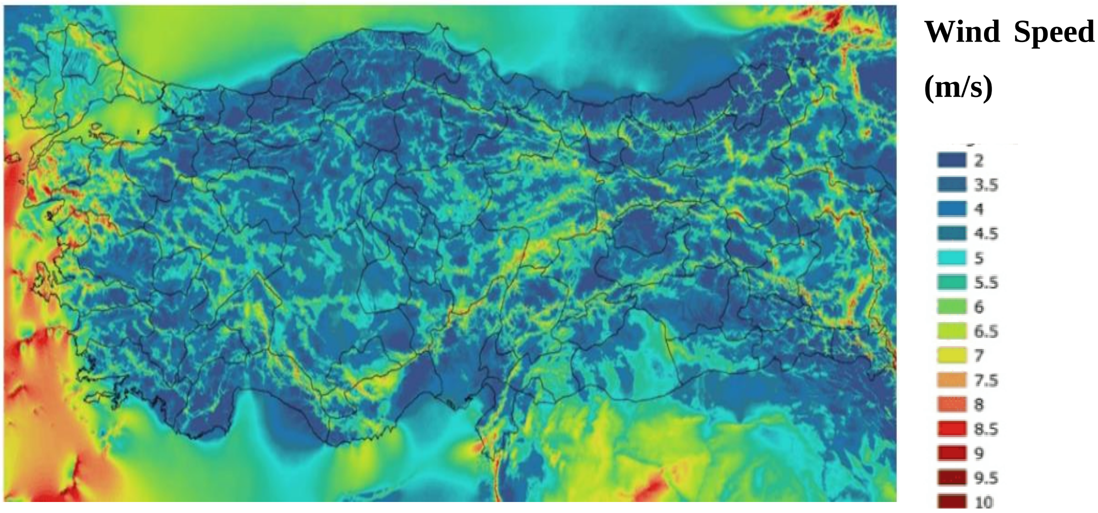


Figure2.8 Distribution of wind power [54]

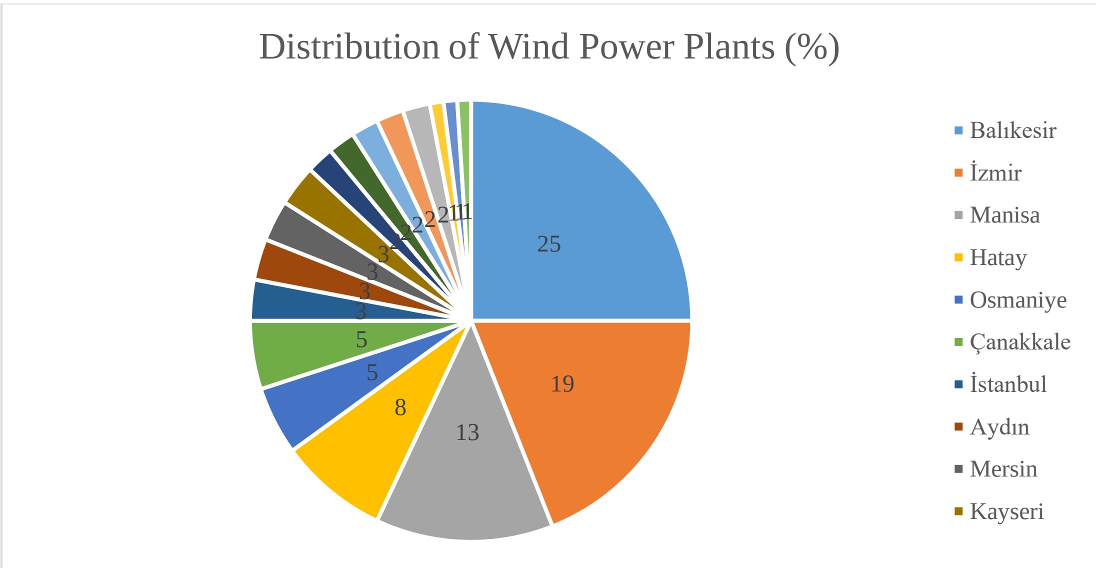


Figure 2.9 Distribution of wind power plants in the enterprise by provinces [55]

Looking at Figure 2.8, the places where the wind level is fastest are the Aegean sides. Therefore, it may be more appropriate to establish a wind power plant in places close to these regions. If we look at the distribution of the number of wind power plants by province in Figure 2.9, the places with the highest number are Balıkesir, İzmir and

Manisa. In other words, the number of power plants is high in the places where wind energy is used the most.

2.2.3 Solar Energy

In the core of the sun, a fusion reaction transforms hydrogen gas into helium, giving rise to immensely powerful solar energy. To harness this energy, various technologies such as solar collectors, solar power plants, and solar cells (photovoltaic cells) have been developed. These advancements enable us to utilize solar energy directly as heat or indirectly by converting it into electrical energy through these Technologies [51].

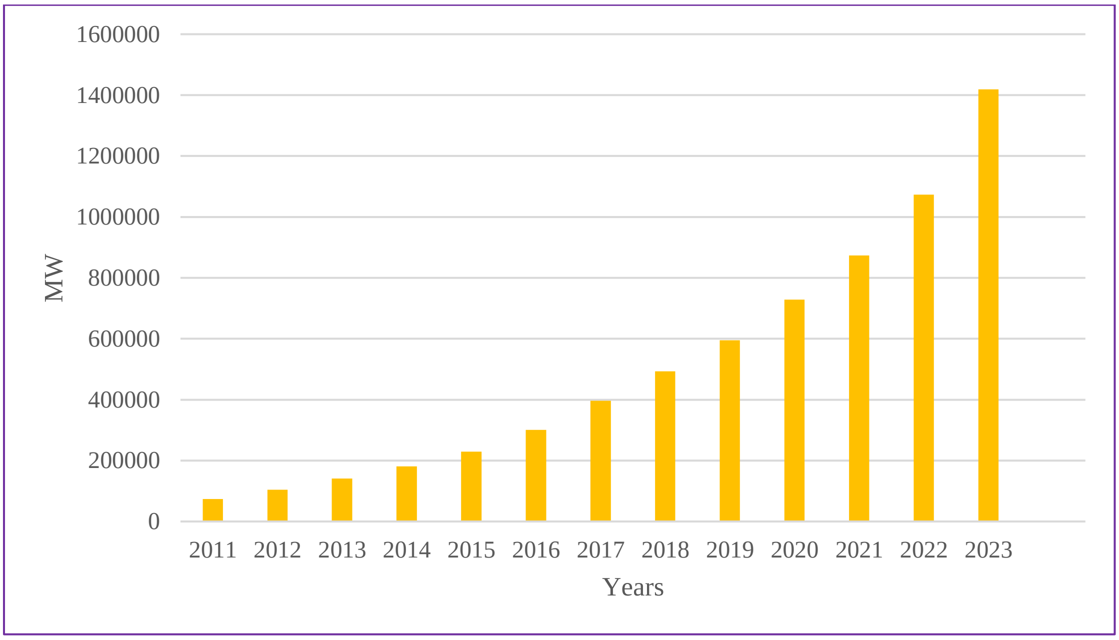


Figure 2.10 Installed power for solar energy in the World [56]

As seen in Figure 2.10, solar energy has experienced substantial growth globally over the past decade, emerging as one of the foremost renewable energy sources. Since 2011, there has been a remarkable increase of nearly 1,400,000 MW in installed solar power capacities worldwide [56].

Power plants designed to harness the vast energy potential of solar rays are still facing economic challenges. The primary issue with solar power plants is their dependence on sunlight, which diminishes in the evening when electricity demand peaks. Despite this limitation, Türkiye benefits from a high solar energy potential, leading to a significant increase in installed solar power plants over the past decade. Globally and domestically, solar energy applications are predominantly used for generating hot water in residential homes and hotels. Türkiye experiences approximately 2741 hours of sunshine annually, with an average daily solar energy of 3.6 kWh/m² [11, 57].

Türkiye enjoys a strategically advantageous geographical position for harnessing solar radiation. As seen in Figure 2.11, across the country, the levels of global radiation range between 1400 and 2000 kWh/m², highlighting the potential for widespread solar energy utilization. Consequently, various government-supported initiatives promote the adoption of solar energy systems in both agricultural and industrial sectors. This proactive approach has led to a significant increase in Türkiye's solar energy installed capacity, which has reached 12,292 MW in recent years, judging by Figure 2.12 [57, 58].

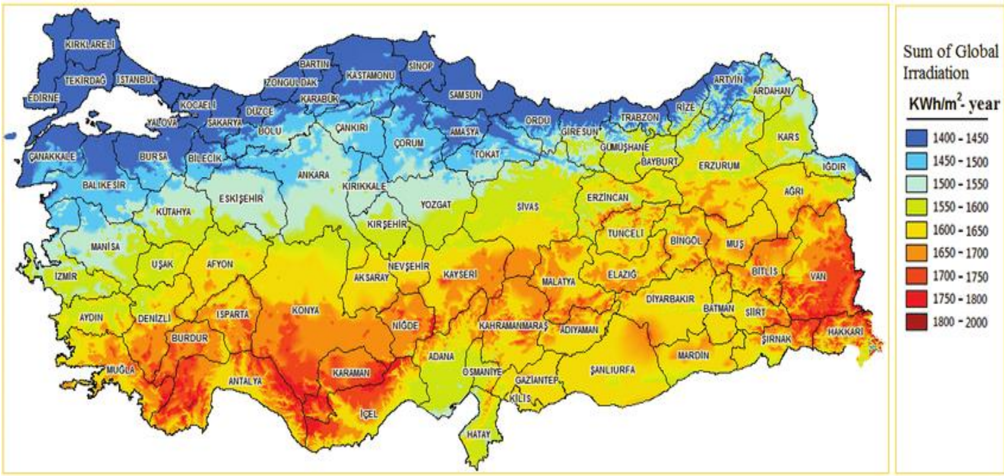


Figure 2.11 Türkiye global horizontal irradiance [57]

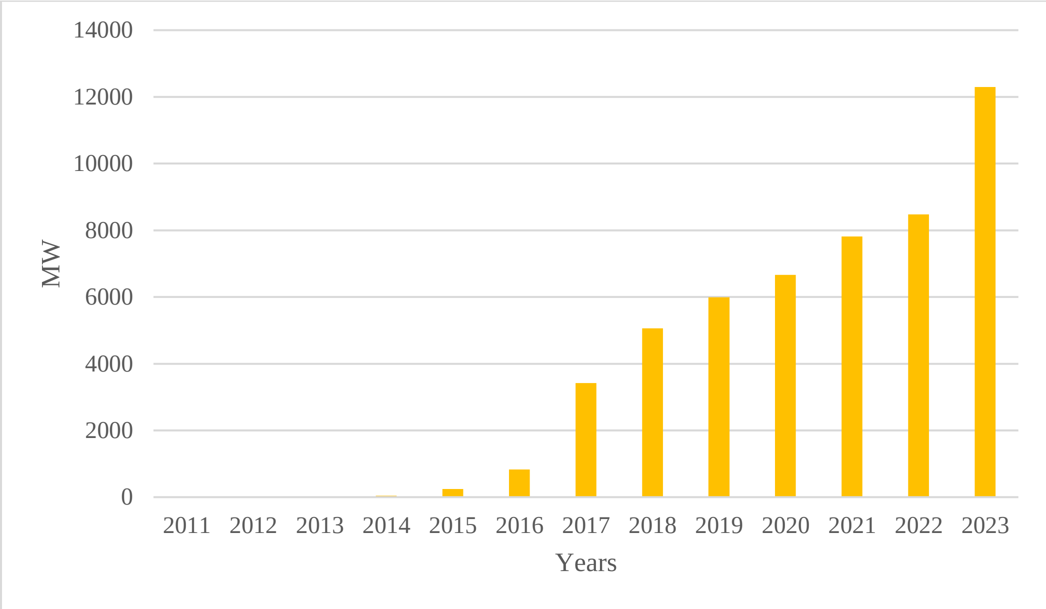


Figure 2.12 Installed power for solar energy in Türkiye [57]

2.2.4 Biomass Energy

Biomass is quantified by its area or volume and refers to the total amount of living plant and animal matter. The majority of the world's biomass consists of animals and microorganisms residing on forest branches, stems, or leaves. It serves as a renewable resource utilized in the production of various types of energy, offering the capability to convert stored solar energy back into usable energy through organic matter. The formation elements of biomass are shown in Figure 2.13. Accordingly, today biomass finds effective applications in transportation, heating and electricity generation through the utilization of food production waste, agricultural and farm residues, as well as methane gas coming from landfills. While global energy consumption from biomass remains relatively low, developed countries notably demonstrate higher utilization rates of biomass resources [59].

It is recognized that 12% of the world's energy demand is met through the generation of electricity from waste gases produced during the biochemical degradation of garbage. Biogas plays a significant role in providing cooking and lighting for approximately 50 million households, particularly in countries like China, India, and Nepal. Mediterranean countries such as Türkiye, known for their high consumption of fresh vegetables and fruits, also generate substantial amounts of fresh green waste. The biodegradable components in this waste contribute to the production of methane gas, which is harnessed for energy production purposes [11].

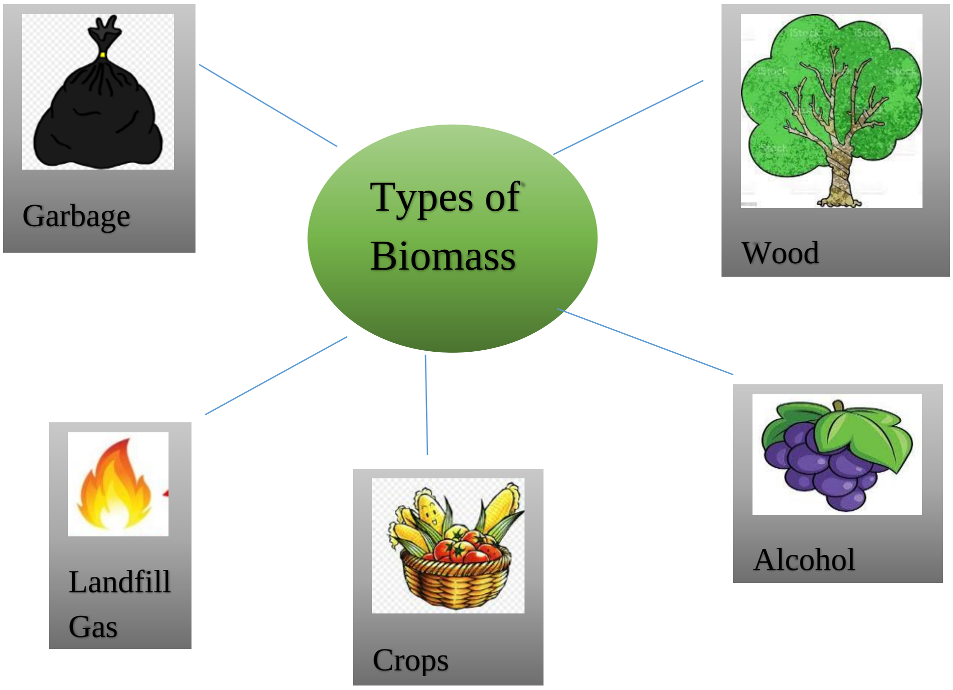


Figure 2.13 The main types of biomass

Biomass plays a crucial role as a primary fuel source for cooking and heating in many countries worldwide. In several developed nations, there is a growing trend towards utilizing biomass fuels to mitigate increased carbon dioxide emissions from fossil fuels. Biomass also serves as a versatile resource for transportation and electricity generation, representing a stored form of chemical energy. Following its production through photosynthesis, plant biomass can be directly burned for heat or processed into renewable liquid and gaseous fuels through various methods. As shown in Figure 2.14, numerous technologies are available to convert biomass from various sources, positioning biomass as an important solution in expanding the use of renewable energy in smart energy systems. Currently, biomass combustion stands out as the most widely adopted and mature conversion technology, making it the forefront choice for biomass utilization today [59].

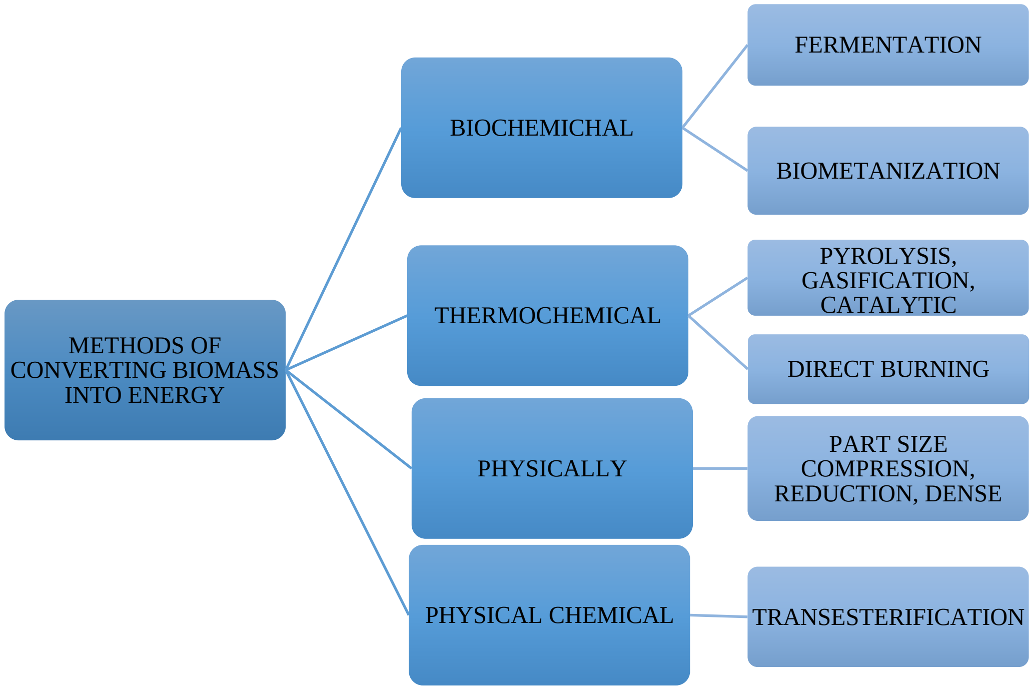


Figure2.14 Methods of converting biomass into energy [60]

Biomass energy sources encompass a range of biological and chemical materials. Through various conversion methods, diverse types of fuels can be produced, thereby determining the potential of biomass energy. Looking at Figures 2.15 and 2.16, when global and Türkiye-specific biomass energy data are examined, it turns out that the installed biomass energy capacity has increased steadily over time [60, 61].

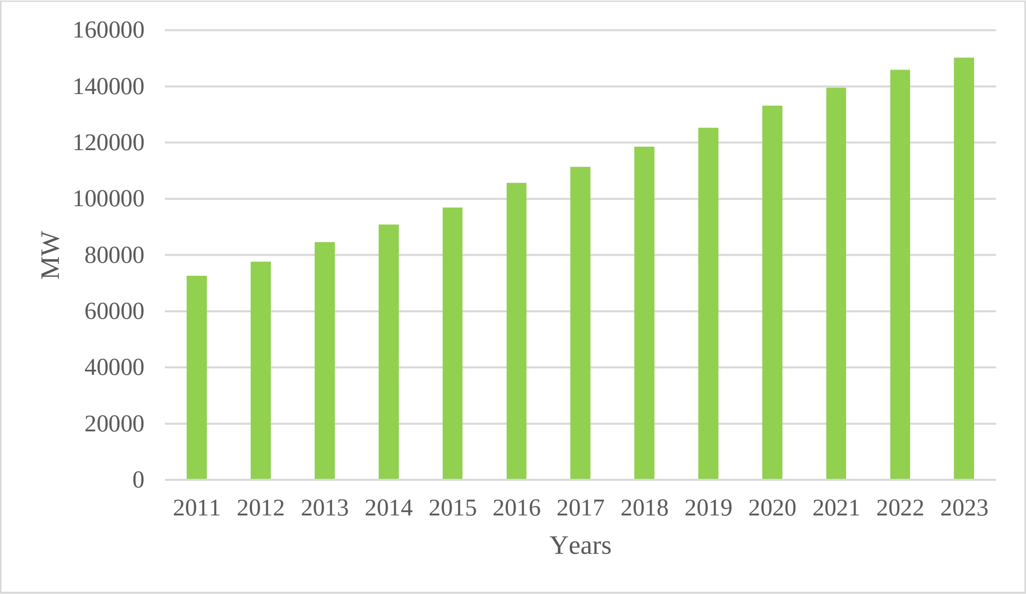


Figure 2.15 Installed power for biomass energy in the World [61]

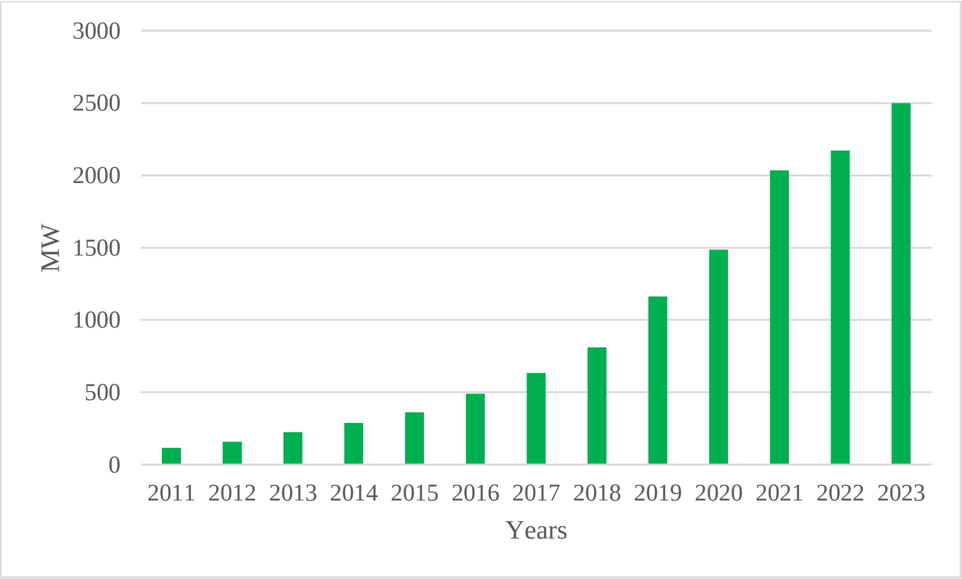


Figure 2.16 Installed power for biomass energy in Türkiye [60, 61]

2.2.5 Hydro Energy

Water naturally permeates every level of the atmosphere, from underground aquifers to aboveground rivers and lakes, ensuring its presence in clean and balanced states. This natural distribution underscores the critical role of hydroelectric power plants in harnessing this abundant and renewable resource [62].

Hydraulic energy stands out as a widely utilized renewable energy source. Through the construction of dams on rivers and the creation of reservoirs, the potential energy stored in the water is harnessed to generate electrical energy via turbines. This method of energy production is prevalent and extensively employed, making hydroelectric power plants a common choice for renewable energy generation [51].

Hydroelectric production presents a strategic choice given the geographical advantages of our country. As a renewable energy source, hydro energy is environmentally friendly, efficient, clean, and sustainable. Therefore, there should be a concerted focus on expanding hydroelectric power plants alongside increasing energy consumption, ensuring a sustainable energy future. As a result, according to Figure 2.17, globally hydroelectric installed power is increasing year by year [63, 64].

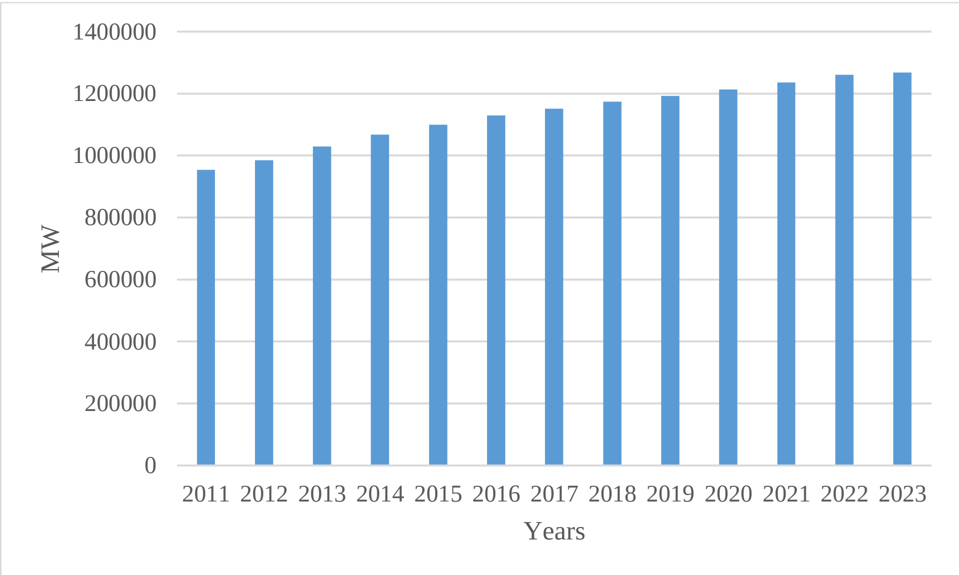


Figure 2.17 Installed power for hydrolic energy in the World [64]

Hydroelectric power has played a pivotal role in Türkiye, serving various essential purposes such as electricity generation, irrigation, water supply for domestic and industrial use, and flood control in surrounding areas. Consequently, the construction of water storage facilities and hydroelectric power plants has consistently been a national priority since the country's inception. Compared to other renewable energy sources, hydroelectric energy meets around %50 of Türkiye's electricity demand, showcasing substantial growth potential. Over the past two decades, Türkiye's electricity demand has shown steady growth, averaging an annual increase of %8-10. In Figure 2.18, it is seen that the hydrolic energy installed capacity in Türkiye is gradually increasing. Rapid economic and population growth further drives this escalating energy and electricity demand. Among renewable energy sources, hydroelectric energy holds significant potential in Türkiye, with a theoretical hydroelectric potential estimated at approximately 433 billion kWh. However, considering technical constraints and economic viability, the usable potential is around 216 billion kWh, with an economically feasible annual average of 160 billion kWh for hydroelectric energy production [63, 65].

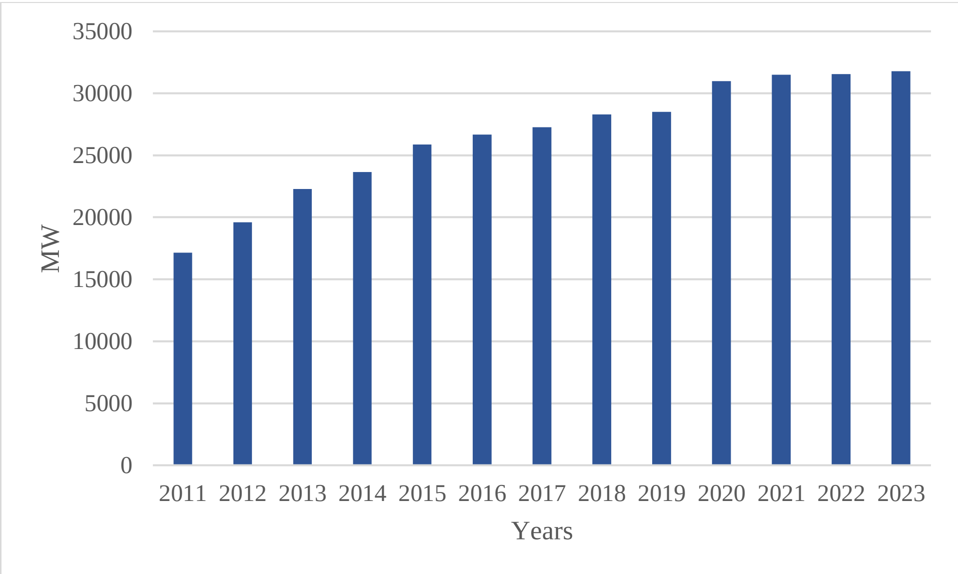


Figure 2.18 Installed power for hydrolic energy in Türkiye [63, 64]

2.2.6 Wave Energy

Wave energy is a renewable energy source derived from the movement of waves generated by wind across the surfaces of seas and oceans. With oceans covering a vast majority of the Earth's surface, harnessing this energy efficiently becomes crucial as global energy demands rise alongside population growth. Recent advancements have spurred research and development into technologies aimed at extracting energy from oceans. These include offshore wind turbines, floating solar photovoltaic systems, and ocean thermal energy conversion systems, but wave energy converters are emerging as a prominent solution. Unlike hydro energy derived from dams or river water, wave energy taps into the natural movement of oceans and seas. This type of energy is particularly favored by countries with extensive coastlines. Nations such as the United States, England, Spain, and Portugal lead in the adoption of wave energy technologies due to their proximity to oceans and seas. When we look at Figure 2.19, there has been an increase in wave energy globally, especially after 2015 [66, 67, 68].

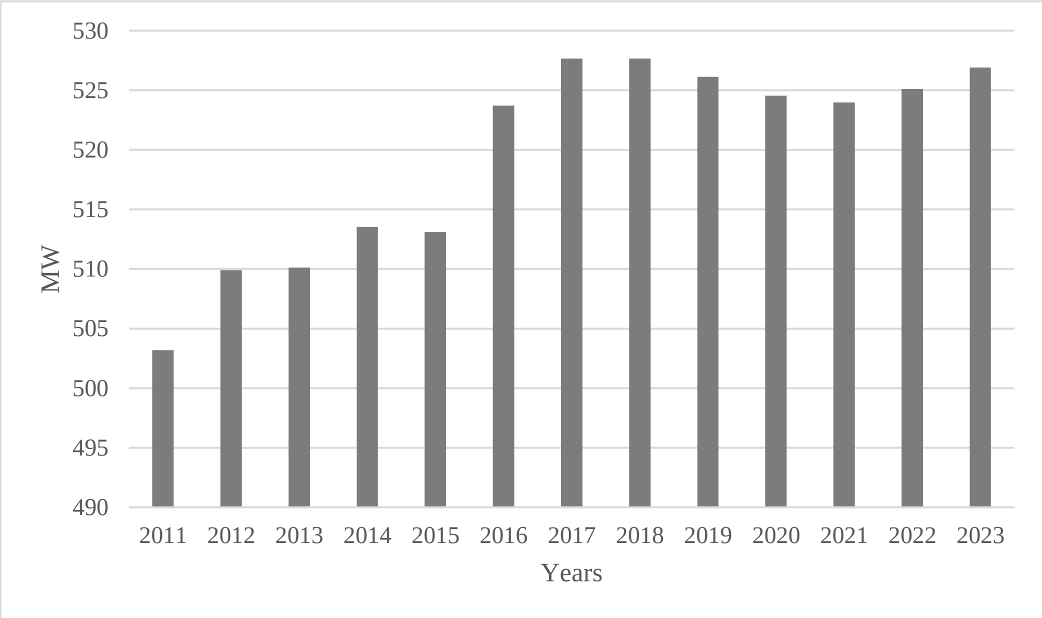


Figure 2.19 Installed power for wave energy in the World [68]

Wave energy, tidal energy, salinity gradient energy, currents, and surface evaporation energy are all forms of energy that can be harnessed from seas and oceans. Considering the geographical location and climate conditions of Türkiye, wave and tidal energy emerge as the most suitable options. As seen in Table 2.1, Türkiye's coastal areas, particularly in the Aegean and Mediterranean regions, exhibit significant wave energy potential. Specifically, cities like Antalya and Izmir stand out for their high potential in wave energy generation [66, 67].

Table2.1 Türkiye's regional wave intensities [66]

Zone	Power
Black Sea	1.96-4.22 kWh/m
Marmara Sea	0.31-0.69 kWh/m
Aegean Sea	2.86-8.75 kWh/m
Mediterranean	2.59-8.26 kWh/m
Izmir-Antalya	3.91-12.05 kWh/m

2.3 Sources of Energy Conversion Systems/Applications

Table 2.2 Renewable energy sources and using areas [66, 69]

Geothermal	**Power generation, hydrothermal system**
Wind Energy	Power generation, wind generators, windmills
Solar Energy	Solar collectors, Photovoltaic, thermal power generation
Biomass	Heat and power generation, transportation fuels
Hydropower	Power generation
Wave Energy	Power generation

The classification of renewable resources according to their application areas is shown in Table 2.2. Ensuring universal access to energy and categorizing renewable resources based on their application areas are crucial for sustaining life on Earth. Proper utilization of renewable energy resources is paramount, not only to meet human needs effectively but also to enhance energy efficiency. The escalating global energy demand, driven by population growth, underscores the necessity to prioritize renewable energy solutions. It is imperative to expand renewable energy applications in alignment with rising energy demands and to intensify research efforts aimed at advancing these technologies [69].

2.4 Renewable Energy-Focused Developments in the World

Energy consumption is steadily rising worldwide, largely driven by population growth. Consequently, existing energy sources are struggling to meet societal demands. Moreover, these sources predominantly rely on fossil fuels, posing significant long-term challenges for global sustainability. As the search intensifies for alternative energy options, prioritizing environmentally sustainable and efficient solutions becomes paramount. This burgeoning interest underscores a growing preference for renewable energy sources [51, 65].

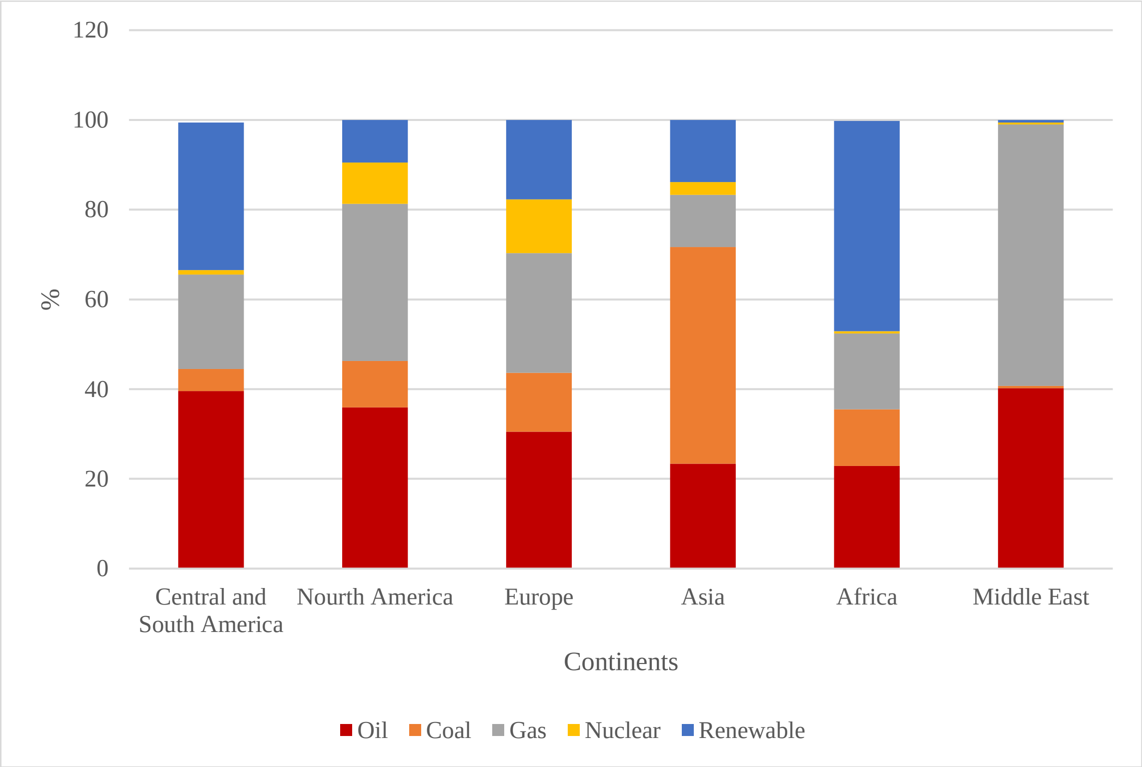


Figure2.20 Total energy supply distributions by continents [70]

Figure 2.20 illustrates the distribution of energy supplies across continents. Fossil fuels, particularly oil, constitute a significant portion, approaching %40 across nearly every continent. In Asia and Africa, this percentage exceeds %20. Coal, another fossil fuel, holds the largest share in Asia, whereas its presence is comparatively lower on other continents. Gas accounts for substantial percentages in continents other than Asia and Africa. European countries lead in nuclear energy adoption, showcasing the highest percentage globally. Renewable energy sources, considered alternatives, exhibit a notably higher proportion in Africa compared to other energy sources' distributions.

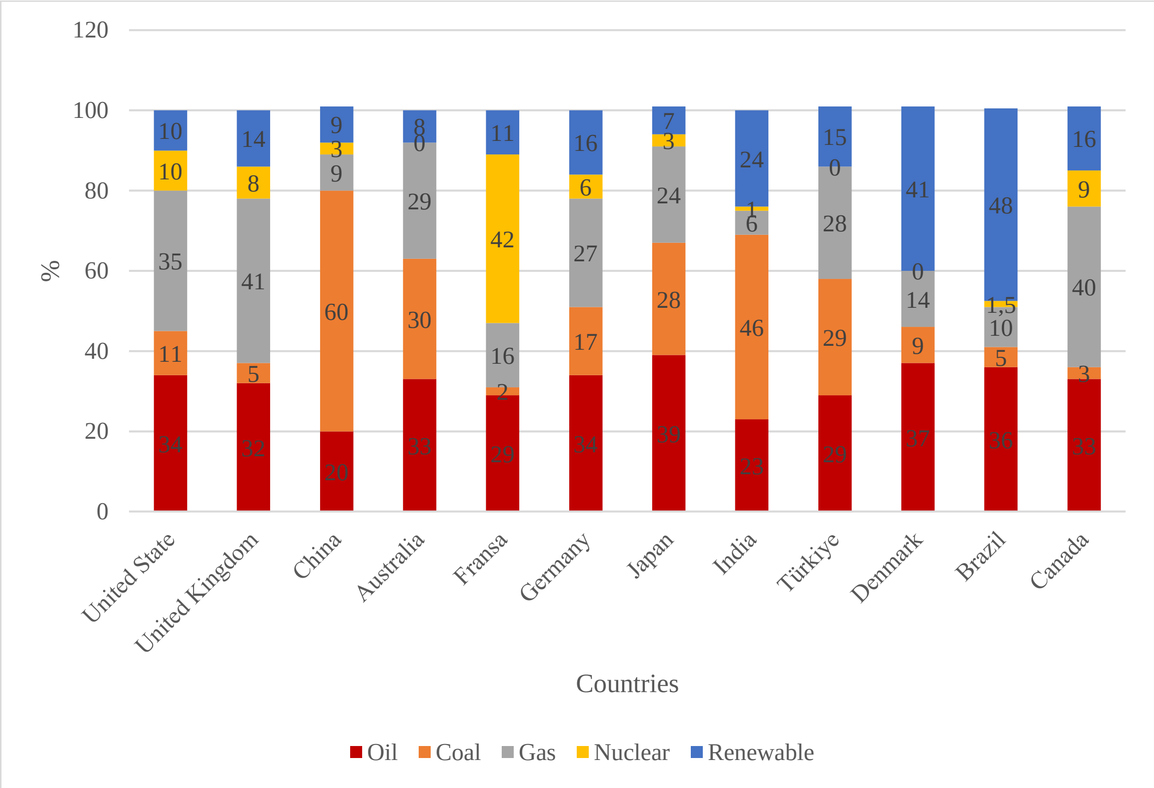


Figure2.21 Total energy supply distributions by countries [71]

Figure 2.21 illustrates the total energy supply distributions across countries. Oil, a fossil fuel, shows relatively consistent percentages, ranging from %20 to %39 among different nations. Notably, China stands out with the highest percentage of coal fuel, whereas France has the lowest. France leads globally in nuclear energy adoption, boasting the highest percentage. Denmark and Brazil are recognized for having the highest proportions of renewable energy sources compared to other countries. In Türkiye, the situation regarding renewable energy reflects an average percentile compared to global standards. However, Türkiye is actively striving to increase its share of renewable energy. The installed capacity of renewable energy is expanding consistently, underscoring Türkiye's commitment to enhance its renewable energy utilization in the face of evolving global energy trends.

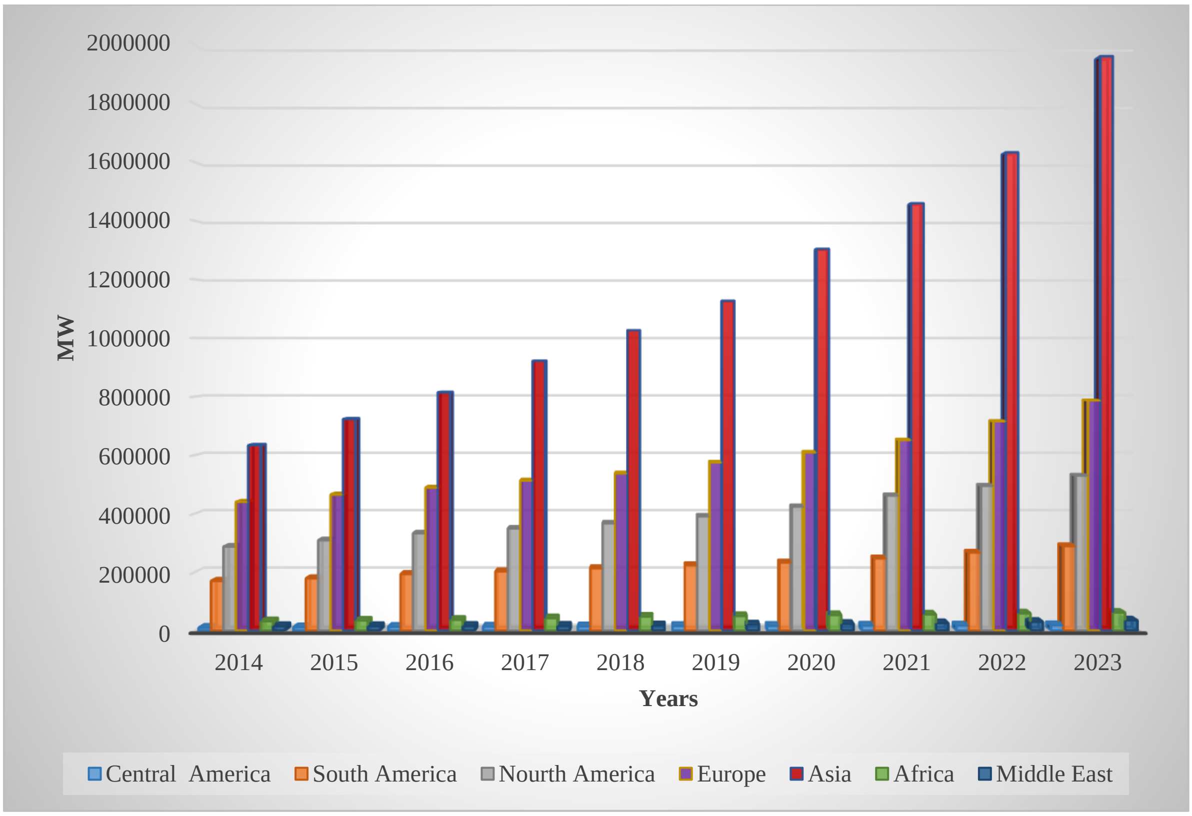


Figure2.22 Distribution of renewable energy capacities in continental by years [18]

As depicted in Figure 2.22, renewable energy capacities in Central World, Africa, and Central America continents are comparatively lower than those in other continents. Asia stands out with significantly higher capacity rates compared to others. Moreover, across each continent, there has been a noticeable increase in renewable energy capacities since 2014.

2.5 Renewable Energy-Focused Developments in Türkiye

Geopolitical positioning plays a pivotal role in shaping countries' identities, potential for evolution over time, and pathways to future development. Türkiye stands out globally as a rare nation bridging two continents and maintaining close ties with Africa. Its strategic location serves as a crucial link between the Western and Eastern worlds, historically hosting some of the most influential civilizations. The country's political and economic dynamics significantly influence the international energy landscape, impacting the global energy market. Türkiye's proximity to major oil and natural gas reserves, coupled with its strategic position as a transit hub between Europe and the East, underscores its geopolitical importance as a significant player. These factors collectively contribute to Türkiye's influential role on the global stage [72].

Türkiye's reliance on fossil fuels, coupled with its strategic position in energy transmission networks, grants it substantial bargaining power. To reduce dependence on foreign energy sources and enhance energy self-sufficiency an essential component of economic stability Türkiye is actively increasing the share of renewable energy resources in its energy portfolio. These initiatives are crucial steps toward bolstering Türkiye's energy security and promoting long-term sustainability [72].

The first legislation regarding renewable energy in Türkiye is Law No. 5346, enacted in 2005, which focuses on the utilization of renewable energy resources for electricity generation. This law established a legal framework encompassing production, utilization, free market mechanisms, and the goal of increasing renewable energy's share in total energy consumption. Two years later, the law underwent its first amendment alongside the introduction of the "Energy Efficiency Law" (Law No. 5627). This amendment provided additional incentives for electricity generated from renewable sources and implemented a base price mechanism for purchasing such electricity. Moreover, it streamlined procedures for obtaining exemptions from requirements like company establishment and licensing. Subsequently, Law No. 5346 was further revised in 2011 through Law No. 6094, solidifying the support mechanism for renewable energy in electricity production. These legislative efforts aim to leverage advanced technologies to reduce the cost of electricity generated from renewable sources [17].

Renewable energy resources play a crucial role in ensuring energy supply security. The 2023 targets for these resources have been set under the "Electricity Energy Market and Supply Security Strategy Document," which is an annex to the decision of the High Planning Council numbered 2009/11. These goals aim to

- Increasing the share of renewable energy sources in electricity generation to %30.
- Harnessing the entire hydroelectric potential for electricity generation.

- Scaling up installed wind energy capacity to 20,000 MW.
- Developing 600 MW of geothermal potential.
- Implementing necessary regulations to utilize solar and other renewable resources effectively.
- Through measures aimed at promoting the use of domestic and renewable energy sources, the objective is to decrease the share of natural gas in electricity generation to below %30 [17].

Currently, energy consumption in our country is rising alongside population growth. Consequently, there has been a noticeable increase in the adoption of renewable energy sources compared to previous years. While a significant portion of our electricity is still generated from coal and natural gas, there is a growing emphasis on renewable energy projects. Solar and wind energy, in particular, play a pivotal role in our electricity production landscape [73].

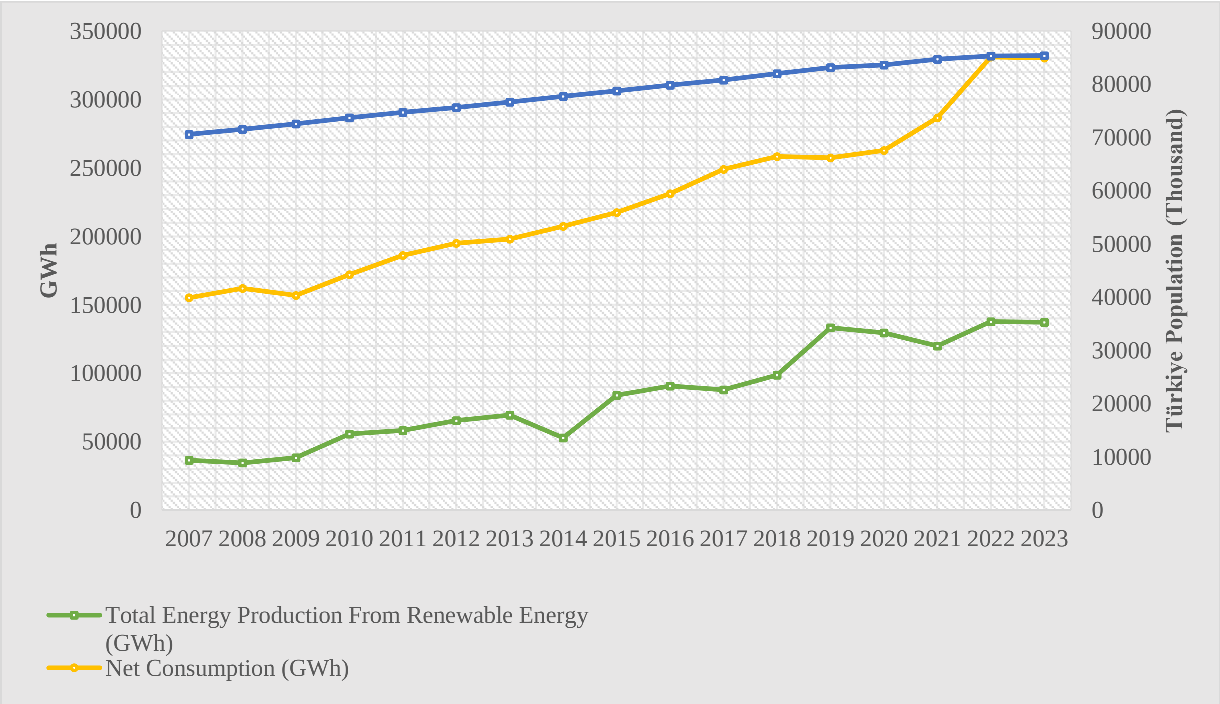


Figure2.23 The relationship between energy production, consumption and population in Türkiye [74-76]

Table 2.3 According to total energy production, total installed power, and installed power capacity usage in Türkiye [74-77]

Year	Total Energy Production MWh/year	Total Installed Power MW	Installed Power Full-Time Working	Installed Power Capacity Usage %
2011	229395100	52 911.1	463501236	49.4918
2012	239496800	57 059.4	499840344	47.91466
2013	240153953	64 007.5	560705700	42.83066
2014	251962817	69 519.8	608993448	41.37365
2015	261783303.5	73 146.7	640765092	40.8548
2016	274407749	78 497.4	687637224	39.90589
2017	297277522.9	85 200.0	746352000	39.83074
2018	304801885	88 550.8	775705008	39.29353
2019	303897559.6	91 267.0	799498848.1	38.01101
2020	306703092.4	95 890.6	840001715.6	36.5122
2021	331491000	99 819.6	874419808.4	37.90982
2022	324517000	103 541.2	907020912	35.77834
2023	324793000	107 000.0	937320000	34.65124

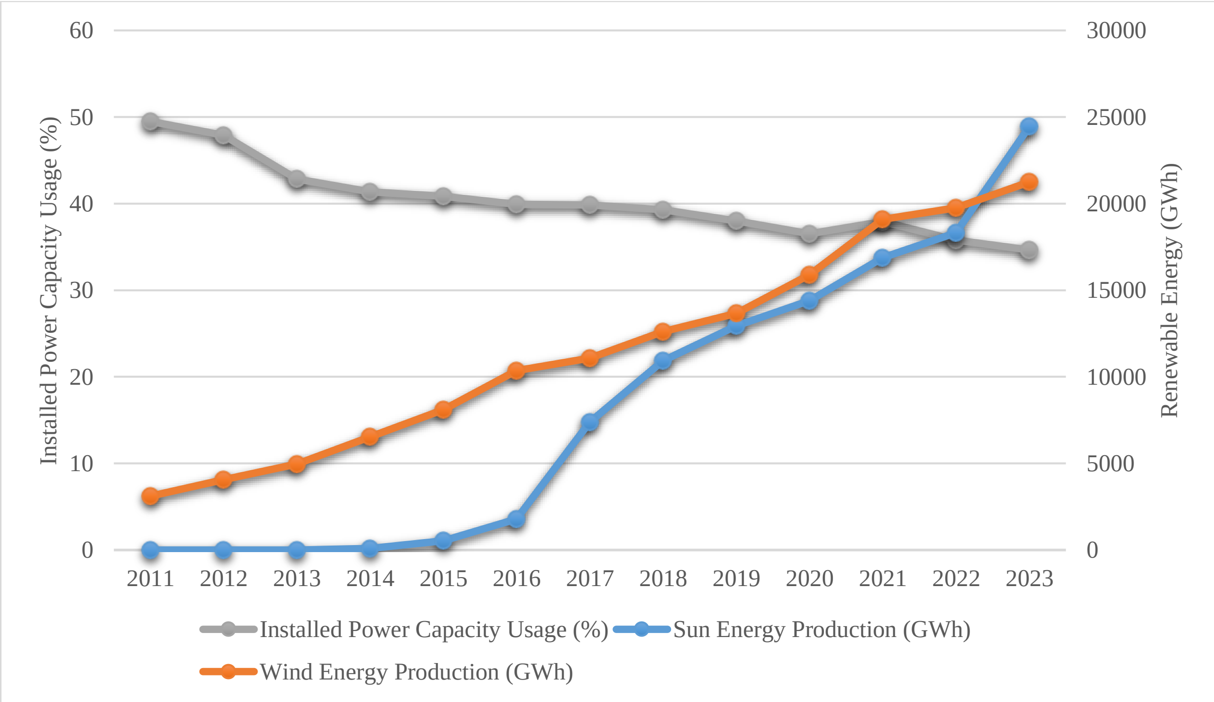


Figure 2.24: The relationship between installed power capacity usage (%), sun and wind energy production in Türkiye [74-77]

When Figure 2.23 is examined, it is seen that both net energy consumption and population are increasing. However, production is also increasing in parallel with the potential of renewable energy resources. This trend is further highlighted in Figure 2.24, which shows the increasing interest in renewable energy as well as the increase in installed capacity over the years. When Figure 2.24 linked to Table 2.3 is examined, it highlights a remarkable trend in which production exceeds consumption and therefore the capacity ratio in installed power decreases. Given the potential of renewable energy sources, there is a clear imperative to continue installing more renewable energy plants to meet energy consumption demands while ensuring consumption remains below production levels.

The Worldwide Fund for Nature, a prominent global conservation organization, in collaboration with Bloomberg New Energy Finance and the European Climate Foundation, has conducted extensive research on whether Türkiye's increasing power demand, driven by economic growth, can be met sustainably with a blend of environmentally friendly and cleaner energy sources. Their analysis concludes that by 2030, Türkiye has the potential to fulfill approximately %50 of its energy needs from renewable sources, predominantly solar, wind, and hydroelectric power. The report outlines specific projections: 5,000 MW of new hydroelectric capacity is expected to be operational by 2022, with no further additions planned for the remainder of the decade; a 4.8 GW nuclear plant, consisting of four reactors, is slated for commissioning by 2025; and annual installations of 800 MW of wind and 650 MW of solar energy are anticipated up to 2030. These initiatives are projected to significantly increase Türkiye's energy capacity, as indicated by their findings [78].

CHAPTER 3

3. HYDROGEN PRODUCTION

Hydrogen serves as a crucial energy carrier across various industries and energy sectors. Traditionally, hydrogen production has heavily relied on non-renewable sources such as hard coal, crude oil, and natural gas. The predominant method for industrial hydrogen production is steam methane reforming, which accounts for about half of the current hydrogen demand and boasts high efficiency. However, this process generates carbon emissions. In contrast, water electrolysis offers a cleaner alternative by producing hydrogen without fossil fuels. This method utilizes electrical energy, which can be sourced from surplus energy or directly from renewable sources like solar or wind power. Electrolysis occurs within electrolysers comprising two electrodes: the positive (anode) and negative (cathode) electrodes. Oxidation occurs at the anode, while reduction takes place at the cathode, facilitating the separation of hydrogen from water molecules. This sustainable approach is crucial for reducing carbon footprints and advancing towards renewable energy integration in hydrogen production [79].

The overall reaction of the water electrolysis process can be written as:

$$H_2O = H_2 + 1/2O_2 \quad [79]$$

3.1 Hydrogen Technologies

In recent years, the global increase in energy consumption has paralleled the growth in population. The transportation sector, reliant primarily on fossil fuels, faces diminishing reserves worldwide. This trend is compounded by escalating CO_2 emissions, environmental degradation, and rising costs associated with fossil fuels, prompting a search for alternative energy sources. Hydrogen, the most abundant element in nature, exists in a diatomic form and is widely applicable due to its versatility. It is odorless, tasteless, and colorless, with minimal flammability. As a clean energy carrier, hydrogen boasts a high energy content per unit mass. Moreover, it burns at a high temperature without producing toxic by-products; combustion results solely in water vapor. Comparatively, hydrogen yields 1.13 times more energy than petroleum products. Hydrogen's applications extend to fuel cells, which generate electricity in engines and gas turbines. This capability positions hydrogen as a pivotal player in advancing clean energy solutions for a sustainable future [80].

In terms of energy efficiency, resource diversity, and environmental impact, hydrogen stands out as a superior alternative to fossil fuels. Hydrogen can be derived through various methods such as gasification of hydrocarbon compounds, steam reforming, and electrolysis. Notably, electrolysis is particularly advantageous as it utilizes renewable electricity to produce hydrogen, rendering it an inexhaustible energy source. Hydrogen is widely regarded as a clean fuel due to its chemical and physical properties, which have minimal environmental impact. It burns cleanly, producing only water vapor as a byproduct, and does not contribute to greenhouse gas emissions or air pollution. This characteristic makes hydrogen a promising solution for reducing our dependence on fossil fuels and advancing towards a more sustainable energy future [80].

In light of regional and global developments, a greater emphasis on renewable energy is essential, prioritizing sustainability. It is crucial to enhance the adoption of renewable energy through the utilization of safe, efficient, and environmentally friendly technologies that support sustainable practices. By doing so, we can effectively mitigate environmental impacts and pave the way towards a more sustainable future [11].

To achieve this goal, it is paramount to decrease our nation's reliance on foreign energy sources. Developing domestic and national technologies for electrolyzers and fuel cells, leveraging our existing advantages, is crucial. This approach enables the production of green hydrogen and its integration across various sectors of the economy. Hydrogen production and consumption methods and applications are shown in Figure 3.1 [11, 80].

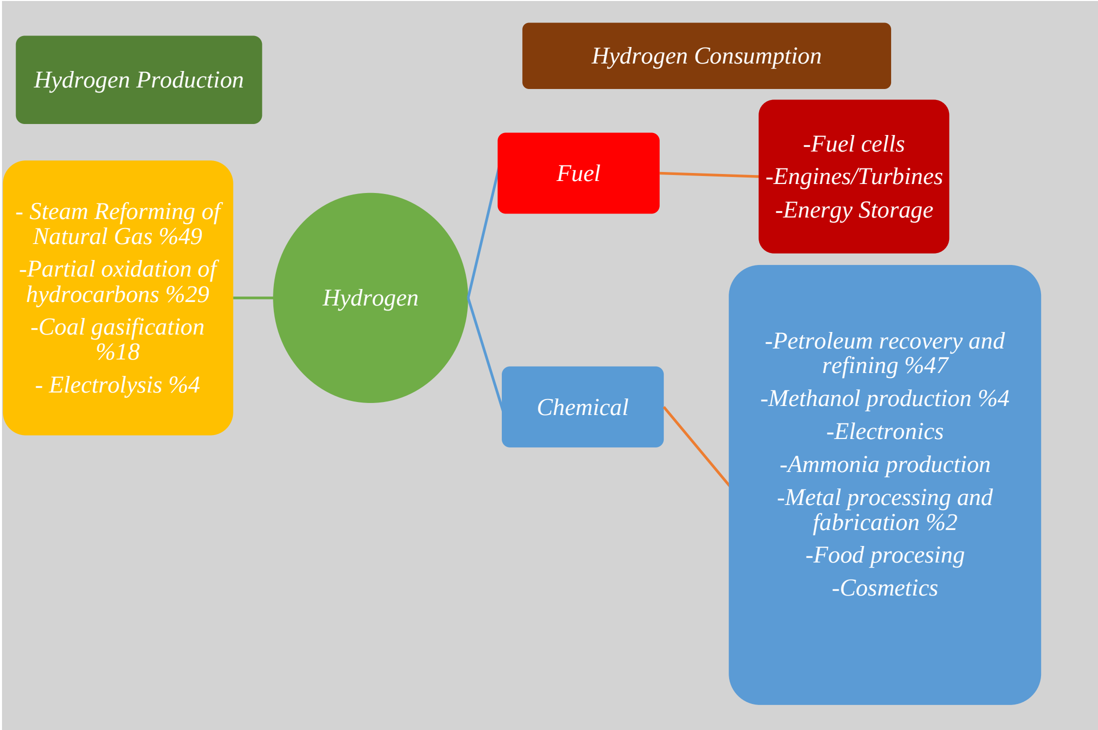


Figure 3.1 Major hydrogen production methods and applications [81]

3.1.1 Hydrogen Transmission and Distribution

Given its properties, hydrogen is recognized as a potent energy carrier. Hydrogen does not exist independently in nature but can be produced from various sources. Once hydrogen is produced from these sources, it needs to be transported to distribution points and stored for future use [82].

Transporting hydrogen requires a well-established distribution network. Hydrogen can be transported in different forms: through pipelines, tube trailers, cylinders in gaseous form, or cryogenic tanks in liquid form. For long distances, hydrogen is typically transported in super-insulated tanks or rail cars in its cryogenic liquid form, which is then vaporized upon delivery to end users. Alternatively, high-pressure cylinders are suitable for shorter distances [82].

Storing hydrogen is crucial due to its wide application across various sectors. However, hydrogen's properties pose challenges as it is a light gas that occupies significant volume even in small quantities. There are several methods for storing hydrogen: as pressurized gas, liquid, and cryogenically. Additionally, hydrogen can be stored in solid form or chemically through substances like sodium borohydride ($NaBH_4$), aluminum hydride (AlH_3), ammonia borane ($NH_3 – BH_3$), and liquid organic compounds. Each method offers distinct advantages depending on specific application requirements and infrastructure capabilities [12, 82].

3.1.2 Hydrogen Usage Areas and Sectors

Given the chemical properties of hydrogen, its applications are increasingly diverse across sectors, particularly in energy and chemicals. Additionally, hydrogen finds utility in advanced fields such as space programs, aviation, and transportation. As global energy demands continue to rise, there is a growing imperative to promote the production of environmentally sustainable hydrogen [12].

As global usage of hydrogen rises, its application in refining and chemical sectors is increasingly prevalent, yet the predominant method of hydrogen production remains fossil fuels. Hence, there is a pressing need to promote environmentally friendly, low-emission methods for hydrogen production [83].

Industries and governments, especially in the energy sector, must take proactive measures to formulate robust policies aimed at expanding environmentally friendly hydrogen production [83].

3.2 Colours of Hydrogen

Hydrogen production relies on primary energy sources, which determine its categorization into various types. "Green hydrogen" is produced using renewable energy sources, "blue hydrogen" from fossil fuels with carbon capture and storage (CCS) systems, "turquoise hydrogen" from fossil fuels without CO_2 emissions via processes like pyrolysis, "pink hydrogen" from nuclear energy, and "brown hydrogen" from natural gas reforming without CCS, also known as "gray hydrogen," or from coal gasification without CO_2 capture. Decarbonizing hydrogen production is crucial for meeting emission reduction goals. In Table 3.1, there are methods categorized according to primary energy sources [84]:

Table 3.1 Hydrogen color shades and their technology, cost, and CO2 emissions [81]

HYDROGEN COLOR	TECHNOLOGY	SOURCE	PRODUCTS	COST ($ KG/H2)	CO2 EMISSIONS
BROWN HYDROGEN	Gasification	Brown coal (lignite)	H_2+CO_2	1.2-2.1	High
BLACK HYDROGEN	Gasification	Black coal (Bituminous)	H_2+CO_2	1.2-2.1	High
GREY HYDROGEN	Reforming	Natural gas	H_2+CO_2 (released)	1.02.2001	Medium
BLUE HYDROGEN	Reforming and carbon capture	Natural gas	H_2+CO_2 (captured 85-95%)	1.5-2.9	Low
GREEN HYDROGEN	Electrolysis	Water	H_2+CO_2	3.6-5.8	Minimal

In Table 3.1, hydrogens are classified according to technology, source, production, cost and CO_2 emissions. Accordingly, the emission levels of coffee and black hydrogens are high, while the emission levels of green hydrogen are low.

3.3 Renewable Energy-Powered Hydrogen Production

Hydrogen can be sourced from a variety of energy inputs, including both fossil fuels and renewable sources. Historically, a significant portion of hydrogen production has relied on fossil fuels, but the environmental repercussions of this approach have rendered it unsustainable. Recent studies underscore the potential of alternative energies in fostering environmentally viable hydrogen production from renewable sources. The advancement of renewable energy technologies has facilitated the emergence of more efficient production systems tailored to this purpose [85].

3.3.1 Solar Energy For Hydrogen

The sun stands out as a crucial resource for fulfilling the world's distinctive energy requirements. It serves as a clean alternative fuel, promising affordable electricity and paving the way for advancements in solar hydrogen production. Solar energy facilitates the conversion of sunlight into hydrogen through innovative renewable energy storage techniques, offering a dependable and cost-effective solution. This approach not only enables the production of hydrogen without greenhouse gas emissions but also underscores the practicality and sustainability of solar hydrogen [85, 86].

Photovoltaic (PV) power generation involves converting solar energy directly into electricity by altering the electrical potential of materials through mechanical pressure. Conversely, photothermal power generation employs reflector arrays to capture solar energy, using heat exchangers to generate heat for driving steam turbines. This process enables power generation through steam, which is then used to produce hydrogen via water electrolysis a method supported by various contemporary technologies. Among these, alkaline water electrolysis and proton exchange membrane technologies are currently prominent for hydrogen production. Proton exchange membrane technology, particularly noted for its compatibility with renewable energy sources, stands out as a preferred option. As seen in Figure 3.2, in photovoltaic systems, direct current (DC) energy from renewable components must be converted to alternating current (AC) for hydrogen production. Afterwards, the current passes through the electrolyzer and hydrogen production is achieved. PV technology is recognized for its ease of maintenance, environmental friendliness, and absence of greenhouse gas emissions. Extensive research and measurements have been conducted throughout history to evaluate the efficacy of photovoltaic systems. These studies focus on sustainable hydrogen production using solar energy, exploring the integration of solar modules with electrolysis and quantifying hydrogen production levels. Furthermore, economic and thermodynamic assessments have affirmed the suitability of photovoltaic systems, leading to the development of optimized models. Consequently, photovoltaic systems are acknowledged for their capability to supply the requisite load and energy for electrolysis and hydrogen production, affirming their role in advancing renewable energy solutions [85, 86].

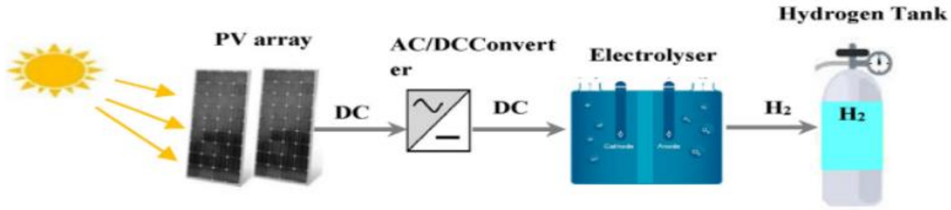


Figure 3.2 Shematic of solar hydrogen production [85]

Türkiye boasts significant solar energy potential, making it imperative to scale up investments in solar energy systems accordingly. A robust understanding of solar systems is crucial for their development in Türkiye, where planar solar collectors, widely used and ripe for advancement, play a pivotal role. Türkiye enjoys an average of approximately 7 hours of sunshine per day, totaling around 2741 hours annually. This abundant sunlight presents a substantial opportunity for energy consumption, particularly in buildings equipped with 4th generation district heating systems. Given hydrogen's role as an energy reservoir, solar energy assumes critical importance as a sustainable green energy source. The high solar energy potential across numerous provinces in Türkiye underscores its efficacy in producing green hydrogen. As such, leveraging Türkiye's solar energy abundance holds considerable promise for advancing sustainable energy solutions [57, 87].

3.3.2 Wind Energy For Hydrogen

The growing global interest in renewable energy and the concerted efforts of nations to expand their reliance on sustainable sources cannot be overstated. Among these, wind energy holds significant promise for electricity generation. Recognized for its reliability, cleanliness, and sustainability, wind power stands out as a preferred investment option provided challenges in managing wind energy systems are effectively addressed. As illustrated Figure 3.3, hydrogen production can be achieved by coupling wind energy with hydrogen processing equipment and a DC/AC converter. This process involves converting wind-generated electricity into hydrogen through water electrolysis for long-term storage. While wind energy installations are steadily increasing, a proportional rise in hydrogen production is anticipated to bring substantial benefits to our country [85].

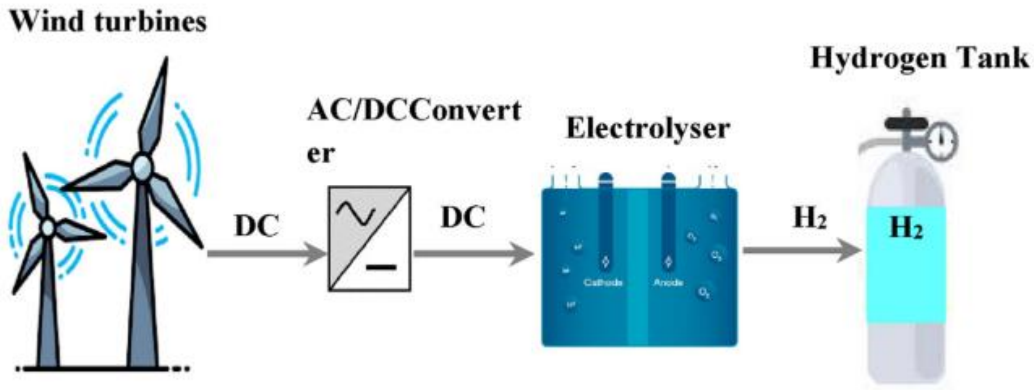


Figure 3.3 Schematic of wind hydrogen production [85]

Wind energy, as a renewable source, has outpaced other forms of renewable energy in its development. Numerous studies have thoroughly examined wind characteristics and the cost of wind energy estimation in Türkiye. These studies have calculated the annual average wind speeds across different regions of Türkiye, analyzed wind power density, and investigated average wind speeds in various parts of the country. They have consistently shown that Türkiye offers ample locations suitable for wind turbine installation. Furthermore, comparisons have been made between Türkiye's wind energy potential and that of European OECD countries. Based on extensive research, Türkiye stands out with a technical wind energy potential estimated at 83,000 MW, making it the leader among these nations in terms of wind energy capacity [88].

3.3.3 Geothermal Energy for Hydrogen

Hydrogen production from geothermal energy systems is increasingly favored in many countries due to its environmental responsibility and sustainability. Geothermal resources offer a compatible and straightforward approach to synthesizing hydrogen. This method supports a swift transition to economies driven by hydrogen-based technologies. Moreover, geothermal fluids can be utilized not only to generate electricity but also to heat water within geothermal power plant hydrogen generation systems. Efforts to reduce installation costs and enhance operational efficiency in geothermal energy systems could make these integrated systems an attractive option. Compared to other sources of hydrogen production, geothermal energy systems generally exhibit advantages such as minimal land use, high water discharge quality, and fewer environmental concerns. Direct comparisons across various parameters for hydrogen production sources can be challenging due to their diverse nature. Nonetheless, geothermal energy integrated with hydrogen generation systems holds promise for contributing significantly to sustainable energy solutions [89, 90].

Türkiye's geographical landscape, characterized by mountainous terrain and high altitudes, poses challenges for geothermal power plant installations, particularly in the Central, Eastern, and Southeastern Anatolian regions where hard underground structures hinder access to deep basins. Conversely, the Aegean region, notably Aydın, Denizli, and Manisa, stands out for its significant potential in hydrogen production. This area benefits from existing geothermal power plants and notably high underground temperatures compared to other parts of Türkiye. The production of hydrogen from geothermal sources requires access to high-temperature geothermal reservoirs. While establishing new geothermal power plants adjacent to existing ones may slightly increase installation costs, it enhances the green hydrogen production capacity of these cities. This strategic positioning underscores the Aegean region's advantageous position for advancing sustainable energy initiatives in Türkiye [89].

In Türkiye, the potential for geothermal energy remains largely untapped, with the Geothermal Energy Association (GEA) estimating that only %6.9 of its total potential has been utilized to date. When considering systems that utilize geothermal energy directly for hydrogen production, thermochemical cycles offer higher efficiency compared to electrolysis, which incurs greater energy losses [89].

3.3.4 Biomass Energy For Hydrogen

Hydrogen exists abundantly in nature but is typically bound within chemical structures. Biomass, for instance, is a complex material containing approximately %6 of its mass as hydrogen and about %25 as methane. Extracting hydrogen from these sources requires energy inputs. Water, for example, can be decomposed into its constituent elements through processes such as electrolysis or high-temperature reactions. Hydrocarbons and biomass can also undergo steam reforming reactions with water, which can be more efficient compared to water decomposition because the hydrogen bonded to carbon atoms requires less energy to extract. In some cases, biomass can be partially burned to generate heat, facilitating the conversion to pure hydrogen. Additionally, there are biological systems that can catalyze similar reactions using oxygen, light, and/or nutrients instead of heat, albeit with longer reaction times. The efficiency of converting biomass to hydrogen depends significantly on the hydrogen source and the specific requirements of the system, impacting overall performance [91].

Forest wastes play a crucial role in biomass utilization, especially given the significant financial impact of residues from wood processing plants like furniture factories. In Türkiye, agricultural and domestic solid wastes are also economically viable as energy sources, making biomass a key player in our country's energy production and consumption landscape. Türkiye boasts abundant sources of biomass energy, including various agricultural residues such as grain dust, wheat straw, and hazelnut shells. These residues can be effectively converted into gaseous products rich in hydrogen through steam gasification methods. This process harnesses the potential of biomass to generate hydrogen, contributing to sustainable energy solutions [92].

3.3.5 Hydropower Energy for Hydrogen

Global power consumption has surged dramatically in recent years, exacerbated by natural disasters and pandemics, which have profoundly impacted global energy dynamics. Consequently, scientists and researchers have intensified efforts to explore cleaner energy solutions. Renewable energy has emerged as a promising alternative due to its clean and environmentally friendly nature. However, the intermittent nature of renewable energy sources has spurred research into overcoming these challenges. Power-to-gas conversion technologies have garnered attention, often utilizing fossil fuel-based energies for storage in a suitable energy format. In contrast, hydroelectric power harnesses green energy, generating technically non-polluting electricity. This green energy is then converted into hydrogen, serving as a clean energy carrier. Assessing the cost-effectiveness of green hydrogen production necessitates a detailed analysis of electricity and electrolysis costs. While converting electricity to hydrogen may result in lower efficiency, advancements in electrolyzer and energy storage systems are poised to enhance feasibility. Exploring more efficient electrolyzer systems is crucial for optimizing this technology. In Türkiye, the hydroelectric energy potential holds promise for hydrogen production using alkaline electrolyzers (AWE) across various regions. Leveraging renewable energy from existing and planned hydroelectric power plants aligns with economic feasibility, considering installation costs. Efficiency assessments for electrolyzers should encompass multiple parameters. Given Türkiye's geographical features, including abundant rivers and coastal areas, regions like the Black Sea, Southeast, and Sivas-Kayseri-Adana corridor are deemed optimal for green hydrogen production from hydro energy. These areas benefit from favorable natural water flow conditions compared to other regions, bolstering the viability of hydrogen production initiatives [93].

3.4 Global Perspectives on Hydrogen: Current Trends and Future Outlook

As global energy consumption continues to rise, there is a growing interest in hydrogen as an energy source. This surge is particularly notable in the refining, chemical sectors, and other conventional applications, where hydrogen production is predominantly supported by fossil fuels. This reliance delays the transition to clean energy. However, future projections suggest that as hydrogen usage expands, new applications will also increase by 2030. Consequently, it is imperative for countries to implement policies that foster environmentally friendly hydrogen production. These policies will play a crucial role in advancing the global shift towards sustainable energy solutions [83].

Hydrogen usage has steadily increased worldwide, albeit with interruptions during 2019 and 2021 due to the COVID-19 pandemic and economic conditions. Despite this, hydrogen usage continues to rise today, although it has seen a decline in Europe, largely influenced by the energy crisis resulting from the conflict between Russia and Ukraine. Conversely, significant growth in hydrogen usage has been observed in the Middle East and northern parts of the Americas. China, holding the top position globally, maintains stable hydrogen usage levels [83].

The anticipated increase in hydrogen production aligns with its growing use as a pivotal energy source in the future. Developing various methods to harness hydrogen as a clean energy source is crucial, prompting countries to formulate robust policies for environmentally sustainable hydrogen production and utilization [83, 12].

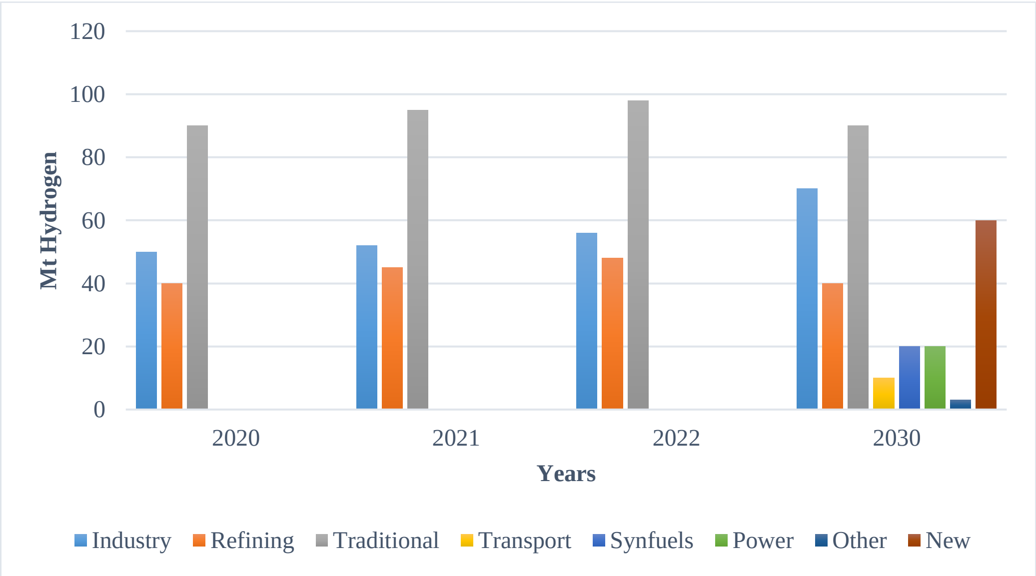


Figure 3.4 Hydrogen use according to sector [83]

Figure 3.4 shows the usage areas of hydrogen according to its sectors. Accordingly, the largest share stands out as traditional use and its value has not changed much during the year. After traditional, the largest sector in which hydrogen is used is industrial. If we look at the plans for 2030, it seems that 5 usage areas will join the industry. In fact, the focus is on 2030 in terms of new applications. Figure 3.5 shows the percentage of dehydrogen usage by region. The largest percentage area here belongs to China. China's determination of hydrogen-focused strategies and its efforts to benefit from hydrogen resources in a versatile way have made China active in the world hydrogen market.

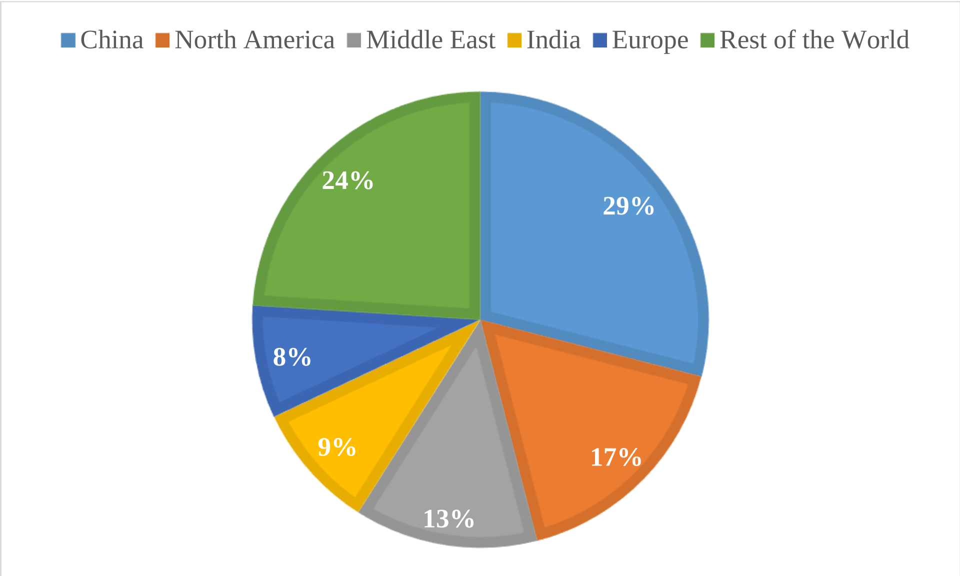


Figure 3.5 Hydrogen use according to region [83]

3.5 Cultivating Green Hydrogen: A Global Perspective

Climate change, burgeoning global population, and the subsequent surge in energy demand have spurred a quest for alternative energy sources. In this pursuit, the emphasis is shifting towards affordable and sustainable energy production, moving away from reliance on fossil fuels [94].

The rapid population growth in developing countries has necessitated a significant rise in electricity consumption. Consequently, while dependence on fossil fuels has become widespread, there is an imperative shift towards environmentally friendly and cost-effective energy sources. Embracing environmentally sustainable and economically viable energy sources is crucial for a healthier and better future, highlighting the growing significance of green hydrogen [94].

Green hydrogen stands as a pivotal sustainable energy source for our future, primarily due to its environmentally benign production process that eliminates greenhouse gas emissions. Produced via electrolysis, green hydrogen harnesses clean energy sources like wind, solar, and hydropower. These natural sources not only ensure minimal environmental impact but also offer cost-effectiveness, making them highly preferable options [12, 94].

Incorporating policies that address climate change and reduce the greenhouse gas impact of fossil fuels is crucial for meeting global energy demands. In this context, green hydrogen emerges as a preferred alternative energy source due to its robust energy potential, sustainability, and indirect presence in nature [12, 94].

According to European Union plans, hydrogen consumption is projected to surpass other consumption rates by 2050. Hence, it is imperative for countries to formulate a clear strategy and embrace sustainable hydrogen sources. In line with this objective, European Union countries aim to diminish their reliance on fossil fuels and produce 10 million tons of green hydrogen by 2030. Reflecting governmental policies until 2030, the demand for low-emission hydrogen production is estimated to reach approximately 30 million tons [12, 83].

Figure 3.6 shows the total electrolyzer capacity globally in 2023. As of 2022, global electrolyzer capacity has exceeded 0.5 GW, and by 2023, it has surpassed 2 GW. Projections indicate that by the end of 2030, planned electrolyzer capacity is expected to soar to approximately 175 GW, with potential for further expansion if green hydrogen receives enhanced support from countries during this period. Europe is poised to dominate this capacity, while significant increases in electrolyzer projects are anticipated in Latin America and Australia. In the United States, hydrogen production includes a mix of natural gas, but green hydrogen is increasingly utilized in sectors such as steel production and refineries. By 2050, around %77 of green hydrogen is earmarked for electricity consumption. China and several other countries are actively advancing electrolyzer technologies through governmental initiatives. Moreover, North America and Asia are pursuing numerous projects aimed at utilizing green hydrogen in electricity generation, heat production, industrial applications, and transportation, promoting renewable, low-carbon energy solutions. Concurrently, substantial efforts are underway globally concerning hydrogen distribution, storage, and safety protocols [83, 85, 95, 96].

Figure 3.7 shows the planned electrolyzer capacities by country until 2030. In Europe, countries like Denmark, Spain, the Netherlands, and Germany are leading supporters of hydrogen production through electrolysis. Germany, for instance, aims to generate 100 TWh of electricity by 2030 using a 5 GW electrolyzer capacity, predominantly supported by wind energy to bolster its renewable energy portfolio. By 2030, Australia anticipates reaching an electrolyzer capacity of approximately 50 GW, targeting around 6 Mt of green hydrogen production through electrolysis. Meanwhile, the Netherlands and Spain are planning for an electrolyzer capacity of about 4 GW each by 2030. China has made significant strides in hydrogen production, with ambitious plans backed by government support for future projects. China's strategy includes minimizing energy recovery losses and achieving %30 of energy demand from renewable sources, aiming to achieve a robust 38 GW electrolyzer capacity by 2030. In Canada, more than half of the energy demand is projected to be met by renewable sources by 2035, with Canadian-produced hydrogen exported to countries such as Japan, the United States, and China. France, targeting renewable sources to satisfy approximately half of its energy demand by 2030, plans to integrate green hydrogen into residential energy by 2050 [12, 83, 85].

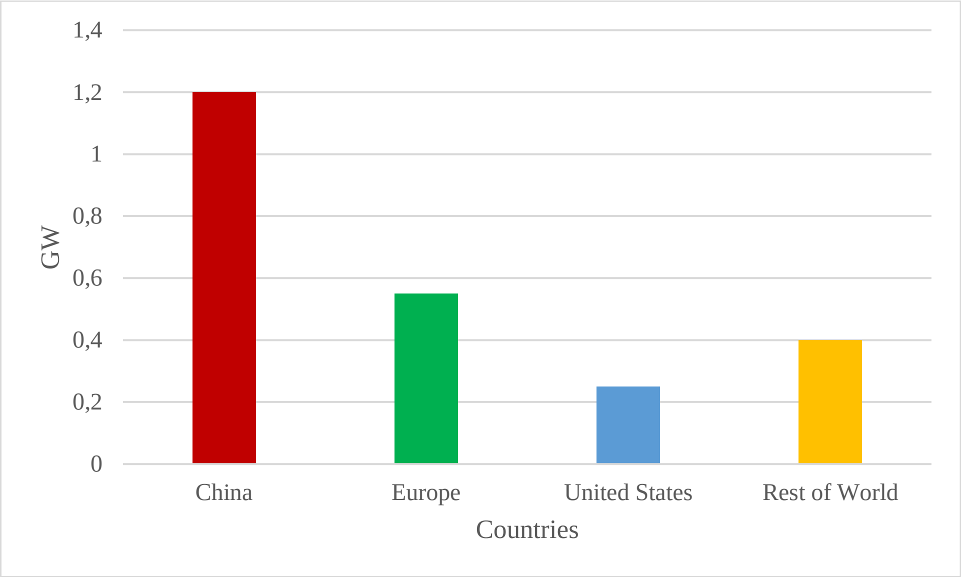


Figure 3.6 Total Electrolyzer Capacity in 2023 (GW) [83]

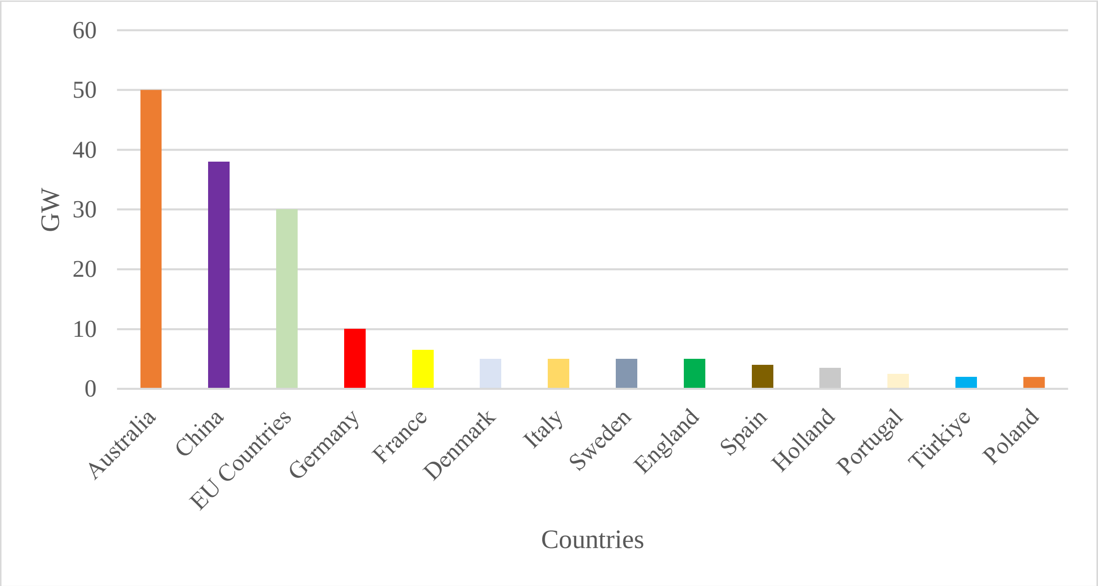


Figure 3.7 Projected Total Electrolyzer Capacity in 2030 (GW) [12]

3.6 Current Situation of Green Hydrogen in Türkiye

As the population in Türkiye continues to grow, so does the demand for energy. Türkiye's strategic location near natural gas and oil reserves necessitates foreign support to meet its energy needs, primarily sourced from fossil fuels like natural gas and oil. In recent years, however, there has been a shift towards renewable energy sources to ensure both environmental efficiency and sustainable energy production. With ample renewable energy potential due to its geographic advantages, Türkiye stands poised to capitalize on resources such as solar, geothermal, and wind energy. Government support could significantly bolster interest and investment in these renewable energy sectors, paving the way for a more sustainable energy future [12, 97].

In Türkiye, the initiative to promote hydrogen utilization began with its recognition as an alternative fuel, officially published in the gazette in 2007. Subsequently, in 2011, comprehensive research was conducted on hydrogen's potential in fuel consumption, leading to the issuance of regulations pertaining to hydrogen-fueled vehicles. At the 2020 hydrogen conference, a pivotal agenda emphasized the imperative for increased adoption of renewable energy sources and a reduction in carbon emissions within heat technologies. Hydrogen plays a crucial role in carbon mitigation efforts and holds significant promise for energy transmission and storage. Thus, integrating green hydrogen into Türkiye's energy strategy, particularly in the manufacturing and transportation sectors, emerges as a critical component moving forward [12, 97].

In Türkiye, the abundant boron mines and hydrogen sulfide reserves are considered pivotal for advancing hydrogen energy initiatives. Boron, particularly crucial for hydrogen storage, warrants further encouragement in its utilization. Moreover, hydrogen's prominence in the battery technology of domestically manufactured TOGG vehicles underscores the potential for expanding its application in automotive batteries. Shifting towards boron from lithium in batteries holds significance for enhancing efficiency and environmental sustainability. Türkiye aims to pioneer these efforts and is anticipated to achieve significant milestones in both domestic and international arenas through proactive hydrogen utilization strategies [12, 97].

The sustainability and reliability of energy are crucial for enhancing the quality of life, making hydrogen energy pivotal for Türkiye. Studies conducted by the Presidential Science, Technology and Innovation Policies Board underscore the strategic importance of hydrogen technologies. Türkiye aims to reduce its dependence on foreign energy by advancing hydrogen technologies and aims to establish a strong position in exporting these technologies. Moreover, Türkiye has set a target of achieving zero emissions by 2053, with plans underway to achieve this through a blend of hydrogen and synthetic methane.The South Marmara Hydrogen Coast Platform, an industrial initiative geared towards achieving zero carbon emissions by 2053, holds significant promise for substantial hydrogen production. This project not only boosts Türkiye's hydrogen economy but also facilitates a transition towards a greener hydrogen-centric lifestyle [12, 97, 98].

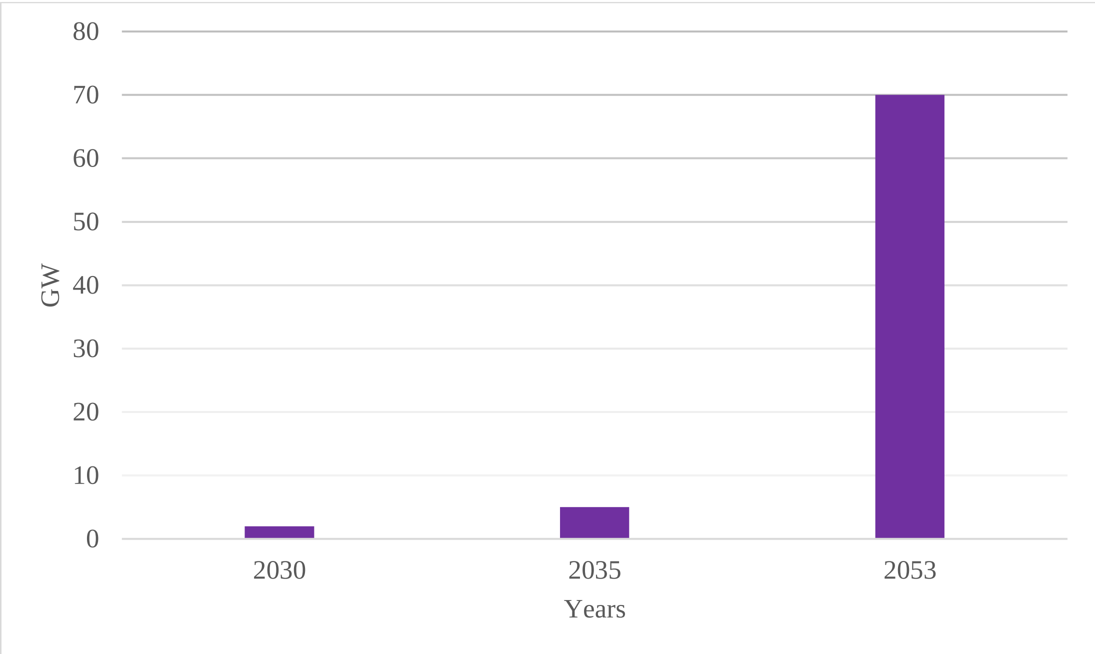


Figure 3.8 Projected Electrolyzer Capacity in Türkiye(GW) [12, 83]

As indicated in Figure 3.8, the electrolyzer capacitor values planned by Türkiye over the years are determined as 2 GW in 2030, 5 GW in 2035 and 70 GW in 2053. If the necessary research and studies are carried out, correct and reliable strategies will be determined and this success will be inevitable.

3.7 Water Electrolysis Technologies

Jules Verne famously coined water as the coal of the future in his novel "The Mysterious Island." Early experiments in water electrolysis date back to 1789 when researchers utilized an electrostatic machine to discharge electricity onto gold electrodes submerged in water. Alessandro Volta's invention of the Voltaic stack in 1800 marked a significant advancement, employing copper electrodes for electrolysis experiments. Subsequently, J. Ritter successfully conducted real water electrolysis, collecting both oxygen and hydrogen, although industrial-scale electrolysis faced engineering and technical challenges, delaying widespread adoption until the late 1800s. Water, an abundant and invaluable resource, holds the potential for hydrogen to become the purest form of energy if derived from renewable sources. Hydrogen production methods include electrolysis, thermolysis (or thermochemical water splitting), and photo-electrolysis (or photoelectrochemical water splitting). The general structure of the electrolysis system consists of the power supply, drying system, separator, electrolyzer stack, and pump as seen in Figure 3.9. Electrolysis involves splitting water into its constituent elements, a process opposite to that of a fuel cell, which uses hydrogen and oxygen to generate electricity and water. This method requires a cost-effective supply of water and electricity, making it ideal for hydrogen production. Electrolysis is an endothermic process, necessitates electrical energy input for the separation of hydrogen at the cathode and oxygen at the anode. As efforts continue to harness renewable energy sources, electrolysis stands out as a pivotal technology for producing clean hydrogen, paving the way for sustainable energy solutions. The general development of the water electrolysis system over the years is shown in Figure 3.10 [99].

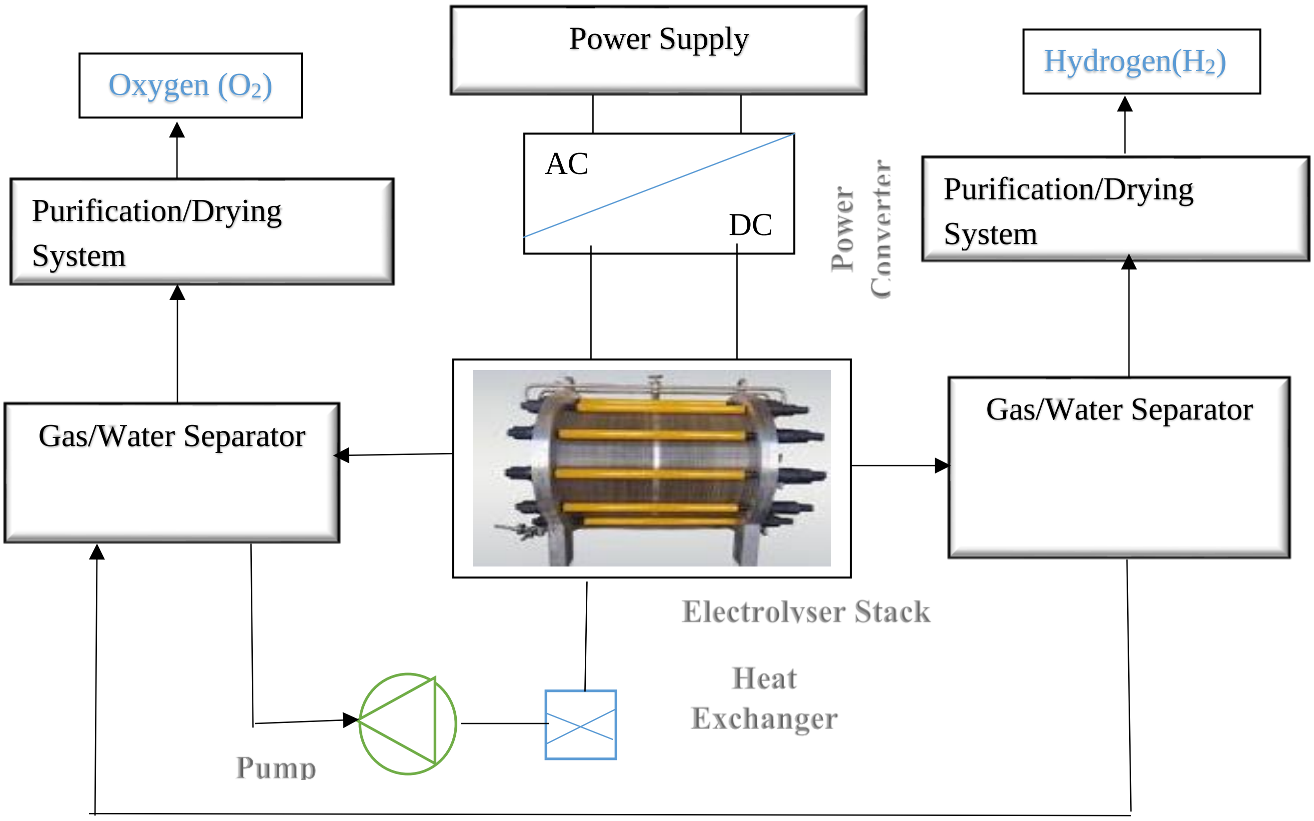


Figure 3.9 System structure of electrolyser [99]

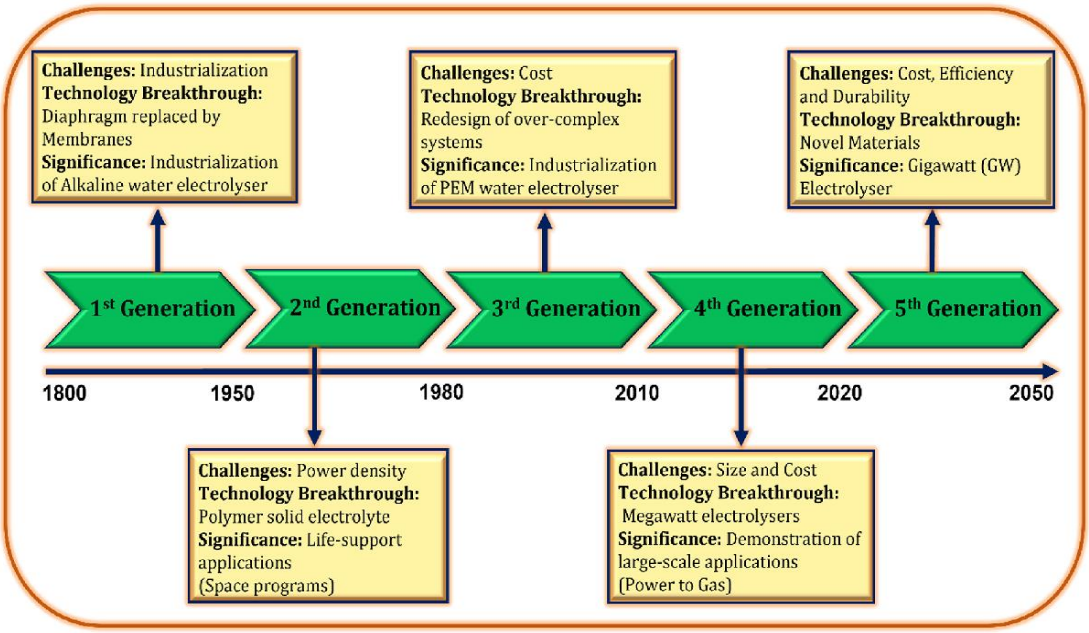


Figure 3.10 Generations of water electrolysis development [81]

Using electricity derived from renewable sources to produce hydrogen represents a promising pathway toward a cleaner and more sustainable world. Hydrogen, recognized as a clean and efficient energy carrier boasting the highest gravimetric energy density, holds immense potential to transform our energy landscape. The development of water electrolysis technology for hydrogen production from renewable sources underscores its pivotal role as a sustainable energy solution, aligning with global environmental goals. Despite its promise, the economic viability of water electrolysis remains a challenge due to high energy input costs and efficiency concerns compared to conventional methods. Water electrolysis involves a thermodynamically challenging reaction, as indicated by the positive Gibbs free energy, necessitating overcoming significant kinetic barriers. Effective electrode design plays a crucial role in minimizing these barriers and improving overall efficiency. To enhance water electrolysis efficiency, there is a pressing need to advance electrocatalysts that are highly active, possess low charge transfer resistance, and are cost-effective in terms of energy consumption. Based on the separation mechanism and operational conditions, water electrolysis can be classified into three main categories: alkaline electrolysis using OH- ions, proton exchange membrane electrolysis utilizing H+ ions, and solid oxide electrolysis employing O_2- ions. These classifications delineate the type of electrolyte used and the specific ionic conduits involved in the electrolysis process. As research and development in electrolysis technologies progress, innovations in electrocatalysts and electrolysis systems will be crucial in realizing the full potential of hydrogen as a sustainable energy carrier, driving forward the transition to a cleaner and greener energy future [100].

There are several electrolysis technologies utilized for hydrogen production, each with distinct characteristics and applications. These include Solid Oxide Electrolyzer Cells (SOEC), Proton Exchange Membrane (PEM) cells, Alkaline Water Electrolysis (AWE), and Anion Exchange Membrane (AEM) electrolysis. AWE, being one of the oldest technologies, has established itself as a commercially viable option. It typically employs KOH or NaOH aqueous solutions as electrolytes within an alkaline environment. Operating at temperatures between 60 and 80 degrees Celsius under 30 bar pressure, AWE requires robust and cost-effective catalysts suitable for large-scale electrolysis plants. A separator is used to facilitate the crosswise movement of bubbles, although it presents challenges such as lower hydrogen purity and pressure operating limits. Its inflexibility in adapting to fluctuating input conditions and slower response times are notable drawbacks. PEM electrolyzers utilize a proton exchange membrane composed of a solid polymer electrolyte. During operation, hydrogen and oxygen combine at the cathode side, with the membrane facilitating the passage of hydrogen protons while splitting water. PEM technology stands out due to recent advancements, increasing market share, and its capability to produce high-purity hydrogen with efficient cooling mechanisms. These electrolyzers are compact, equipped with membrane electrode assemblies, and are well-suited for integrating renewable energy variability. Despite their advantages, PEM electrolyzers are generally more expensive due to their use of precious metal catalysts. They operate effectively at temperatures between 50 and 80 degrees Celsius and below 200 bar pressure, achieving higher current densities than AWE and yielding superior purity in hydrogen gas. PEM systems are characterized by their rapid response times and flexibility in varying operational conditions. In summary, while AWE offers a proven and cost-effective solution suitable for stable operating environments, PEM electrolyzers represent a technologically advanced option capable of high-purity hydrogen production and adaptability to dynamic renewable energy inputs, albeit at a higher cost. Both technologies play significant roles in advancing hydrogen production for a sustainable future, each addressing specific industrial and environmental demands with distinct advantages and considerations [86, 101].

In the 1980s, Donitz and Erdle initiated pioneering work on Solid Oxide Electrolyzers (SOEC), using a tubular electrolyte supported under a project. SOEC gained significant attention for their ability to produce hydrogen efficiently at low voltages, converting electrical energy into chemical energy. Although SOEC technology is still under development, research has surged over the past decade, with global companies, research centers, and universities actively engaging in this field. SOEC operate at extremely high temperatures and hold potential for significantly higher efficiency compared to PEM and alkaline electrolyzers. This process, known as high-temperature electrolysis or steam electrolysis, utilizes a solid ceramic material as the electrolyte. Electrons from the external circuit react with water at the cathode, forming hydrogen gas and negatively charged ions. Oxygen migrates through the ceramic membrane and undergoes a reaction at the anode, producing oxygen gas and generating electrons for the external circuit. Despite their promising attributes, SOEC are less technologically mature than other electrolyzer types. Several electrolyzer technologies, such as photoelectrolysis, show potential for future improvements despite current limitations in efficiency and cost-effectiveness. Photoelectrolysis harnesses sunlight directly to split water molecules without requiring external electricity. However, its reliance on semiconductors that are still in development poses challenges to widespread adoption. In summary, while SOEC offer high efficiency and potential advancements in hydrogen production technology, ongoing research and development efforts are crucial to overcoming current technological barriers and enhancing their practical application in sustainable energy systems [86, 101].

Anion Exchange Membranes (AEM) are designed to operate effectively under alkaline conditions, making them suitable for utilizing cost-effective, non-noble metal electrocatalysts for both Oxygen Evolution Reaction (OER) and Hydrogen Evolution Reaction (HER). However, the electrolysis efficiency of AEM is currently lower compared to Proton Exchange Membranes (PEM), prompting the exploration of new materials and advancements in membrane electrode assemblies to enhance performance. Optimizing AEM is crucial to achieving more flexible operating parameters and improving overall efficiency in electrolysis processes [102].

3.7.1 Alkaline Water Electrolysis (AWE)

Research on Alkaline Water Electrolysis (AWE) has a long history, spanning several decades. Modeling studies for AWE began in the 1990s and since the early 2000s, numerous research papers and articles have contributed to understanding its electrochemical processes. While there has been a slight decline in electrochemical modeling studies in recent years, research on thermal dynamics and gas purity models has gained momentum. The focus on gas purity has intensified due to its critical importance in AWE, especially when integrating with intermittent renewable energy sources where stability is a concern. One effective method to mitigate Ohmic losses in AWE is to position the electrodes directly adjacent to the separator with zero clearance, a technique adopted by manufacturers since the 1950s to enhance efficiency and performance [103, 104].

In alkaline water electrolysis (AWE) systems, maintaining a low operating current density is crucial to minimize cell overvoltage, which tends to increase with higher current densities. Past studies have focused on addressing this issue by proposing improved electrodes designed for new manufacturing processes. Furthermore, advancements include the development of zero-gap cell designs that reduce the distance between electrodes and separators, thereby optimizing the active field effect and mitigating ohmic voltage losses caused by the liquid electrolyte. Recent reviews have delved into the electrochemical reactions occurring within AWE cells and the exploration of new materials to enhance overall batch performance. Various studies have analyzed electrolysis performance, initially considering temperature variables and later developing performance models that incorporate additional operational parameters such as pressure, electrode-separator distance, and electrolyte concentration. Additionally, multi-physics models have been developed to predict electrolysis performance comprehensively, integrating geometric variables, electrochemical reactions, thermodynamic phenomena, and biphasic flow dynamics. The utilization of nickel sulfide-based electrocatalysts has been a significant focus in recent research, aimed at improving system performance. Studies have demonstrated that these electrocatalysts exhibit high efficiency and can sustain stable hydrogen production even at low voltages [105, 106].

3.7.1.1. System Structure for AWE

As shown in Figure 3.11 and 3.13, the electrolyzer system in alkaline water electrolysis (AWE) comprises several essential units: electrolyzer, power module, control module, pump, heater, and gas-liquid separator cooling system. The control module plays a critical role in maintaining flow and temperature parameters at preset values, ensuring efficient operation. The electrolyzer itself is compact and typically features a bipolar stack secured with screws. It serves as the core component where the electrolytic reaction occurs, housing key elements such as electrodes, diaphragm, and bipolar or monopolar plates. The electrolyzer is divided into cathode and anode compartments separated by a diaphragm and may be in the form of tiny gap and zero gap as in Figure 3.12. During operation, direct current flows between the electrodes: electrons migrate from the negative pole of the power source to the cathode, where they combine with hydrogen ions to produce hydrogen gas. Concurrently, hydroxide ions move from the cathode to the anode through the diaphragm, releasing electrons to generate oxygen gas. These released electrons return to the positive pole of the power source. In this setup, ohmic losses can occur, which are minimized by ensuring close contact between the electrodes and the diaphragm. Electrolyzers can be either monopolar or bipolar, depending on their circuit configuration. Bipolar designs, where electrodes are arranged in parallel, offer a more compact structure and longer system lifespan. Although this design can lead to material constraints and power losses, it is crucial for preventing gas leakage. Therefore, bipolar electrolyzers are preferred over monopolar ones in practical applications [103].

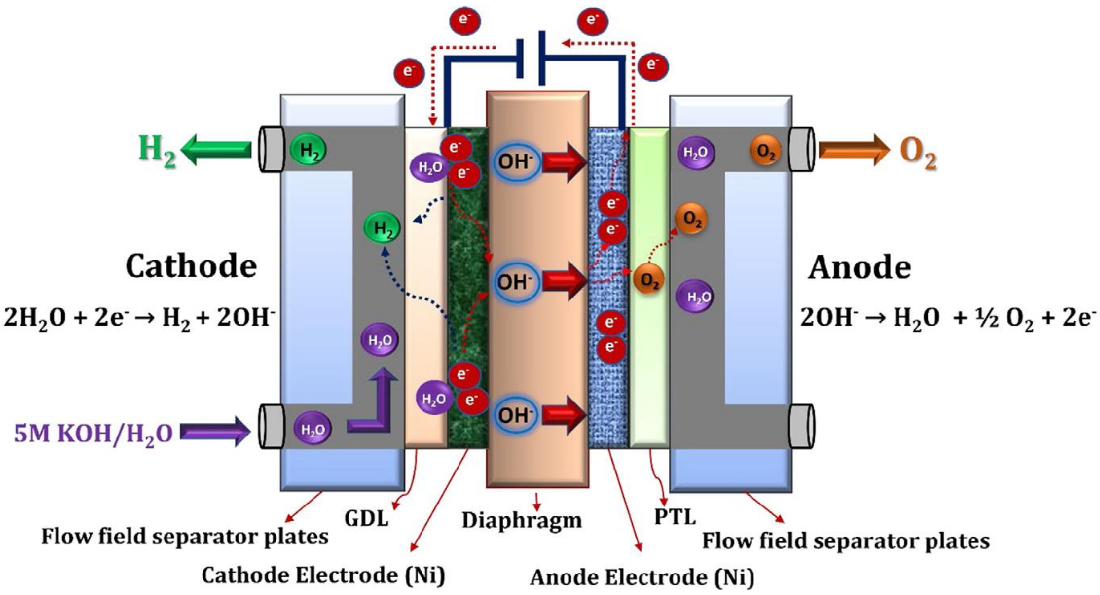


Figure 3.11 AWE electrolyzer structure [81]

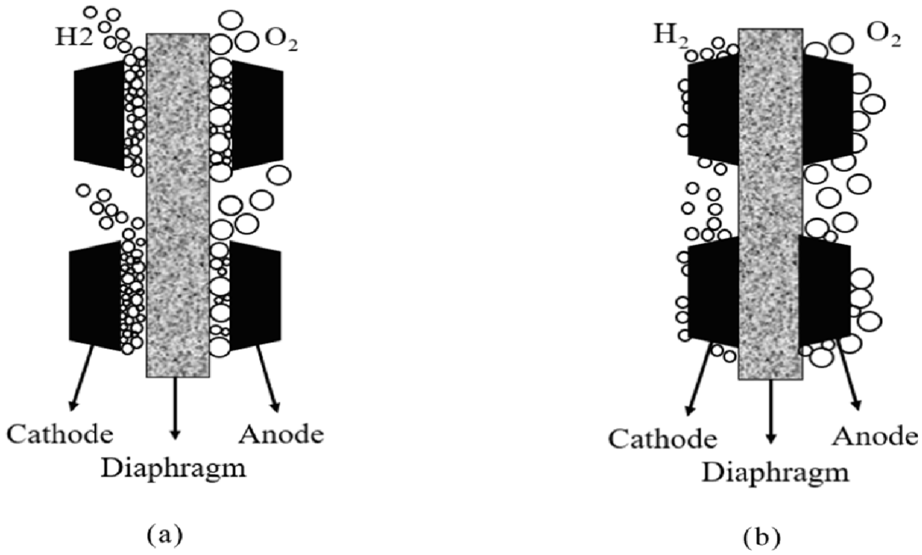


Figure 3.12 AWE electrolyzer structure: (a) tiny gap and (b) zero gap [103]

1) Fixed plate 2) Gasket 3) Electrode and nickel mesh 4) Electrolyte flow channel 5) Oxygen outlet 6) Hydrogen outlet 7) Diaphragm

Figure 3.13 Internal structure of AWE [104]

3.7.2 Proton Exchange Membrane Water Electrolysis(PEM)

Research on PEM (Proton Exchange Membrane) electrolyzers has seen significant advancements in recent years, marking notable milestones in their development. In 2010, there was a pivotal study focusing on the numerical optimization of high-pressure PEM electrolyzers and exploring various electrocatalysts for the electrodes. This effort aimed to enhance efficiency and performance. Subsequently, in 2011, extensive research continued to improve the efficiency of single-cell PEM electrolyzers through advancements in materials and design. The focus then shifted towards achieving higher efficiency through the development of multicellular configurations. By 2015, studies delved into understanding the influencing factors on PEM performance, including membrane and electrode thickness, operating temperature, pressure conditions, and current densities within the electrolyzer system. In 2018, further investigations utilized the finite volume method to analyze PEM performance under various operational conditions, refining understanding and optimizing operational parameters. Over the past decade, there has been a notable rise in the utilization of PEM electrolyzers in non-continuous power supply scenarios, necessitating comprehensive modeling and analysis to optimize performance and operational strategies. Commercial research and development efforts for PEM electrolyzers gained momentum in the early 2000s, with significant strides made towards enhancing their practical applications. In 2022, studies employing MATLAB were conducted to deepen insights into cell performance, focusing on variables such as temperature, pressure, and current density, highlighting ongoing efforts to advance PEM electrolyzer technology [107, 108].

Over the past decade, significant advancements in computational fluid dynamics have revolutionized the study of PEM (Proton Exchange Membrane) electrolyzers, driven by their complex and versatile nature. Scientists and engineers have conducted numerous analysis studies, considering various parameters to optimize PEM electrolysis. Researchers have meticulously calculated flow regimes and temperatures within PEM electrolyzers, emphasizing fundamental principles such as pressure dynamics, temperature effects, pore structure, and membrane thickness. In-depth studies have employed three-dimensional two-phase models to investigate mass and heat transfer behaviors. These models have shown that enhancing the number of inlet flow areas can achieve more uniform temperature distributions, while reducing inlet hole diameters in porous electrodes improves mass transfer efficiency. Furthermore, investigations into temperature effects on voltage and electric current requirements have underscored the critical role of heat transfer in electrolyzer performance. Design considerations, influencing both performance and cost, highlight the importance of optimizing transport flow areas for efficient PEM water electrolyzers. Achieving uniform water distribution and efficient gas removal from porous structures are key factors positively impacting performance and longevity. Both experimental and computational flow modeling approaches have become standard practice, evaluating how water movement, pressure effects, and operational costs impact performance. Studies on PEM membranes have explored alternatives to Nafion membranes, including ceramic and inorganic options. However, research consistently demonstrates that Nafion membranes exhibit superior compatibility with high-temperature operations compared to other materials. They have proven to be more conductive and environmentally resilient, offering greater durability and flexibility against degradation. Recent advancements have positioned PEM electrolyzers as highly efficient systems worthy of extensive research. Their ability to operate under flexible conditions and integrate seamlessly with renewable energy sources makes them particularly advantageous for energy production and hydrogen storage. Leveraging renewable sources for energy production ensures sustainability, with excess energy efficiently stored as hydrogen, further enhancing the system's utility and environmental impact [106, 109, 110].

3.7.2.1 System Structure for PEM

The PEM electrolysis cell typically consists of two separator layers, known as the anode and cathode, and a membrane, as seen in Figure 3.14 and 3.15. In this system, along with water molecules, ions migrate from the anode to the cathode through the membrane, where they undergo electrochemical reactions, decomposing into oxygen, protons, and electrons. Essentially, electrical energy provided to the system at the anode initiates the electrolytic decomposition of water. During this process, electrons travel through the external circuit to the cathode. Oxygen generated at the anode is released, while the remaining protons permeate through the membrane to the cathode. At the cathode, electrons and protons combine to produce hydrogen [81, 110].

PEM electrolysis stands out as a preferred system for green hydrogen production due to its appropriate catalyst materials, robust and advanced cell design, and compatibility with renewable energy sources. It excels in commercial applications by operating at high current densities, necessitating larger cell areas to overcome limitations in hydrogen production efficiency compared to other electrolysis systems. In PEM water electrolysis systems, the use of high-cost noble metals such as iridium and platinum in anode and cathode catalysts is common. Efforts to reduce the noble metal content in these catalysts have led to some cost savings. Thin film catalysts are increasingly favored, enabling a reduction in the use of expensive noble metals and exploring more cost-effective alternatives [107, 108].

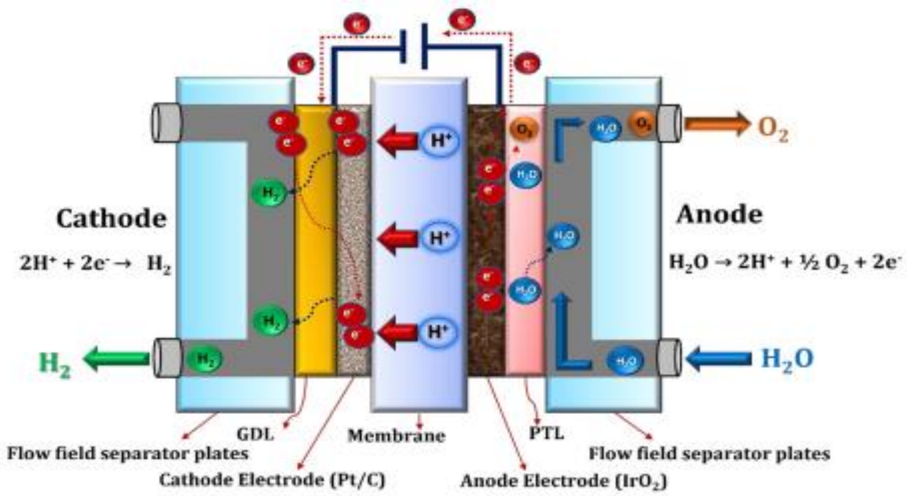


Figure 3.14 Internal structure of PEM [81]

Figure 3.15 Photograph of a PEM stack [125]

3.7.3 Solid Oxide Water Electrolysis (SOEC)

Solid oxide water electrolysis cells are advanced systems that convert electrical energy into chemical energy, producing hydrogen at the cathode and oxygen at the anode. Originating in the 1970s in the United States and further developed in Germany, these systems excel in electrolyzing water vapor at elevated temperatures, typically between 800 and 1000°C. This high temperature operation ensures efficient electrolysis, which has been a focal point of recent research aiming to reduce hydrogen production costs through improved energy efficiency. Recent advancements have focused on optimizing power consumption in solid oxide water electrolysis, crucially integrating thermal energy to supplement electrical input. Unlike other electrolysis methods, solid oxide electrolyzers do not rely on expensive noble metals; instead, they utilize cost-effective ceramics such as nickel-doped Nickel Oxide (NiO), Yttrium Stabilized Zirconium (YSZ), and Lanthanum Strontium Manganite (LSM). This makes them compatible with various chemicals like methanol and ammonia, broadening their potential applications. Despite their high efficiency, commercial adoption has been constrained by challenges in electrolyte stability at high temperatures. Ongoing research aims to address these issues, potentially extending the operational lifespan and reliability of solid oxide electrolysis systems. Integration with waste heat from power plants has shown promise in enhancing efficiency over the long term, positioning them favorably for integration into nuclear hydrogen production facilities. In conclusion, while solid oxide water electrolysis systems offer significant advantages in efficiency and versatility, ongoing research is pivotal in overcoming stability challenges and advancing their commercial viability in the hydrogen economy [81, 86, 112, 113].

3.7.3.1 System Structure for SOEC

Solid oxide electrolysis systems are composed of essential components such as catalysts, flow field separator plates, anode, cathode electrodes, and an electrolyte with a high ceramic content capable of conducting oxide ions. The SOEC water electrolysis cell is shown in Figure 3.16. The choice of high ceramic content in the electrolyte is pivotal due to the high operating temperatures of solid oxide electrolyzer systems. Among the most widely utilized electrolytes in these systems is yttrium-stabilized zirconium dioxide (YSZ), renowned for its exceptional performance under high-temperature conditions. YSZ is also noted for its chemical and thermal compatibility, facilitating integration into various applications. The cathode, which serves as the hydrogen electrode, features a composition typically comprising zirconium dioxide and nickel. These non-noble metal catalysts exhibit excellent conductivity, crucial for efficient hydrogen production. On the other hand, the anode, serving as the oxygen electrode, utilizes perovskite materials like LSCF (lanthanum strontium cobalt ferrite), which offer a combination of high electronic and ionic conductivity (10^2 and 10^{-2} S cm^{-1} respectively) along with superior oxygen diffusion properties. LSM (lanthanum strontium manganite) is commonly favored as the reference material due to its high-performance characteristics. In summary, the selection of materials such as YSZ, zirconium dioxide, nickel, LSCF, and LSM in solid oxide electrolysis systems underscores their capability to operate efficiently at high temperatures while delivering robust performance in hydrogen and oxygen production. These advancements highlight their potential in advancing sustainable hydrogen production technologies [81, 114].

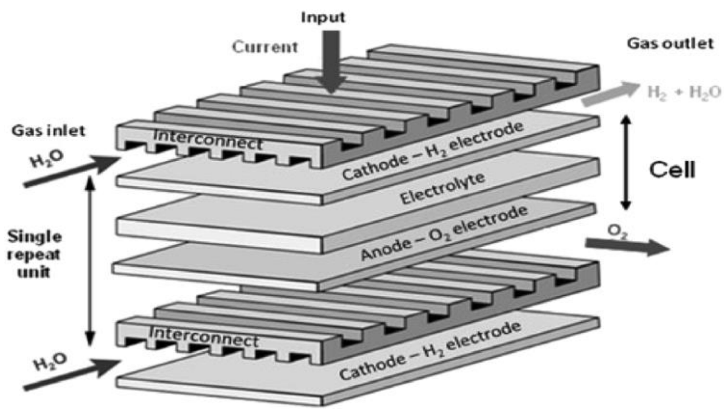


Figure 3.16 Schematic of a SOEC cell showing the internal components [113]

Solid oxide water electrolysis is a process that produces environmentally friendly hydrogen and oxygen at extremely high temperatures using water vapor, as shown in Figure 3.17. At the cathode, water molecules are dissociated by the addition of two electrons, resulting in the formation of hydrogen ions. These hydrogen ions then combine to form hydrogen gas, which is subsequently released from the cathode surface. Simultaneously, oxide ions migrate through the electrolyte membrane to the anode. Upon reaching the anode, these oxide ions undergo a reaction where they are split into oxygen and electrons. The released oxygen is liberated from the surface of the anode. The remaining electrons travel through the external circuit towards the cathode, where they participate in the reduction process, facilitating the continuous production of hydrogen ions. In summary, solid oxide water electrolysis involves complex electrochemical processes where water vapor is utilized to produce hydrogen and oxygen at high temperatures. This method demonstrates potential for sustainable hydrogen production, leveraging advanced materials and precise control of electrochemical reactions [81, 113].

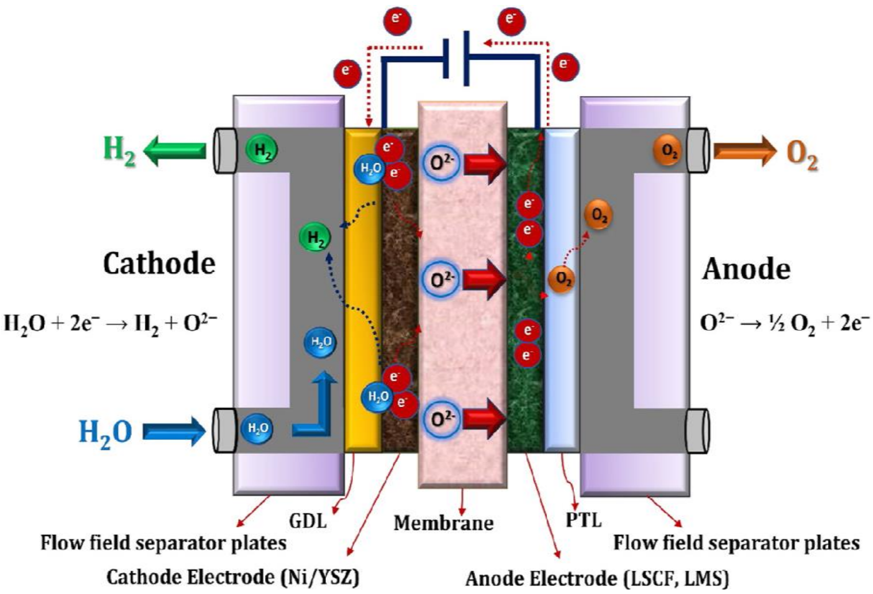


Figure 3.17 Schematic of solid oxide water electrolysis and working principle [81]

3.7.4 Anion Exchange Membrane Water Electrolysis (AEM)

Anion exchange membrane (AEM) water electrolysis systems have garnered significant global attention from research institutions and organizations. The first research publication on AEM systems dates back to 2011, marking the beginning of ongoing innovations aimed at enhancing their commercial viability by addressing stability issues and reducing costs. AEM systems are specifically engineered to utilize cost-effective, non-noble metal electrocatalysts, leveraging their compatibility with alkaline environments. Recent advancements focus on improving system performance through novel materials for membranes and separator plates. In research endeavors, a 3D oxygen electrode has been developed to boost efficiency, alongside enhancements in the performance of KOH solutions within the system. Mathematical modeling plays a crucial role in exploring the operational parameters of AEM systems, though current efforts in modeling durability and performance aspects remain limited. Studies indicate that membrane thickness and ionic conductivity significantly influence electrolyzer performance under varying operating pressures and temperatures. AEM systems, employing gapless cells, find extensive industrial applications compared to traditional alkaline water electrolyzers. Moreover, their solid polymer electrolytes exhibit low gas permeability, ensuring compact mass volume due to thinner electrolyte layers compared to traditional diaphragms, thereby minimizing energy losses. These systems excel in producing high-purity hydrogen efficiently and safely. Research on AEM membranes has been influenced by the development of alkaline aqueous-based redox batteries, which offer flexibility, low degradation, and effective scaling capabilities. This has spurred comprehensive studies on chemical stability, such as investigating the suitability of polyethylene glycol alkaline solutions across various AEM membrane sections [81, 102, 115].

3.7.4.1 System Structure for AEM

Anion exchange water electrolysis systems comprise several key components: membranes, separator plates, gas diffusion layers, and end plates. The resulting structure of the system is shown in Figure 3.19. Membranes play a crucial role in conducting OH^- ions and separating O^2 and H^2. In these systems, anode and cathode materials typically feature transition metal-based electrocatalysts, often composed of Ni and NiFeCo alloy materials. Gas diffusion materials for the anode and cathode consist of nickel-based or carbon fabric. Separator and end plates, essential for structural integrity, are typically made from nickel and stainless steel. The anion exchange electrode facilitates water separation through a combination of electrical and chemical processes. Through electrochemical reactions at the electrodes, hydrogen evolution reaction and oxygen evolution reaction occur in their respective cells. As shown in Figure 3.18, initially, water molecules enter from the cathode side where they encounter electrodes. This interaction leads to the formation of hydrogen (H^2) and hydroxyl (OH^-) ions. The negatively charged hydroxyl (OH^-) ions migrate towards the anode, while the positively charged hydrogen (H^2) ions are discharged at the cathode. At the anode, hydroxyl (OH^-) ions lose electrons, resulting in the formation of water molecules and oxygen. The oxygen molecules formed are then released from the anode into the environment [81, 102, 116, 117, 118].

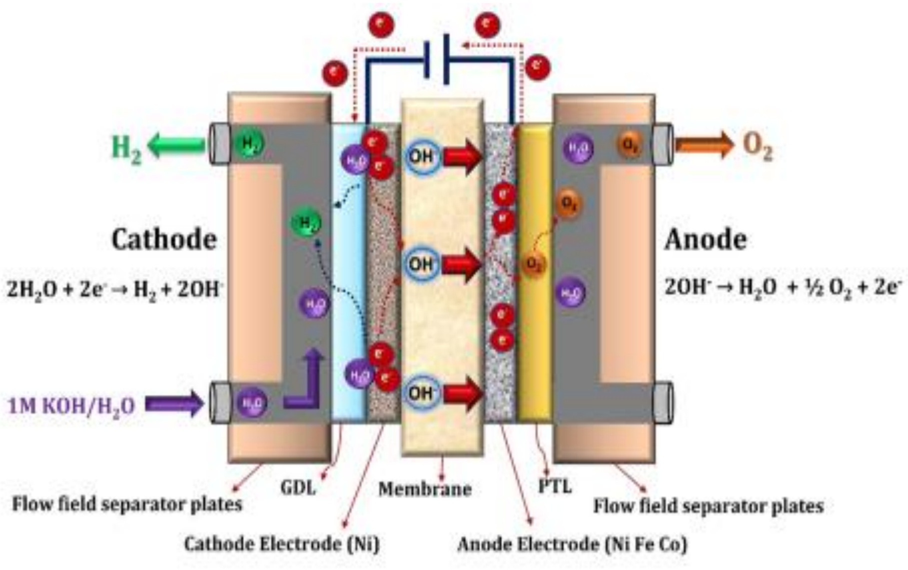


Figure 3.18 Schematic of AEM and working principle [81]

Anion Exchange Membrane (AEM) systems excel in producing high purity hydrogen with high efficiency at elevated current densities. They are also exceptionally compatible with renewable energy sources. Operating at high purity and lower alkaline levels helps reduce corrosion, thereby extending the electrolysis system's lifespan.

Unlike PEM electrolysis stacks, which typically operate in the megawatt range, AEM systems are compact, with stack sizes typically in the kilowatt range. This compactness makes them suitable for various applications where space is a consideration. However, operating at high current densities can lead to fluctuations, necessitating continuous improvements and research efforts focused on enhancing membrane durability and polymer stability within the membrane.To enhance membrane durability and mitigate polymer degradation, incorporating high-conductivity polymer components can significantly increase membrane stability. This approach aims to ensure the long-term reliability and performance of AEM systems in hydrogen production applications [81, 102, 116, 118].

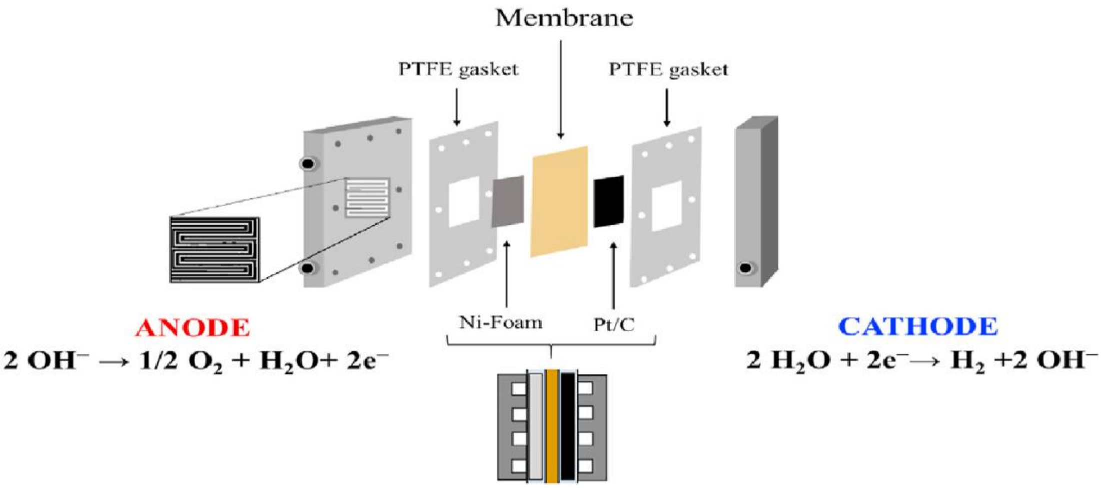


Figure 3.19 Anion exchange membrane electrolysis cell [117]

3.8 Comparison of Water Electrolysis Systems

Table 3.2 Comparison of water electrolysis systems [81, 100, 103, 106, 113, 114, 116, 119-127]

	AEM	AWE	PEM	SOEC
Cathode Reaction	$2H_2O + 2e \rightarrow H_2 + 2OH^-$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H + 2e- \rightarrow H_2$	$H_2O + 2e \rightarrow H_2 + O_2^-$
Anode Reaction	$2OH^- \rightarrow H_2O + 1/2O_2 + 2e^-$	$2OH^- \rightarrow H_2O + 1/2O_2 + 2e^-$	$H_2O \rightarrow 2H + 1/2O_2 + 2e^-$	$O_2^- \rightarrow 1/2O_2 + 2e^-$
Overall Reaction	$H_2O \rightarrow H_2 + 1/2O_2$	$H_2O \rightarrow H_2 + 1/2O_2$	$2H_2O \rightarrow H_2 + 1/2O_2$	$H_2O \rightarrow H_2 + 1/2O_2$
Electrolyte	DVB polymer support with KOH or NaHCO3 1 mol L−1	Potassium hydroxide (KOH) 5 mol	Solid Polimer Electrolyte	Yttria stabilized Zirconia
Separator	Membrane; Quaternary ammonia polysulfone (QAPS)	Diaphragm; Zirfon or Nikel(Potassium hydroxide (KOH) 5 mol)	Membrane; Perflurosulfonated acid,Nafion	Solid electrolyte (Yttria stabilized Zirconia)
Anode Reaction (Oxygen Side)	Nikel or NiFeCo alloy	NiFe-based alloys	İridium Oxide	Perovskite-type
Cathode Reaction(Hydrogen Side)	Nikel	Nikel	Platinum	Nikel -Yttria stabilized Zirconia
Bipolar Plates	Nikel-Coated Stainless Steel	Nikel-Coated Stainless Steel	Platinum or Gold Coated Titanium	Cobalt Stainless Steel
Electrode Area (cm^2)	<300	10,000-30,000	≤3000	200
Technology Maturity	Research and Development	Widespread commercialization	Commercial for small scale	Research and Development
Operating Temperature (C^o)	40-80	30-80	50-85	500-850
Operating Pressure (bar)	1-35	1-30	30-70	1

Current Density (A/cm^2)	0.2-2	0.2-0.4	1-2	0.3-1
Cell Voltage (V)	1.4-2	1.4-2.4	1.4-2.5	1-1.7
Hydrogen Purity (%)	99.99	99.3-99.9	99.99	-
Hydrogen Production Nm^3/hr	0.25–1	<760	0.265–30	-
Cell Presure (bar)	<30	<30	<70	<30
Lifetime Stack (h)	< 30000	55000-120000	50000-100000	10000-20000
Load Range (%)	5-100	15-100	5-130	30-125
Cold Start Time (min)	<20	15-50	<15	60<
Advantages	-Use of low cost noble metals - Low concentrated liquid electrolyte. -Low capital cost.	-Long stability -Low capital cost -Use of low cost noble metals - Mature Technology	-Commercialized technology -Compact design -High purity for gas -Fast response speed -High current densities operation	-High efficiency -Low energy
Disadvantages	-Limited stability - in development	-Slow response speed -Limited current densities -Highly corrorive	-High cost metal catalysts -Including acidic elektolyte	-Low durability -Short life -Quick degradation -High cost material

Table 3.2 compares the features, advantages and disadvantages of 4 types of water electrolysis systems. If we look at the features of the four electrolysis systems, the system used in the most common commercial applications is AWE in technological developments. Apart from that, PEM seems to be suitable for small capacities at the moment, and SOEC and AEM continue to be researched and developed. AWE's electrolysis area is larger compared to others. This may also be suitable for lower costs. PEM includes a higher investment cost compared to others. SOEC's stack life is low. AWE is more successful in long-term operations and is a low-cost electrolysis compared to others. In addition, AWE is more durable when looking at stack lives. AWE and PEM offer a wider range of operation when looking at the flow density and voltage values.

CHAPTER 4

4. MARKET ANALYSIS OF HYDROGEN

The potential of hydrogen is getting stronger and strategic studies and projects on hydrogen are increasing worldwide. Considering the cost, technology, and efficiency factors of hydrogen trade, it is important to transport hydrogen from low-cost production places to high-demand places. Therefore, to enable hydrogen trade, the transportation cost as well as the production cost at the exporting location are expected to be low. For transportation, existing unused natural gas pipelines can also be adapted and used for hydrogen transportation. As a result, it is necessary to carefully calculate the cost of hydrogen production, transportation, and storage methods [12, 128, 129].

4.1 Global Hydrogen Analysis: Current Trends and Future Projections

Hydrogen production, trade, and investment processes also aim to minimize fossil fuel use. Producing hydrogen at the lowest cost in line with the correct principles is also of great importance for the global future. Different relationships may emerge in the rapidly growing hydrogen energy sector between countries. More than 30 countries are focused on hydrogen, and producing low-cost and environmentally friendly hydrogen by determining appropriate strategies and making import or export plans appropriately is also important for the development of these countries [128].

Figure 4.1 shows the global trade map of hydrogen. As hydrogen becomes more widespread worldwide, hydrogen trade routes, import and export, will continue to develop and many countries will begin to benefit from hydrogen energy.

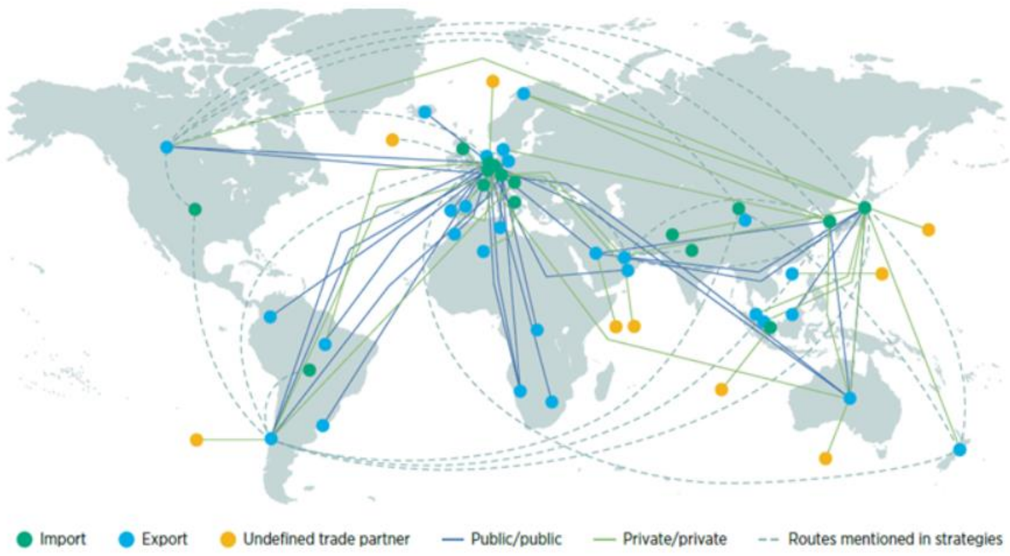


Figure 4.1 Bilateral trade announcements for global hydrogen trade until March 2022 [128]

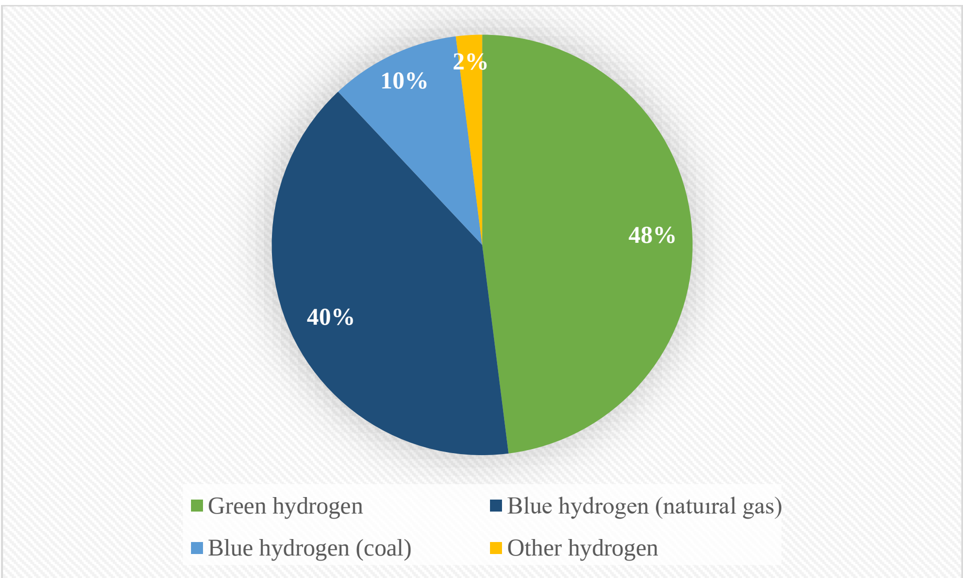


Figure 4.2 Forecast production share of hydrogen worldwide in 2050, by technology [130]

Figure 4.2 shows the percentages of hydrogen production in 2050. Although coal and natural gas production is higher than green hydrogen in most countries, green hydrogen will come to the forefront with many strategies determined by countries in 2050.

In the hydrogen sector, the focus of governments is on the environment rather than efficiency when producing hydrogen. Accordingly, care is taken to ensure that projects have low emissions. Based on data in 2021, more than 30 countries are focused on the hydrogen sector. 17 of these countries have determined their hydrogen strategies. While hydrogen-based projects have been created since 2021, large-capacity projects have not been carried out much. However, supporting large-capacity investments will pave the way for many hydrogen-based projects. Accordingly, governments will make the most accurate investment decisions. The largest investments are the 2 GW green hydrogen project in Saudi Arabia and the 320 MW green ammonia project in Oman. Globally, the largest hydrogen producer is known as China. China's annual hydrogen demand is around 35 Mt. There is a long-term plan between 2021 and 2035 that includes hydrogen-related support in China. With this plan, it focused on the widespread use of hydrogen-supported vehicles and also contributed to the establishment of hydrogen fuel stations. It is predicted that higher profits will be achieved through the transportation sector in China, but it is important to create hydrogen-focused projects in the industrial sector as well. China is also determined to achieve its hydrogen targets by developing multifaceted hydrogen policies. The hydrogen plans published in the USA in 2020 include ensuring that hydrogen becomes widespread in the industry, working on fuel cells, and providing a certain budget for research and studies on hydrogen. They also aim to reduce the cost of US hydrogen production by %80 and eliminate marketing and corporate problems. In Australia, there are many hydrogen-focused strategies. Australia has generally focused on green hydrogen and has allocated a large budget in this field. In Russia, they created hydrogen strategies for the first time in 2020. Afterward, they published two more reports focusing on hydrogen. These reports aim to ensure energy policies until 2035 and the development of hydrogen-supported projects until 2024. Thus, steps were taken towards the development of hydrogen energy in Russia [83, 97, 131].

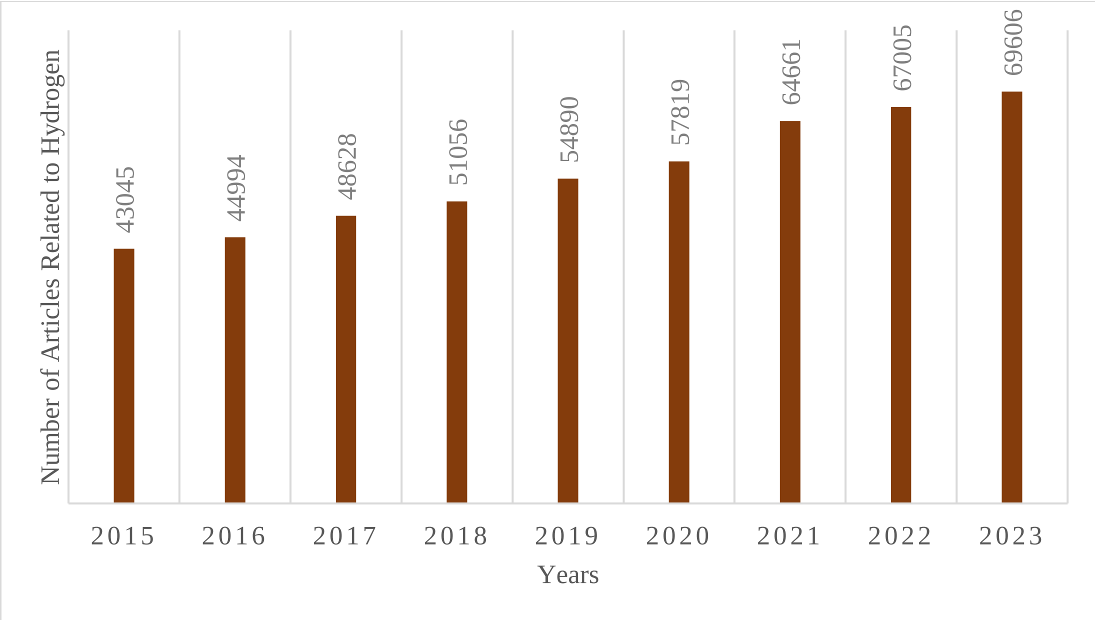


Figure 4.3: Number of hydrogen-related articles Worldwide [132]

With the advancement of hydrogen worldwide and the increasing interest in hydrogen, the number of hydrogen-focused research and studies in the world is gradually increasing. As can be seen in Figure 4.3, the number of articles on hydrogen in 2015 was 43045 and increased until 2024. By the end of 2024, the number of articles will most likely exceed the number of articles in 2023.

4.2 Global Green Hydrogen Analysis: Trends and Future Projections

Although 95 Mt of hydrogen will be produced in 2022, most of this production is gray hydrogen originating from fossil fuels. To bring green hydrogen to the fore, efforts should be made to keep its costs at a low level, and therefore, green hydrogen production should be focused on along with renewable energy sources. In regions where renewable energy resources are abundant, the cost of green hydrogen production will be at affordable levels. Solar and wind energy are especially important for green hydrogen production. The cost of the electrolyzer used for green hydrogen production is also expected to be low. Therefore, electrolyzers made of costly materials should be avoided. The use of cost-effective electrolyzers also provides a significant reduction in investment costs. In addition, increasing the size of green hydrogen production facilities reduces costs and keeps efficiency high. Therefore, hydrogen valleys may be important for large-scale industrial use. To offset green hydrogen production costs, countries need to create strategies for green hydrogen, focus on renewable resources, and work on large-scale and low-cost projects. In general, most governments are focused on green hydrogen, and therefore governments are investing significant amounts in hydrogen. These investments are increasing compared to the previous year, and green hydrogen projects and research are increasing day by day. The 2 GW project in Saudi Arabia and the 320 MW green hydrogen projects in Oman, which have emerged in recent years, are the most important examples of these projects [83, 96, 133].

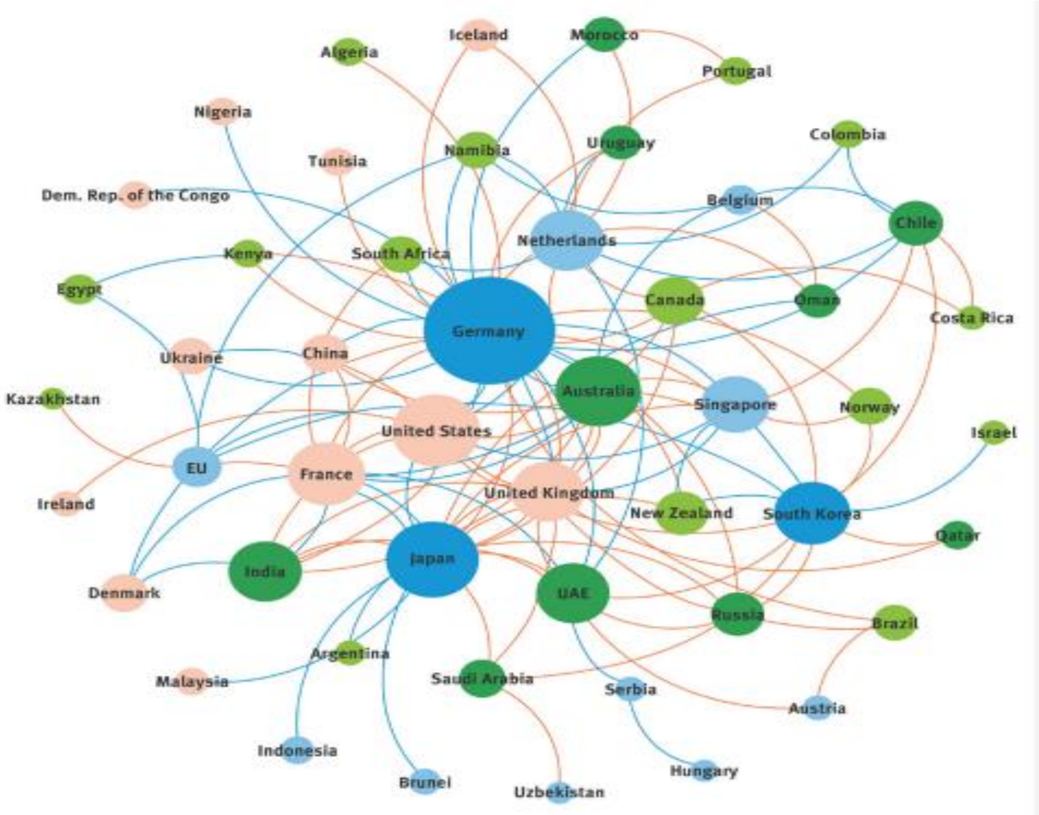


Figure 4.4 Green hydrogen globally [133]

As shown in Figure 4.4, the demand for green hydrogen is highest in the blue ones, Japan, Germany, and Korea, because they have reached agreements and established partnerships with exporting countries on hydrogen. Apart from that, they have made agreements with various regions such as Singapore, Netherlands and Belgium to import. Green colored places indicate places that export hydrogen. Regions such as Australia India are among the leading places that export hydrogen. The regions covering the red areas are in a neutral position regarding exports and imports [133].

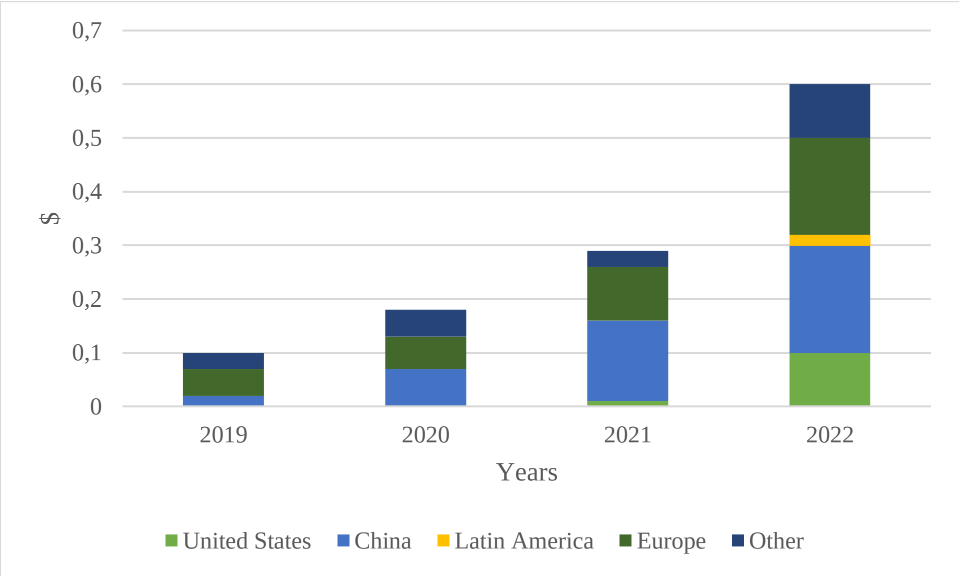


Figure 4.5: Green hydrogen investment for electrolyzer installations (according to regions) [83]

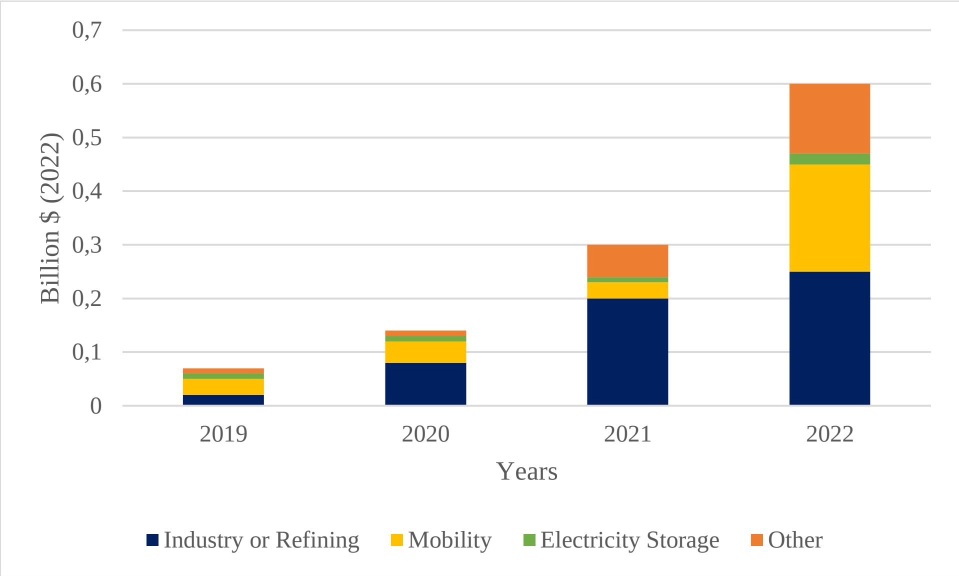


Figure 4.6: Green hydrogen investment for electrolyzer installations (according to usage areas) [83]

Electrolyzer investments by region are given in Figure 4.5. It is observed that investments in China and Europe are higher than in others, and investments have been increasing in recent years. The graph in which investments are classified according to their areas of use is shown in Figure 4.6. Accordingly, it is observed that the most investments are in industry and refining.

In addition to its cost, the cost of hydrogen production also includes transportation and storage costs, if any. In addition, production costs using split energy are lower. Especially the affordable cost of electrolyzers makes green hydrogen production attractive. Another factor affecting the cost of green hydrogen production is electricity. The attractive electricity price in the region where production will be made reduces the cost of green hydrogen production. The cost of materials in the facility also affects the cost. It is not appropriate to use materials such as Iridium, which make up the electrolyzer, because they are expensive. Care should be taken to ensure that the materials are highly durable, long-lasting, and have properties that will increase system efficiency [133].

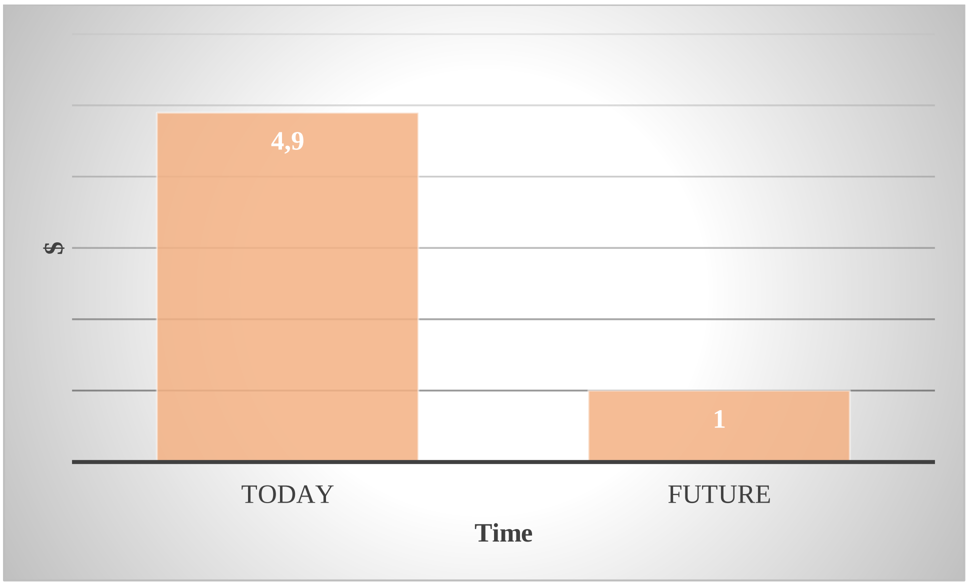


Figure 4.7 Green hydrogen cost forecasts [133]

Looking at Figure 4.7, hydrogen production is taken as an average of 4.8 dollars per kilogram. It is possible to reduce this to 1 in the future, but some conditions must be met. For example, it is necessary to reduce the electrolyzer cost by %80, reduce the default electricity cost to reach the target, significantly increase the electrolyzer efficiency, ensure the long life of the system, and reduce the average capital cost.

Figure 4.8 Number of green hydrogen-related articles Worldwide [134]

Figure 4.8 shows the distribution of the number of studies on green hydrogen by year. Accordingly, the number of scientific research and studies on green hydrogen is increasing worldwide.

4.3 Marketability Analysis of Hydrogen Energy in Türkiye

Türkiye's geopolitical location is advantageous in terms of hydrogen economy, and it is important for hydrogen trade to be easily carried out and for export relations to be established with its neighbors. A certain budget should be allocated for the production, transportation and storage of hydrogen, and this budget should be used in the most appropriate way. A secure hydrogen policy is achieved by providing low hydrogen costs and taking the right path in foreign trade relations. Although hydrogen exports in Türkiye increased during the year, a slight decrease was observed due to 2019 COVID. Apart from that, there is stability in hydrogen exports. Türkiye also works in harmony with other countries in terms of hydrogen trade and makes sufficient investments in hydrogen. If Türkiye moves hydrogen production and exports to an important position, the regions around Türkiye may also be affected by hydrogen-focused regions. In order for Türkiye to gain a significant place in the hydrogen market, it is necessary to determine many targets and policies [135, 136].

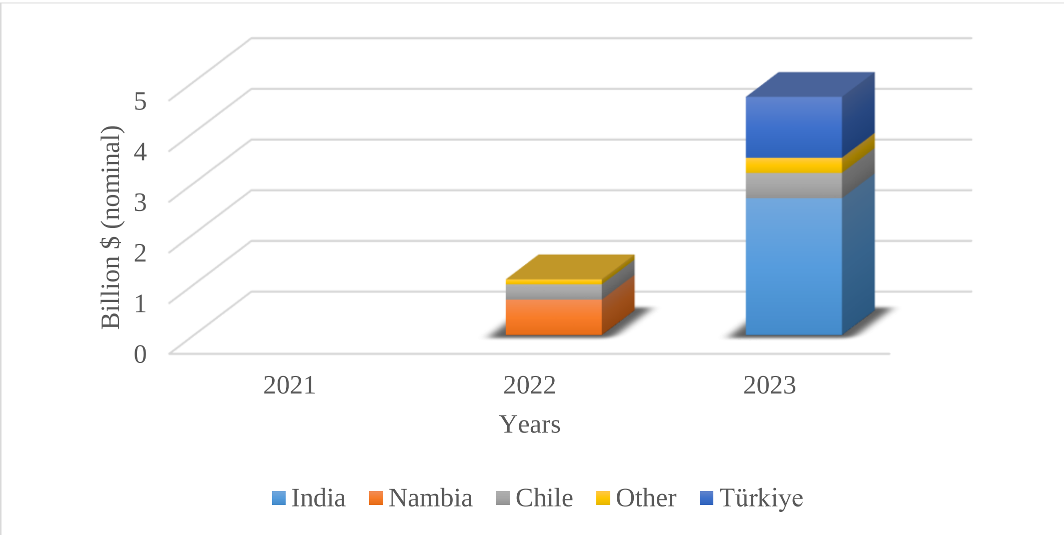


Figure 4.9 Financial commitments to hydrogen by multilateral development banks, by source and partner country, by year of announcement, 2021-2023 [83]

Globally, multilateral development banks have increased their capital to certain countries in recent years to increase the number of hydrogen projects and technologies and to expand the hydrogen market. These banks have focused on countries that are developing themselves in the hydrogen field, have hydrogen-focused projects, and want to trade in hydrogen. The distribution of banks' capital by country in recent years is shown in Figure 4.9 [83].

Hydrogen use in Türkiye occurs in various areas. It continues to be used especially in the chemical, oil refining, food, aviation, transportation and energy sectors. 80 percent of hydrogen use is in the production of ammonia and methanol, plastic production in the chemical industry. It is also expected to be used significantly in the refinery sector because it is aimed to increase the variety of petroleum products. In addition, hydrogen is a necessary use for systems operating at different capacities in the field of energy, such as fuel cell production, generators, and unmanned vehicles. The use of hydrogen will increase further in various sectors day by day and the use of hydrogen is aimed to be significant. [135]

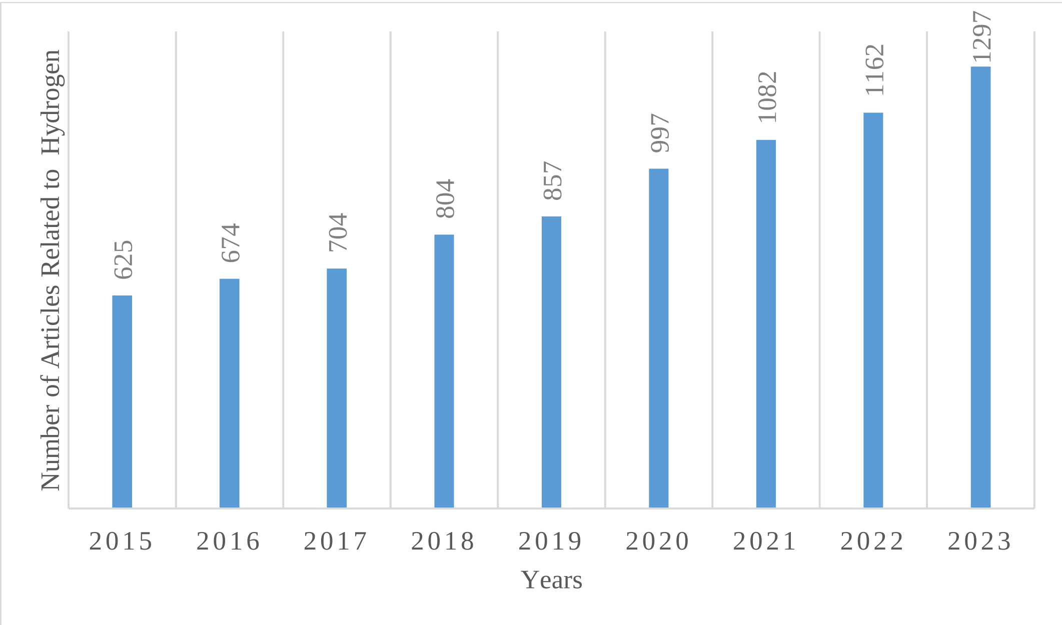


Figure 4.10 Number of hydrogen-related articles in Türkiye [137]

Since Türkiye has focused on hydrogen-based energy in recent years, the number of research and studies conducted on hydrogen in Türkiye is shown in Figure 4.10, and the number of studies on hydrogen is increasing with each passing year.

4.4 Marketability Analysis of Green Hydrogen Energy in Türkiye

In Türkiye, hydrogen-focused energy production and trade is becoming increasingly important. Focusing on green hydrogen production is of great importance for the future of the country. Türkiye is in a good position in terms of the existence of renewable energy sources. Especially by using wind solar and biomass resources, hydrogen green hydrogen production can be made widespread and we can keep the cost of green hydrogen production low with electrolysis systems [12].

In Türkiye, production and trade for green hydrogen has become important for Türkiye. The steel and cement sector has a large share in Türkiye. For this reason, low-cost hydrogen facilities can be established near regions where consumption is high, such as steel and cement. There are many natural gas pipelines in our country. A certain part of these pipelines can be revised and used at low cost in hydrogen transportation. Accordingly, Energy and Natural Resources Minister Fatih Dönmez announced in his speech at the meeting that Türkiye will test mixing hydrogen into its natural gas distribution network pipes by 2021. When creating financing for green hydrogen, attention should be paid to the fact that the projects have zero carbon emissions. The budget should be created by considering efficient and low-cost projects. Electricity production can be provided by using the renewable energy in Türkiye in the last decade. In addition, the cost of green hydrogen production decreases significantly with the production of domestic, durable and low-cost electrolyzers. If we look at the current situation in Türkiye, there is a hydrogen potential of approximately 4.6 million tons of oil equivalent in Türkiye. This value is stated as approximately %5 of the total energy consumption in Türkiye and the total electrolyzer installed power capacity in Türkiye should be approximately 12 GW. Accordingly, the total investment need is estimated to be approximately 45.4 billion US dollars [12, 138].

Table 4.1 Green hydrogen production plan in Türkiye [12]

2025	**500 kW Electrolyser**			
2030	500kW-5 MW	Advanced biological/microbial H production technologies		
2035	5-50 MW	Development of domestic biomass gasification demo systems		
2040	50-500MW	Development of biogas pyrolysis systems	Development of biogas reforming systems	Innovative bioreactor designs and process optimization studies 3 3 >15m H /day, >10m reactor
2053	500MW- 1GW			

Table 4.1 shows the strategies determined for green hydrogen production in Türkiye. Accordingly, it is expected that electrolyzer capacities will increase significantly and it is aimed to use more biogas in green hydrogen production.

Table 4.2 Capacity status of renewable energies in Türkiye [20, 52, 54, 57, 60, 63, 66, 74, 139, 140]

	2024 Year Installed Power (MW)	**Annual Used Capacity (GWh)**	**Annual Eceonomic Maximum Capacity (GWh)**	**Annual Unused Energy (GWh)**
Sun Energy	12600 MW	27216 GWh	380000 GWh	352784 GWh
Wind Energy	12000 MW	21600 GWh	414720 GWh	393120 GWh
Hydroenergy	32000 MW	78126 GWh	414262 GWh	336136 GWh
Geothermal	1700 MW	7344 GWh	41472 GWh	34128 GWh
Wave Energy	0 MW	0 GWh	33.97 kWh/m	33.97 kWh/m

When Table 4.2 is examined, the total renewable installed capacity of Türkiye is 58,300 MW. According to the current total installed capacity, the annual total capacity rate of renewable energies is approximately 134,286 GWh. The economic maximum unused capacity rate in Türkiye is approximately 1,250,455 GWh. When we compare the unused energy rate with these values, the unused capacity rate is approximately 1,116,170 GWh. This means that although the renewable energy installed power and capacity rates have increased over the years, there are still many capacity areas in Türkiye that need to be evaluated. Therefore, the current capacity rates need to be activated for renewable energy use and, accordingly, energy dependency needs to be eliminated. [20, 52, 54, 57, 60, 63, 66, 74, 139, 140]

With the use of green hydrogen as 10% in the manufacturing industry and natural gas networks, Türkiye 's green hydrogen demand is expected to be 0.5 Mt/year in 2030, and it is expected to reach 1.9 Mt/year in 2050. Türkiye 's current green hydrogen production cost varies between 4$/kg and 9$/kg. One of Türkiye's goals is to reduce the green hydrogen cost to below 1.2$/kg in 2053. It seems possible to reach the 2053 target with correctly planned economic strategies and the evaluation of unused capacity rates. When we look at the installed solar and wind power rates in Türkiye, an increase of approximately 1500 MW per year is observed in the installed solar power. The installed power rate in wind energy increases by approximately 1000 MW per year. As stated in previous data, Türkiye has a capacity target of 70 GW in 2050. Considering the installed capacity increase rates of solar and wind energy and the unused capacity rates, it seems that the 70 GW installed capacity target in 2050 can be easily achieved. If we assume that 40 percent of 70 GW is used in green hydrogen production, the average green hydrogen production can be determined as 1196 kt per year by 2050. [12, 20, 52, 54, 57, 60, 63, 66, 74, 139, 140, 141]

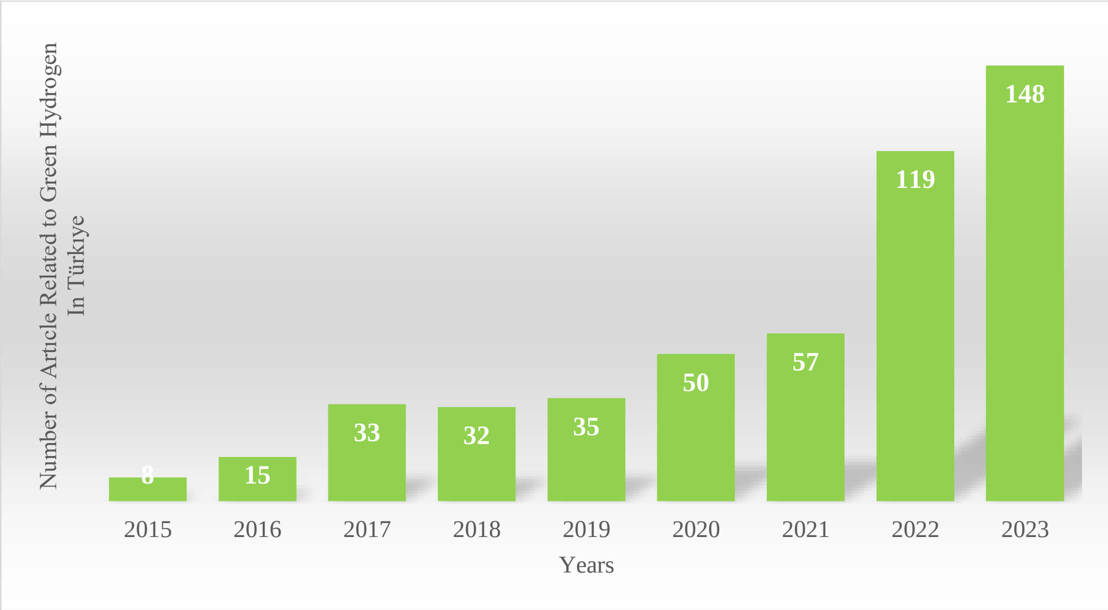


Figure 4.11 Number of green hydrogen-related articles in Türkiye [142]

Figure 4.11 shows the number of green hydrogen studies conducted in Türkiye. Accordingly, the number of studies increases every year, especially in the last two years.

4.5 Efficiency of Water Electrolysis Systems

When designing any system, efficiency is as important a factor as production. This also applies to water electrolysis systems. When designing a water electrolysis system, the durability of the elements that make up this system, how they will adapt to operation, and the energy consumption of the system are important in terms of efficiency. It is desirable to produce large amounts of hydrogen from water electrolysis. However, this requires high current density. Due to its high current density, it requires high operating voltage. In regions where electricity prices are low, the production of electrolysis systems is more intense, and their efficiency increases. The voltage required to split water into electrolytes is 1.229 V. When standard pressure and temperature values are taken, the enthalpic voltage is taken as V = 1.48. Generally, under normal conditions, the voltage value of the systems is in the range of 1.8-2.6V. This value range is higher than the theoretical value and the voltage value taken at standard pressure and temperature. Accordingly, the efficiency of water electrolysis systems can be calculated [9, 10, 126, 127, 143].

$$\eta = \frac{\text{Vtheoric}}{\text{VOp}} = \frac{1.48}{\text{VOp}} \quad \textbf{(4.1)}$$

When calculating the efficiency of a water electrolysis system, the energy released by hydrogen throughout the system is also important. When calculating the efficiency, the power capacity of the electrolysis system and the amount of hydrogen produced can be taken into account to calculate the full efficiency of the system.

$$\eta = \frac{m(1\ day) * Hydrogen\ energy\ value}{Electroyser\ power\ capacity/(hour)} \quad \textbf{(4.2)}$$

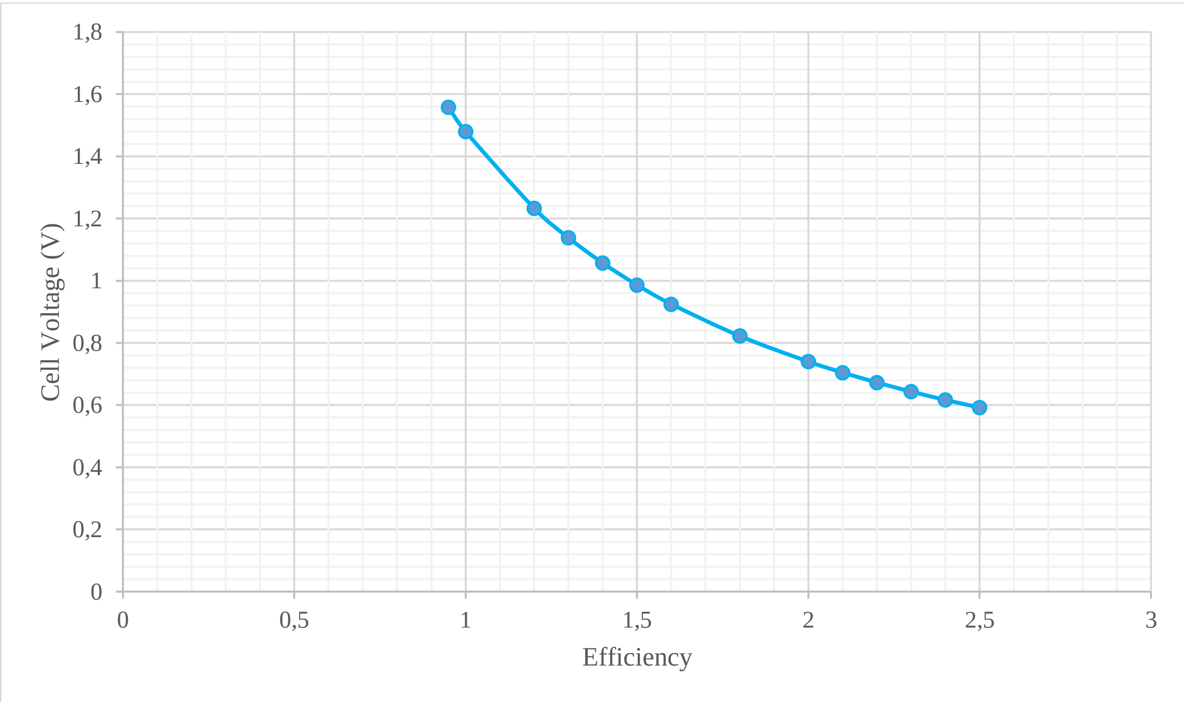


Figure 4.12: Relationship between cell voltage and efficiency [10, 142]

In Figure 4.12, the relationship between cell voltage and efficiency is seen to be inversely proportional.

4.6 Techno-Economic Analysis for Water Electrolysis Systems

Water electrolysis systems play a crucial role in producing green hydrogen, thereby facilitating the adoption of renewable energy sources. Consequently, economic evaluations of these systems are imperative. To promote their widespread commercialization effectively, focused research on economic analysis is essential. The Sargent research group conducted a study aimed at advancing the commercialization of water electrolysis systems. This group has developed a detailed economic model specifically tailored for analyzing these systems [8, 122].

Careful evaluation of cost-determining factors is essential for charting a strategic path forward. It is crucial to conduct thorough analyses and consider assumptions in light of potential unforeseen changes. Several studies suggest that large-scale electrolysis systems offer greater efficiency and economic benefits compared to small-scale ones. Specifically, unit production costs in these systems have the potential to decrease with increasing electrolysis capacity. Consequently, initial investment costs per unit area can also decrease as capacity expands [122, 144].

In 2022, Zghaibeh, Benalcazar, and Komorowska conducted modeling studies aimed at reducing the levelized cost of hydrogen, focusing on lowering the cost per kilogram of hydrogen. Jang's research compared three types of electrolysis systems, identifying alkaline water electrolysis as the most economically suitable option. In 2018, Salkuyeh explored the economic analysis of hydrogen production through biomass gasification. Stiber and collaborators investigated PEM electrolyzers, highlighting how system components influence hydrogen production costs. Lee, Jang, and others studied various electrolysis systems and renewable energy sources, concentrating on economic analyses such as levelized hydrogen cost and efficiency. Their findings indicated that the alkaline water electrolysis (AWE) system, powered by wind energy, offered the lowest levelized cost of hydrogen (LCOH), while the PEM system, using solar energy, showed the highest LCOH. Additionally, Fan and colleagues researched green hydrogen production using solar and wind energies, with wind energy demonstrating a lower levelized cost of hydrogen. Burdack similarly compared wind and solar energies, finding wind energy to yield a lower levelized cost of hydrogen. Numerous studies emphasize the feasibility of green hydrogen production, focusing on supply, transportation, and storage. Future research should expand to include these aspects for a more comprehensive economic evaluation. Recent studies, including yours, have evaluated hydrogen supply economically, considering factors like wind and natural gas availability and facility size. Although natural gas production showed economic advantages, its environmental impact makes it less favorable for widespread adoption [7, 9, 122, 145, 146].

4.6.1 Cost of Green Hydrogen Production

The cost of hydrogen production via water electrolysis is influenced by specific parameters. To accurately determine these costs, it is essential to explore key concepts. Conducting a successful economic analysis of hydrogen production requires a thorough examination of the levelized cost of hydrogen (LCOH). This entails investigating factors that impact costs, such as capital expenditures (CAPEX) and operational expenditures (OPEX) [6, 147].

4.6.1.1 Area calculation

The multiplication of the cell area where hydrogen will be produced by the number of cells and the number of stacks indicates the area of the system where production will be made. If the cell area is known, the total area is determined by the number of cells and stacks.[8, 10, 148]

$$System\ area = \frac{\text{Electrolyser capacity}/(J*V)}{Stack\ number}\ (\text{cm}^2) \quad \textbf{(4.3)}$$

$$Stack\ Area = Cell\ area * Cell\ number (\text{cm}^2) \quad \textbf{(4.4)}$$

$$System\ \ Area = Stack\ area * Stack\ number (\text{cm}^2) \quad \textbf{(4.5)}$$

4.6.1.2 Hydrogen production mass calculation

The hydrogen production formula expresses the hydrogen production in 1 hour. For this production calculation, we need to know, teoric and operational voltage, current density, cell or stack area. This mass value is the hydrogen production rate in 1 hour. [3, 6, 8, 10, 148]

$$(1\text{ hour})m = \left(\mathrm{A}(cm^2) * \mathrm{J}(\mathrm{A}/cm^2) * V_{Operational}(V)\right) * \left(\frac{V_{Theoretical}(1{,}23V)}{V_{Operational}(V)}\right) / hydrogen\ energy\ value\left(\frac{W}{kg}\right) \quad (\mathrm{kg}) \tag{4.6}$$

$$(1\text{ year})m = m(1hour) * 365 * Capacity\ rate \quad (\mathrm{kg}) \tag{4.7}$$

Capital expenditure, often referred to as investment cost or capital cost, represents the expenses required to implement a project. It varies for each system or project and depends on numerous factors. In the economic analysis of electrolyzers, capital cost plays a significant role. The cost of an electrolyzer's capital is influenced by factors such as the cost and size of electrolyzer cells, material durability, operational lifespan, expenses related to membranes and catalysts, and energy consumption. These factors collectively impact the overall cost of hydrogen production. The total capital expenditure (CAPEX) for a water electrolyzer plant encompasses several parameters. It includes costs associated with electrolyzers themselves, electrical and facility control systems, construction of hydrogen production facilities, project management costs, engineering and design tasks, assembly and commissioning activities, expenses for purification and feed systems, and ongoing facility maintenance and repairs. This total CAPEX can vary significantly based on site-specific parameters and may fluctuate accordingly [3, 6, 8, 148].

CAPEX calculation depends on production time interval, total production area, current density, molecular weight of hydrogen, Faraday constant and initial cost. In other words, the ratio of initial cost to mass calculation also gives this value.

$$Capital\ expenditure\ (CAPEX) = \frac{2F(C.mol^{-1}) * IC(\$)}{(T * Capacity\ rate)(s) * A(cm^2) * J(A.cm^{-2}) * (\frac{M}{1000})(kg.mol^{-1})} (\$/kg) \quad \textbf{(4.8)}$$

Operational costs are typically assessed once a planned project becomes operational. These costs can vary significantly depending on the specific system in question. They encompass expenses such as rent, taxes, salaries, raw material costs, fuel, and insurance payments. For electrolyzer systems, operational costs hinge on factors such as the efficiency and durability of electrolysis cells, operational and maintenance requirements, as well as costs associated with taxes and grid fees. Understanding and managing these operational costs are crucial for evaluating the ongoing financial viability of hydrogen production projects. The OPEX calculation represents ten percent of CAPEX [8, 147-148].

$$OPEX = CAPEX * 0.1 (\$/kg) \quad \textbf{(4.9)}$$

Maintenance costs refer to the expenditures necessary to conduct maintenance activities within a system at specified intervals. In an electrolysis system, periodic maintenance is essential to ensure smooth operation. It is crucial to allocate a designated budget for these purposes. Typically, maintenance costs are estimated to be around %10 of the capital cost of the system. This budget allocation helps in planning and managing the necessary upkeep to maintain optimal performance and longevity of the electrolysis system [7].

$$Maintanence\ cost = Capital\ cost * 0.1 (\$/kg) \quad \textbf{(4.10)}$$

Electricity cost is a critical factor influenced by both energy consumption and prevailing electricity prices. This parameter is essential in calculating the levelized cost of hydrogen production. The cost of electricity directly impacts the operational expenses (OPEX) of electrolysis systems, as electricity is a primary input required for the electrolysis process to produce hydrogen. Therefore, understanding and monitoring electricity costs are integral to accurately assessing the overall cost-effectiveness and competitiveness of hydrogen production through electrolysis [8].

$$Electricty\ Cost = Electricty\ price(\frac{\$}{kWh}) * (hydrogen\ energy\ value(\frac{kWh}{kg})/(\frac{V_{Theoretical}}{V_{Operational}})(\$/\text{kg}) \quad \textbf{(4.11)}$$

Systems require control of certain system elements at certain times and replacement accordingly. Especially the replacement of membranes at certain intervals is important for system integrity. However, a certain budget must be allocated for these replacement processes at certain times.

$$Replacement\ cost = Capital\ cost * 0.5(\$/\text{kg}) \quad \textbf{(4.12)}$$

Balance of plant (BoP) analysis encompasses the operational aspects surrounding the electrolyzer cell within a plant, along with the associated cost data and components. This includes considerations such as transformers and power electronics. The BoP analysis aims to optimize the overall efficiency and performance of the electrolysis system by ensuring that all supporting components and systems function harmoniously with the electrolyzer cells. By evaluating and fine-tuning these elements, the BoP analysis contributes to enhancing the reliability, cost-effectiveness, and operational lifespan of the hydrogen production plant [5, 146]

$$Balance\ of\ plant = \text{CAPEX}*0.3\ (\$/\text{kg}) \quad \textbf{(4.13)}$$

Separation and purification costs refer to the expenses associated with chemically separating and purifying products into their components within an electrolysis system. These processes involve separating oxygen and hydrogen at the anode and cathode, as well as the separation of liquid phase products. The costs of these separation and purification processes depend on factors such as the operational efficiency and quality of the anode, cathode, separation membranes, catalysts, and other system components. Typically, the separation and purification costs of the products can be estimated at approximately %20 of the electricity costs. This percentage reflects the portion of operational expenses (OPEX) allocated to the energy-intensive processes required to achieve high purity levels of hydrogen and other by-products within the electrolysis system [8].

$$Separation\ and\ purification\ cost = Electricty\ cost * 0.2\ \ (\$/kg) \qquad \textbf{(4.14)}$$

Additional costs such as piping installation and unforeseen expenses are factors that may arise beyond initial calculations in project planning. These unforeseen costs are typically estimated at around %40 of the capital cost. This allowance covers various incidental expenses that could arise during the construction and implementation phases of an electrolysis system or similar industrial projects. Proper budgeting and contingency planning for these additional costs are essential to mitigate financial risks and ensure the overall feasibility and success of the project [2].

$$Additional\ cost = CAPEX * 0.4\ (\$/kg) \qquad \textbf{(4.15)}$$

Recently, there has been a growing interest in hydrogen due to increased attention towards renewable energy sources. Hydrogen is recognized as a significant carbon-free energy carrier. To effectively harness hydrogen's potential, analysts conduct Levelized Cost of Hydrogen (LCOH) analyses, integrating both Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) to determine the cost of hydrogen production. It is crucial to consider the time value of money in this economic evaluation. As hydrogen production volumes increase, capital costs tend to decrease, thereby reducing LCOH. Systems operating at higher current densities often have lower CAPEX, although stability considerations frequently favor more consistent current densities. LCOH serves as a pivotal metric for assessing economic feasibility, particularly in commercial water electrolysis systems, and for competing with other projects. This approach ensures the adoption of optimal strategies for hydrogen production and facilitates informed decision-making. The LCOH can vary significantly across different technological setups within water electrolysis systems. Variations may arise from systems involving steam methane reforming, those directly connected to renewable energy sources or grid-integrated setups, each influencing hydrogen production costs differently. As a result, LCOH analysis stands out as one of the most critical methods globally for calculating hydrogen production costs [4, 9, 10, 147].

$$LCOH = CAPEX + OPEX + Maintanence\ cost\ + Electricty\ cost + Replacement\ cost + Balance\ of\ Plant\ cost + Separation\ and\ purification\ cost + Additional\ cost\ (\$/kg) \quad \textbf{(4.16)}$$

Current density plays a pivotal role in determining the production cost of hydrogen. Lower current densities generally lead to reduced Capital Expenditure (CAPEX) and Levelized Cost of Hydrogen (LCOH). Maintaining stable current densities and voltage not only enhances efficiency but also helps in stabilizing CAPEX and LCOH at favorable levels. Therefore, there is a preference for stable current densities and voltage in hydrogen production systems. To achieve the desired hydrogen production levels at lower current densities, increasing the capacity of the system becomes necessary. Operating under optimal conditions can further contribute to lowering both CAPEX and Operational Expenditure (OPEX) values. This approach ensures efficient production processes and supports the economic viability of hydrogen production systems [6, 10].

Understanding the economic analysis of water electrolysis systems through Capital Expenditure (CAPEX) provides insight into the cost dynamics of hydrogen production. CAPEX significantly influences the overall production cost of hydrogen. In large-scale commercial facilities, CAPEX tends to be lower because the cost per unit of product decreases with increased installation scale. This scaling effect means the cost per kilogram of produced hydrogen decreases as facility size increases. The relationship between cell area and CAPEX is inversely proportional—larger cell areas correspond to lower CAPEX rates. High current densities in electrolysis systems result in increased electricity usage. Therefore, maintaining an optimal current density is crucial to keep CAPEX at manageable levels. Under optimal operational conditions where high hydrogen production rates are achievable, CAPEX tends to decrease due to economies of scale and efficient resource utilization. These factors underscore the importance of strategic planning and operational optimization in minimizing CAPEX and enhancing the economic viability of hydrogen production systems [6, 10].

The capacity factor is a critical factor influencing green hydrogen production. It represents the ratio of actual system operating hours to the maximum possible operating hours. For instance, if a system is designed to operate continuously for 24 hours a day but, in practice, it operates for only 12 hours a day, its capacity factor would be 0.5. In the context of hydrogen production, a higher capacity factor indicates that the system is operating closer to its maximum potential, thereby maximizing output efficiency. Factors affecting the capacity factor include maintenance schedules, grid availability, and operational constraints. Optimizing the capacity factor is essential for enhancing the overall productivity and economic viability of green hydrogen production system [6, 8].

If the total CAPEX value of the facility is requested in $/kW, the total costs should be calculated as above. The parameters required to find the total CAPEX value can be found with the average bid values requested from the companies. In general, the total CAPEX value can be found by dividing it by the capacity value of the entire facility. [3, 6, 147]

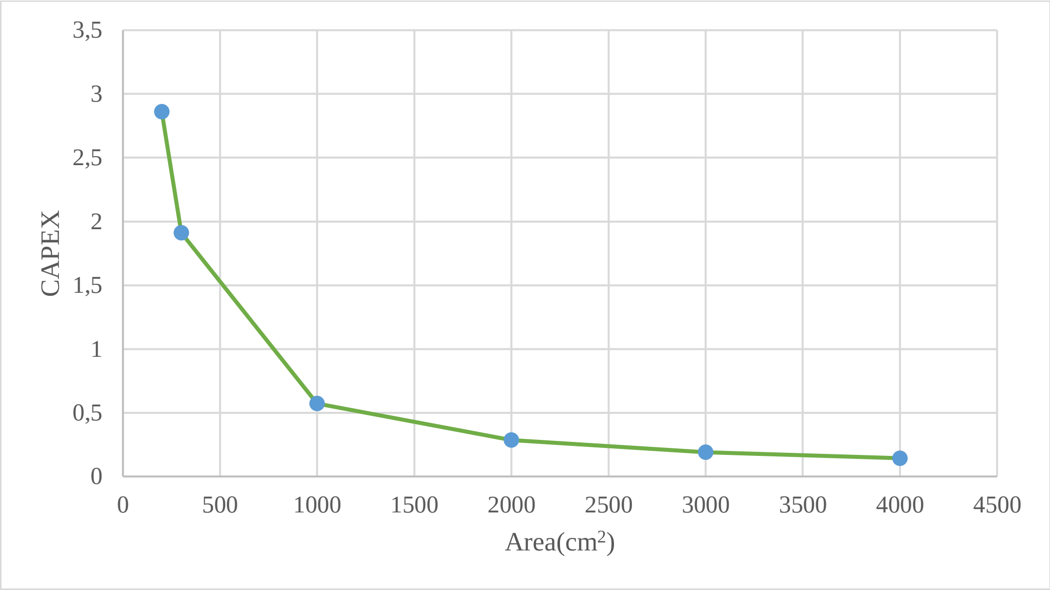


Figure 4.13 CAPEX distribution according to area size [6,8,10]

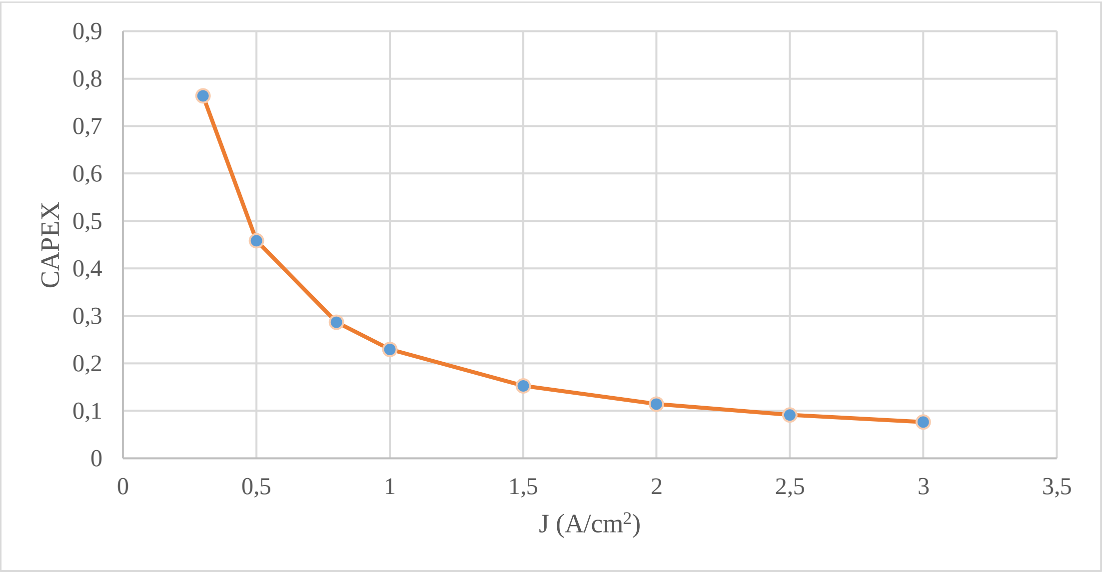


Figure 4.14 CAPEX dıstrıbutıon accordıng to current densıty [6, 8, 10]

Figures 4.13 and 4.14 show how the surface area and flux density of the electrolysis affect CAPEX, and a general CAPEX distribution is shown.

Table 4.3: Comparison of the cost of hydrogen production in water electrolysis systems[1,2,3,6,7,8,10,81,100,103,106,113,114,116,119-127,144 ,147,149,150,151,152]

	AEM	AWE	PEM	SOEC
Current Density (A/cm^2)	0.2-2	0.2-0.6	1-2	0.3-1
Cell Voltage (V)	1.4-2	1.4-2.4	1.4-2.5	1-1.7
Electrode Area (cm^2)	<300	10.000-30.000	≤3000	200
Years (Assumed)	25	25	25	25
Power Capacity (MW) (Assumed)	10 MW	10 MW	10 MW	10 MW
Hydrogen Production (kg) for 25 years,8 hour	10682503.17	10682503.17	10682503.17	12627981.55
Installation Cost (Stack)($)	10000	8000	8500	12500
CAPEX(Stack) ($/kg)	0.73858	0.59086	0.62779	0.92322
Total CAPEX ($)	5215051.007	6311880.535	6706373.068	11658420.2
Total CAPEX($/kW)	521.50	631.18	670.63	1165.84
OPEX ($/kg)	0.07386	0.05908	0.06277	0.0923
Electricity Cost ($/kg) (constant assumed)	2.12376	2.12376	2.12376	1.79656
Maintenance Cost ($/kg)	0.07386	0.05908	0.06277	0.0923
Replacement Cost ($/kg)	0.36929	0.29543	0.31389	0.461610
Separation and Purification Cost($/kg)	0.42475	0.42475	0.42475	0.35931
Balance of Plant($/kg)	0.22157	0.17725	0.18833	0.27696
Additional Cost($/kg)	0.22157	0.17725	0.18833	0.27696
LCOH($/kg)	4.24723	3.9074	3.9924	4.2792

Table 4.3 compares the cost analysis of four types of water electrolysis systems according to certain assumptions and system features. Calculations were made by keeping power capacity, year, hydrogen production and electricity costs constant. According to this analysis, the lowest LCOH was found in AWE.

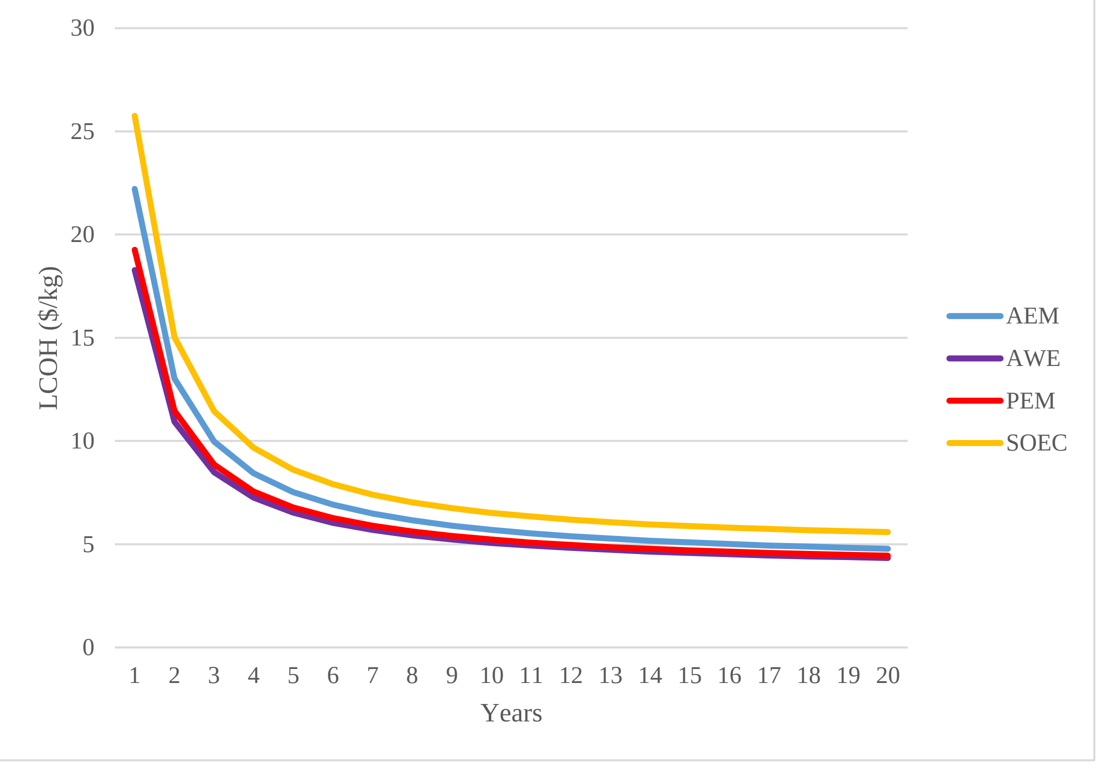


Figure 4.15 Comparison of LCOH value according to years in four different water electrolysis[1, 2, 3, 6, 7, 8, 10, 81, 100, 103, 106, 113, 114, 116, 119-127, 144, 147, 149, 150, 151, 152]

For four different water electrolysis systems with certain characteristics, the LCOH values for the twenty-year and eight-hour time intervals are plotted as in Figure 4.15. According to this graph, the water electrolysis with the highest LCOH value is SOEC. The lowest LCOH value is seen in alkaline water electrolysis.

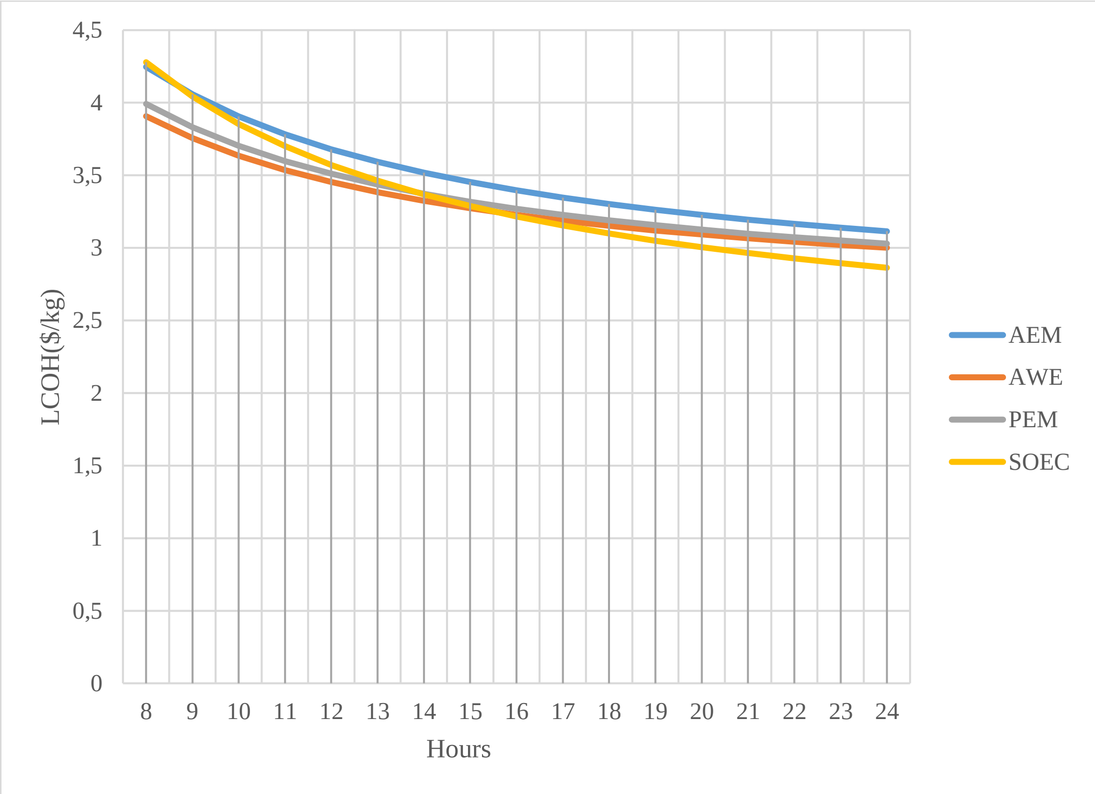


Figure 4.16 Change of LCOH value according to hours in water electrolysis systems [1, 2, 3, 6, 7, 8, 10, 81, 100, 103, 106, 113, 114, 116, 119-127, 144, 147, 149, 150, 151, 152]

Figure 4.16 shows the change in the LCOH value of four different water electrolyses with time. Accordingly, the LCOH value decreases as the hour increases in each electrolysis. While the electrolysis with the lowest LCOH value in the first hour is AWE, the lowest LCOH value at the end of 24 hours is seen in SOEC. The reason for this may be due to the energy value of hydrogen. Thus, as the time interval increases, the electricity cost is also lower than other electrolyses, thus closing the gap.

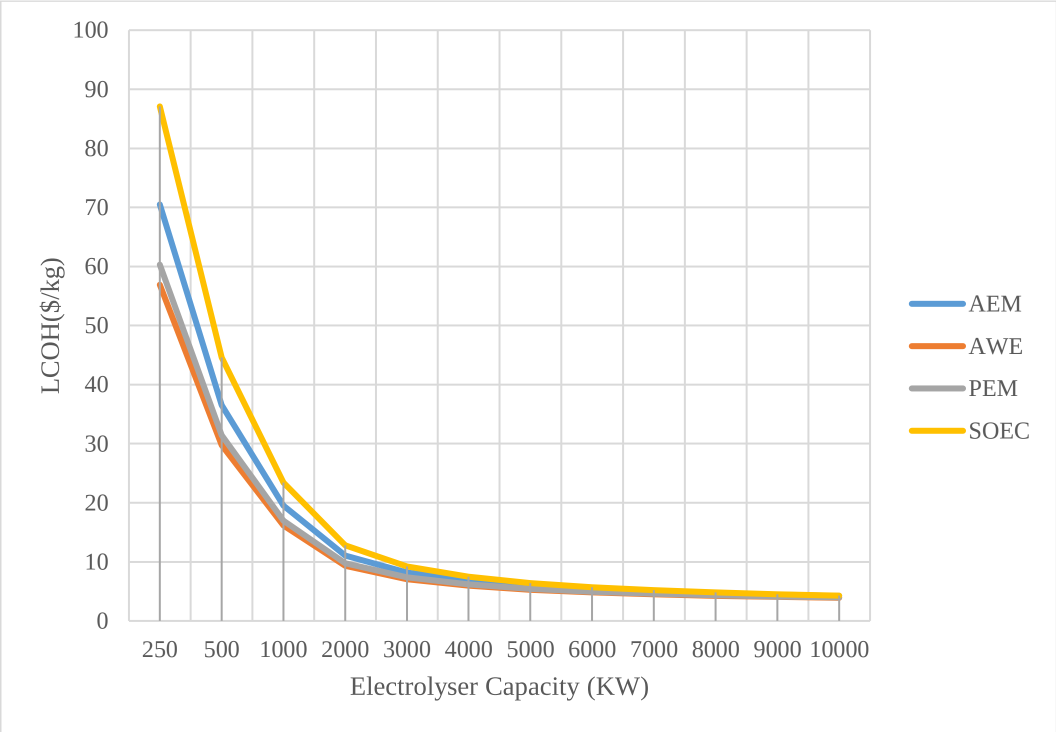


Figure 4.17 Variation of LCOH value according to power capacity ratios in water electrolysis systems [1, 2, 3, 6, 7, 8, 10, 81, 100, 103, 106, 113, 114, 116, 119-127, 144, 147, 149, 150, 151, 152]

Figure 4.17 shows the change in LCOH values of electrolyzers with power capacity ratios. Accordingly, as the capacity ratios increase in electrolyzer systems, LCOH values decrease for all four electrolyzers. As a result, as the capacity ratio increases, the LCOH value decreases. Based on this, when designing an electrolysis system, attention is paid to having a large electrolysis power capacity.

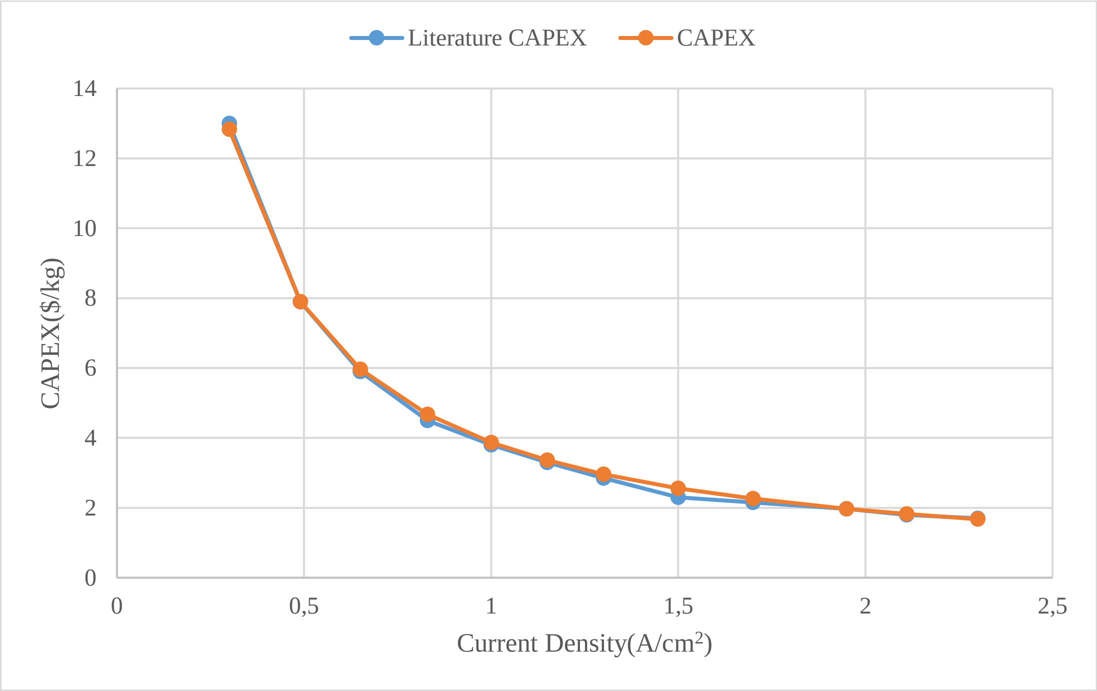


Figure 4.18 Comparison of literature CAPEX and calculated CAPEX in water electrolysis [1, 2, 3, 6, 7, 8, 10, 81, 100, 103, 106, 113, 114, 116, 119-127, 144, 147, 149, 150, 151, 152]

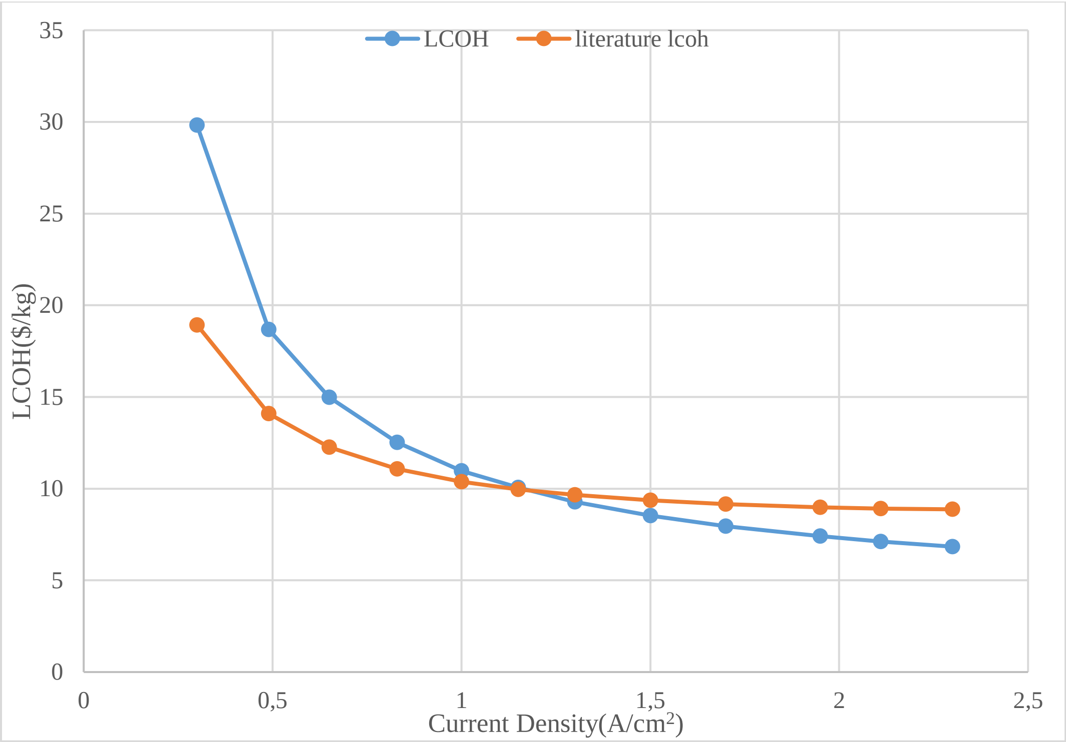


Figure 4.19 Comparison of literature LCOH and calculated LCOH in water electrolysis [1, 2, 3, 6, 7, 8, 10, 81, 100, 103, 106, 113, 114, 116, 119-127, 144, 147, 149, 150, 151, 152]

In Figure 4.18 and Figure 4.19, literature [1] (Villagra and Millet) and calculated values are compared graphically. The formulas and symbols used in the Excel calculation are specified above. According to different fluid density values taken from the literature, CAPEX and LCOH values were calculated above. The graph on the left is the graph taken from the literature. The fluid density values here, again the same literature and formulas from other literatures were transferred to Excel to create tables and graphs. For example, our CAPEX value was 7.9 in Excel where a fluid density of 0.49 was entered. This value is the same as the value in the graph. According to the LCOH formula taken from different literatures, LCOH was 18.68. However, when we consider the OPEX value according to the LCOH calculation in the same literature as the graph, our LCOH value was calculated as 14.1. This value is a correct value when looking at the graph in the literature. When the formula is applied to Excel according to the fluid density of 2.3, the CAPEX value is 1.67 and this value is compatible with the CAPEX value at the fluid density of 2.3 as seen in the graph in the literature. Our LCOH value calculated from different literatures in Excel is 6.83. However, according to the same literature formula as the graph, our LCOH value is 8.87 and this value is the same as the graph in the literature. As a result, our CAPEX values according to Excel were correct. However, our LCOH values differed because they were calculated according to different literature. When the CAPEX values created with the OPEX values in the same literature were added, there was no difference between the LCOH values in the graph taken from the literature. Accordingly, the graph created and the graph in the literature were compared and verification was made. A comparison of water electrolysis systems is shown in Table 4.4.

Table 4.4: Comparison of the cost of hydrogen production for current density [1, 2, 3, 6, 7, 8, 10, 81, 100, 103, 106, 113, 114, 116, 119-127, 144, 147, 149, 150, 151, 152]

CURRENT DENSİTY(A/ cm^2)	Literature CAPEX($ /kg)	CAPEX($ /kg)	Percentage Change(CAPEX) %	LCOH($ /kg)	Literature LCOH($/kg)	Percentage Change(LCOH) %
0.2	16	19.24	20,25	40.224	25.14	60
0.3	13	12.83	-1,31	29.823	18.93	57,543
0.49	7.9	7.9	0,00	18.68	14.1	32,482
0.65	5.9	5.96	1,02	14.986	12.26	22,234
0.83	4.5	4.67	3,78	12.527	11.07	13,161
1	3.8	3.87	1,84	10.977	10.37	5,853
1.15	3.3	3.36	1,82	10.056	9.96	0,963
1.3	2.85	2.96	3,86	9.276	9.66	-3,975
1.5	2.3	2.56	11,30	8.526	9.36	-8,910
1.7	2.15	2.26	5,12	7.956	9.16	-13,144
1.95	1.97	1.974	0,20	7.4174	8.974	-17,345
2.11	1.8	1.82	1,11	7.122	8.92	-20,156
2.3	1.7	1.6733	-1,57	6.837	8.873	-22,944

The scenario was created considering the conditions of Türkiye. Cost calculations were made according to the features of four different electrolysis systems and are shown in detail in Appendice A. The calculation was made by considering the fluid density, voltage value, initial cost and similar features of four different electrolysis systems. The value range of each electrolysis system was taken differently according to its features and the calculation was made in such a way that the most efficient LCOH value was obtained.

Scenario :

Location: Türkiye
Sunbathing time in Türkiye: 7.5 hours
Power capacity:100 MW
Years: 25
Molecular weight:0.002 $kg.mol^{-1}$
Faraday constant: 96485 $C.mol^{-1}$
Number of electron:2
Capacity Factory: %85

Table 4.5: Comparison of the cost of hydrogen production for scenario in water electrolysers

	AEM	**AWE**	**PEM**	**SOEC**
CAPEX($/kg)	0.0649	0.0519	0.0551	0.0985
OPEX($/kg)	0.0065	0.0052	0.0055	0.0098
Electricity cost($/kg)	1.7490	1.7490	1.7490	1.7966
Maintenance cost($/kg)	0.0065	0.0052	0.0055	0.0098
Replacement cost($/kg)	0.0324	0.0260	0.0276	0.0492
Separation and purification cost($/kg)	0.3498	0.3498	0.3498	0.3593
Balance of plant($/kg)	0.0195	0.0156	0.0165	0.0295
Additional cost($/kg)	0.0195	0.0156	0.0165	0.0295
LCOH ($/kg)	**2.2480**	**2.2181**	**2.2256**	**2.3824**

The Levelized Cost of Hydrogen (LCOH) values for the water electrolysis systems, calculated based on the scenario developed for Türkiye, are presented in Table 4.5. The study considered four distinct water electrolysis technologies—Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), and Solid Oxide Electrolysis Cells (SOEC) each with unique characteristics and operating conditions. Given these differences, the analysis was performed to determine the most efficient and cost-effective electrolysis system for hydrogen production in Türkiye.

The calculations revealed that, according to the scenario characteristics and electrolysis system conditions defined, AWE emerged as the most cost-effective technology. It was found to have the lowest CAPEX (capital expenditure) value among the four systems, with a value of 0.0519 $/kg. This suggests that AWE offers the most affordable upfront capital costs for installation and setup.

Additionally, AWE also demonstrated the lowest LCOH (Levelized Cost of Hydrogen), with a value of 2.2181 $/kg. This result confirms AWE's efficiency in terms of hydrogen production costs, making it the most economical option for large-scale hydrogen production. The LCOH value for AWE was found to be consistently low, even when compared to the previous electrolysis calculations made under similar conditions.

In comparison, PEM electrolysis, while more expensive than AWE, still emerged as the second most cost-effective system for hydrogen production. This indicates that, although PEM has a higher hydrogen production cost than AWE, it remains a viable option for production, especially in cases where other operational factors—such as flexibility and scalability—may be important.

On the other hand, SOEC electrolysis was found to be the most expensive technology in terms of hydrogen production. The calculated LCOH for SOEC was 2.3824 $/kg, making it the least economical choice among the four systems examined. This higher cost is likely due to the specific operating conditions and material requirements associated with SOEC technology, which can make it more expensive to operate and maintain.

Based on these calculations, it is clear that AWE electrolysis is the most suitable technology for achieving low-cost hydrogen production in Türkiye. Given its superior CAPEX and LCOH values, AWE should be prioritized as the primary technology for large-scale hydrogen production. Furthermore, PEM electrolysis can be considered as a secondary option, offering a slightly higher cost but still remaining competitive in the market.

By focusing on the implementation of AWE electrolysis, Türkiye will be well-positioned to meet its hydrogen production targets for 2030 and 2050. With AWE leading the way in cost-effectiveness, the country will be able to accelerate the development of its green hydrogen industry, reduce production costs, and make significant progress toward its renewable energy and green hydrogen goals in the shortest time possible.

CONCLUSION

This study addresses the pressing issue of global energy consumption and emphasizes the critical role that renewable energy sources can play in reducing environmental impact. With the world's energy demand steadily increasing, there is a growing need to transition to energy sources that are sustainable and have minimal ecological footprints. Among these, renewable energy sources, particularly solar and wind, are at the forefront due to their abundance, cost-effectiveness, and low environmental impact.

The study compares global renewable energy capacity rates, with a specific focus on Türkiye, highlighting its significant potential in solar and wind energy production. In Türkiye, solar and wind energy are the most widely utilized renewable sources due to the country's favorable geographic location and climate conditions. This makes Türkiye particularly well-suited for the large-scale adoption of renewable energy technologies.

The research then turns to explore the potential of hydrogen energy, with a strong emphasis on the importance of focusing on green hydrogen. Green hydrogen, produced using renewable electricity from sources such as wind and solar, is a key component in decarbonizing the energy sector. The study underlines that the production of green hydrogen becomes significantly more cost-effective when powered by renewable electricity, as compared to using conventional grid electricity.

A key part of the study was dedicated to analyzing electrolysis systems, which are central to green hydrogen production. Four different types of electrolysis technologies—Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), and Solid Oxide Electrolysis Cells (SOEC)—were examined in terms of their operating conditions, material properties, and economic performance. By evaluating these systems under a set of conditions (using a 10 MW system as the base case), the study compared the hydrogen production costs for each technology. The costs of CAPEX (capital expenditures), OPEX (operational expenditures), and LCOH (Levelized Cost of Hydrogen) were calculated for each system.

The study found that, based on the calculations for these four electrolysis systems, AWE (Alkaline Water Electrolysis) had the lowest hydrogen production cost, with a value of 3.9074 $/kg. This made AWE the most economically viable electrolysis system when compared to PEM, AEM, and SOEC. Given these findings, AWE was identified as the most suitable technology for cost-effective green hydrogen production, particularly in the context of Türkiye’s renewable energy resources.

Building upon this, the study examined a 100 MW alkaline electrolysis system powered by solar energy in Türkiye. Using specific assumptions about solar resource availability, the techno-economic analysis found that the system could be designed to operate with an average of seven sunlight hours per day. The analysis involved creating scenarios for all four electrolysis systems, considering the factors necessary to achieve the lowest hydrogen production cost. By considering key variables such as initial costs, flow density, and voltage, the study identified the optimal electrolysis setup.

In the scenario with the 100 MW system operating for a period of 25 years, the hydrogen production cost was found to be lowest for AWE, with an LCOH value of 2.218 $/kg. When compared to other systems, AWE again proved to be the most cost-efficient method for producing green hydrogen in Türkiye. PEM came in secondand LCOH value is 2.225$/kg, followed by AEM in third place and LCOH value is 2.248$/kg, while SOEC had the highest hydrogen production cost among the systems analyzed and LCOH value is 2.382$/kg.

Based on these findings, it is clear that AWE (Alkaline Water Electrolysis) represents the most suitable option for Türkiye’s green hydrogen production, considering both economic factors and technical performance. This conclusion is further supported by the calculated costs and the operating conditions specific to Türkiye’s energy infrastructure.

The study also highlights Türkiye's ambitious renewable energy targets and green hydrogen goals. Türkiye aims to have an installed electrolysis capacity of 2 GW by

2030 and 70 GW by 2050. Additionally, one of the country's primary objectives is to reduce the cost of green hydrogen production to 2.4 $/kg by 2035, and to further decrease it to below 1.2 $/kg by 2053.

When considering the increasing installation rates of solar and wind energy in Türkiye, the study observes a positive trend in the country's renewable energy growth. Solar power capacity is increasing at an average rate of approximately 1500 MW per year, while wind power capacity is growing by around 1000 MW annually. These trends indicate that Türkiye is making significant strides toward meeting its renewable energy targets.

With these expanding renewable energy capacities, the study concludes that Türkiye is on track to meet its hydrogen production targets. By 2050, assuming 40% of the installed renewable capacity is dedicated to green hydrogen production, the potential annual hydrogen production could reach approximately 1196 kt (kilotons) of green hydrogen. This production would be a key contributor to the nation's energy transition and its climate mitigation efforts.

In summary, the study demonstrates that Türkiye's renewable energy infrastructure is well-suited to meet its green hydrogen goals. The combination of solar and wind resources, alongside the cost-competitive AWE technology, offers a promising pathway for Türkiye to become a leader in green hydrogen production, both for domestic consumption and for international trade. By leveraging these resources and technologies, Türkiye can achieve its strategic energy targets while contributing to global efforts in reducing carbon emissions and advancing the green energy transition.

As a result, it is possible to achieve the targets determined with this study in the shortest time.

- By considering certain conditions, four electrolysis systems with 10 MW power capacity were compared and the lowest LCOH value was found to be AWE with 3.9074 $/kg.

- It was observed that parameters such as flow density, efficiency, voltage, system area, and initial cost play a major role in CAPEX and LCOH values in electrolysis systems. Accordingly:

  -The larger the system area electrolysis power capacity, the smaller the CAPEX and LCOH values of the system.

  -The larger the electrolysis power capacity, the smaller the CAPEX and LCOH values of the system.

  -The smaller the voltage value, the smaller the CAPEX and LCOH values of the system.

  -The larger the flow density, the smaller the CAPEX and LCOH values of the system.

- According to the calculations, it will be possible to reduce the green hydrogen production cost to 2.4 US dollars/kgH in 2035 and below 1.2 US dollars/kgH by 2053.
- According to the research, when solar and wind installed power capacity rates are also taken into account, it will be possible to reach 2 GW of electrolyzer installed power capacity in 2030, 5 GW in 2035 and 70 GW in 2053.

The findings of this study indicate that green hydrogen production in Türkiye can be realized at a competitive cost by harnessing the country’s abundant renewable energy resources, such as wind, solar, and hydropower. With its favorable geographic location and substantial renewable energy potential, Türkiye is well-positioned to become a global leader in the production of clean hydrogen.

By establishing green hydrogen production facilities across the country, Türkiye could significantly reduce the cost of electricity generation. This reduction in electricity costs would not only enhance the economic viability of green hydrogen but also promote its integration into various industrial and energy sectors. Additionally, the transition to green hydrogen could provide an alternative to conventional fossil fuels, thereby contributing to climate change mitigation and carbon emission reduction goals.

Moreover, the development of a hydrogen economy in Türkiye could stimulate the domestic market and open up new opportunities for international trade. Given the growing global demand for clean hydrogen, Türkiye could leverage its strategic location to become a key exporter of green hydrogen, particularly to European and neighboring markets. This would not only create new avenues for trade but also enhance Türkiye's energy security and economic resilience by diversifying its energy exports.

Ultimately, the establishment of green hydrogen facilities would generate a range of economic benefits for Türkiye, including the creation of high-value jobs, the development of technological expertise, and the attraction of foreign investments in clean energy technologies. These developments would help position Türkiye as a regional hub for renewable energy and green hydrogen production, fostering long-term economic growth, job creation, and environmental sustainability.

In conclusion, green hydrogen production in Türkiye represents a strategic opportunity to capitalize on the country's renewable energy resources, enhance its energy infrastructure, and strengthen its position in the global energy market, all while contributing to sustainable economic development and achieving climate targets.

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APPENDICES

Appendix A: Detailed Calculations of Water Electrolysis Systems.

Figure A.1 Excel account display

Figure A.2 Excel account display

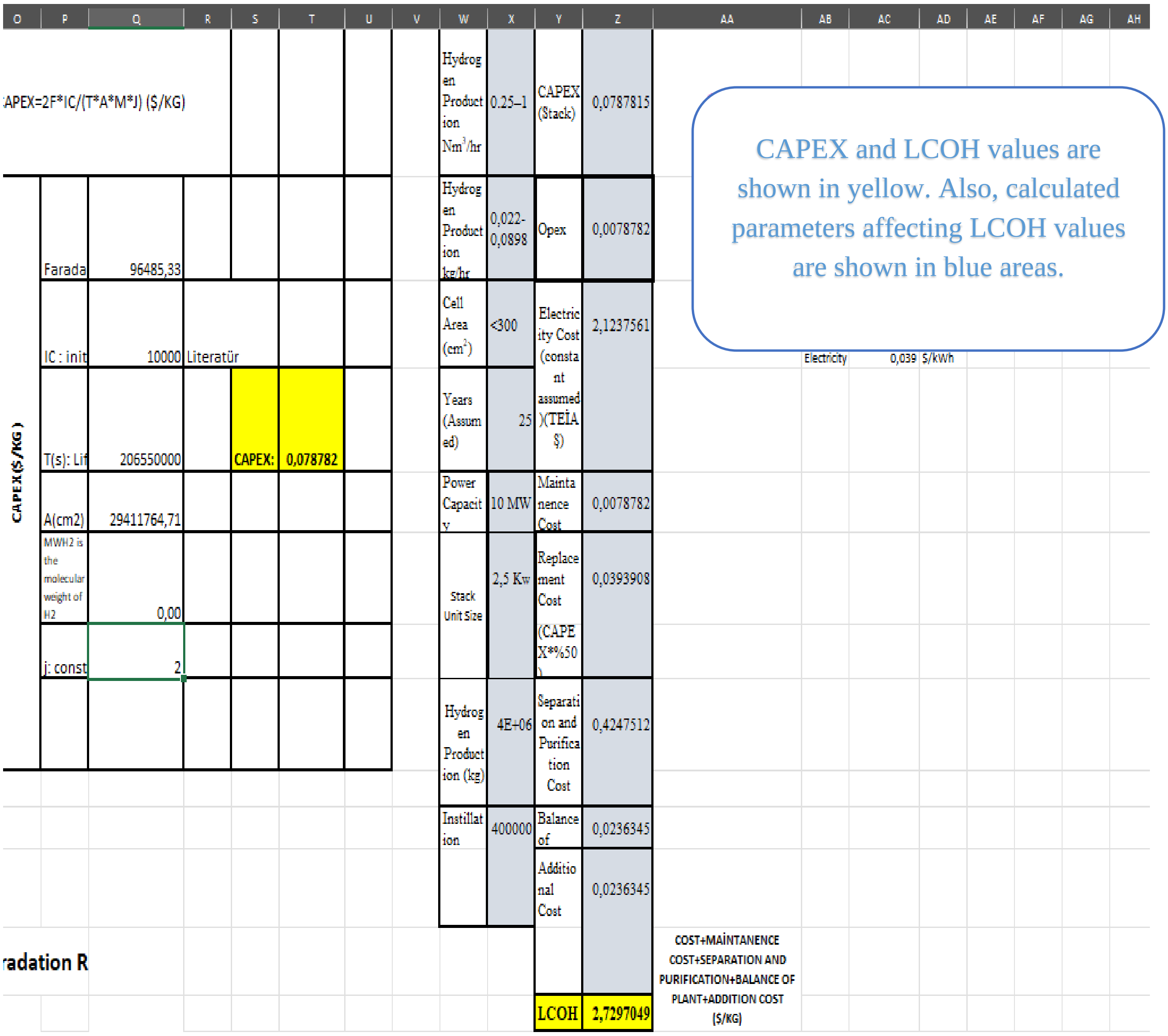
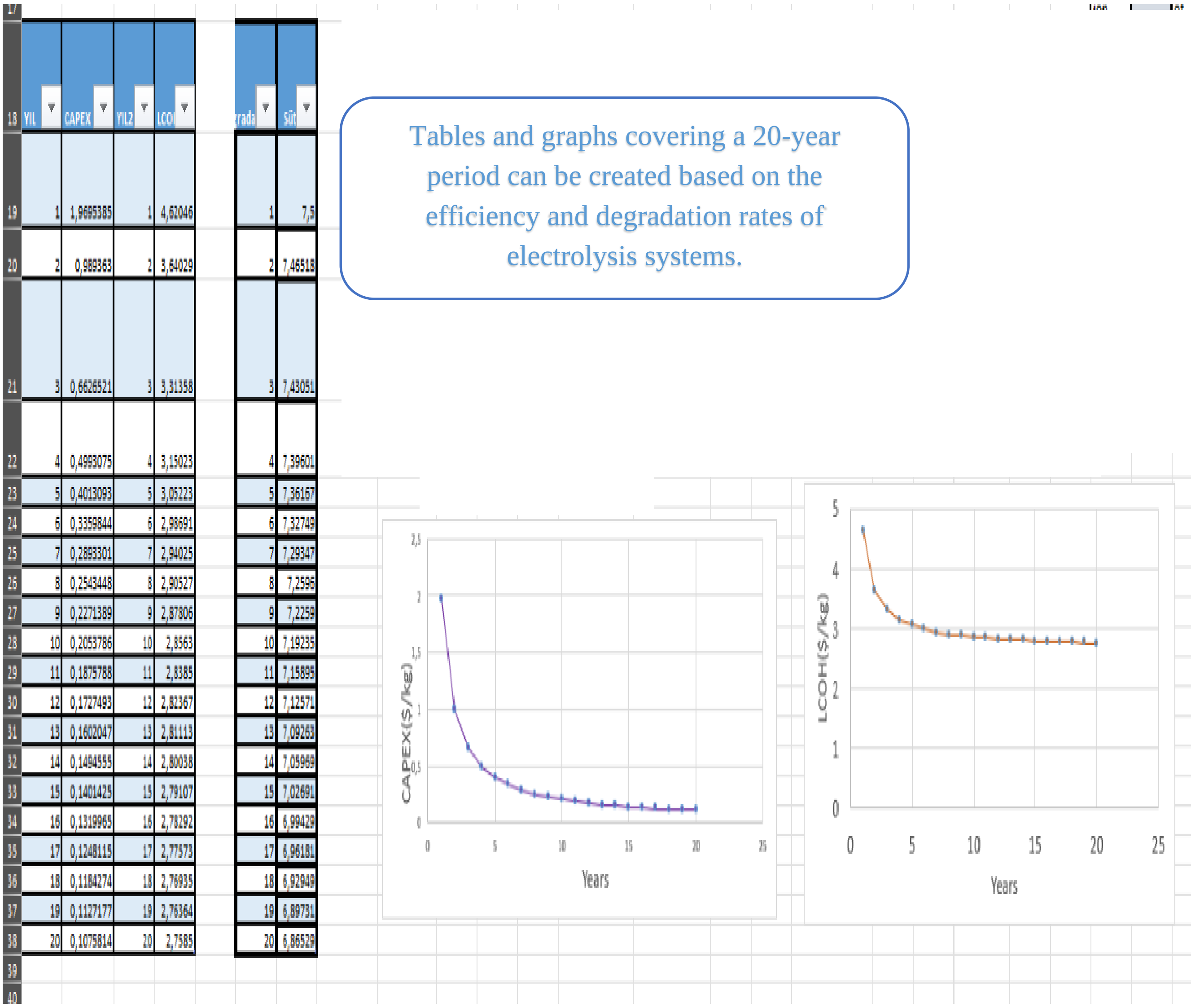


Figure A.3 Excel account display



18	YIL	CAPEX	YIL2	LCOI	rada	Süt
19	1	1,9695385	1	4,62046	1	7,5
20	2	0,989363	2	3,64029	2	7,46518
21	3	0,6626521	3	3,31358	3	7,43051
22	4	0,4993075	4	3,15023	4	7,39601
23	5	0,4013093	5	3,05223	5	7,36167
24	6	0,3359844	6	2,98691	6	7,32749
25	7	0,2893301	7	2,94025	7	7,29347
26	8	0,2543448	8	2,90527	8	7,2596
27	9	0,2271389	9	2,87806	9	7,2259
28	10	0,2053786	10	2,8563	10	7,19235
29	11	0,1875788	11	2,8385	11	7,15895
30	12	0,1727493	12	2,82367	12	7,12571
31	13	0,1602047	13	2,81113	13	7,09263
32	14	0,1494555	14	2,80038	14	7,05969
33	15	0,1401425	15	2,79107	15	7,02691
34	16	0,1319965	16	2,78292	16	6,99429
35	17	0,1248115	17	2,77573	17	6,96181
36	18	0,1184274	18	2,76935	18	6,92949
37	19	0,1127177	19	2,76364	19	6,89731
38	20	0,1075814	20	2,7585	20	6,86529

Figure A.4 Excel account display

Scenario :

Location: Türkiye
Sunbathing time in Türkiye: 7.5 hours
Power capacity:100 MW
Years: 25
Molecular weight:0.002 $kg.mol^{-1}$
Faraday constant: 96485 $C.mol^{-1}$
Number of electron:2
Capacity Factory: %85

AWE: Initial cost: 8000 $

Current density: 0.6 A/cm^2

Cell voltage: 1.4 V

$$Stack\ Area = Cell\ area * Cell\ number(cm^2)$$

$$System\ \ Area = Stack\ area * Stack\ number(cm^2)$$

$$System\ area = \frac{\text{Electrolyser capacity}/(J * V)}{Stack\ number}$$

$$System\ area = \frac{100{,}000{,}000(\text{W})/(0.6(\frac{A}{cm^2}) * 1.4)}{100}$$

System Area= 119047619 cm^2

$$(\text{1 hour})m = \left(119047619(cm^2) * 0.6\left(\frac{\text{A}}{cm^2}\right) * 1.4(V)\right) * \frac{\frac{1.23(V)}{1.4(V)}}{39400\left(\frac{W}{kg}\right)}$$

$$m\text{=2229,876 (kg)}$$

$$(\text{1 year})m = m(1hour) * 365 * 7.5 * 0.85$$

$$m = 5188644.398\ \ (\text{kg})$$

$$(25\ \text{years})m = 5188644.398 * 25$$

$$(25\ \text{years})m = 129716110\ (\text{kg})$$

$$Capital\ expenditure(CAPEX) = \frac{2F(C.mol^{-1})*IC(\$)}{(T*Capacity\ rate)(s)*A(cm^{2})*J(A.cm^{-2})*(\frac{M}{1000})(kg.mol^{-1})}(\$/\text{kg})$$

$$CAPEX = \frac{2*96485.33\left(C.mol^{-1}\right)*8000(\$)}{(360*3600*25*7.5)(s)*0.85*119047619(cm^{2})*0.6\left(\frac{A}{cm^{2}}\right)*0.002016(kg.mol^{-1})}$$

$$CAPEX = 0.0519(\$/\text{kg})$$

$$OPEX = CAPEX * 0.1(\$/\text{kg})$$

$$OPEX = 0.00519(\$/\text{kg})$$

$$Maintanence\ cost = Capital\ cost * 0.1(\$/\text{kg})$$

$$Maintanence\ cost = 0.00519(\$/\text{kg})$$

$$Electricty\ Cost = Electricty\ price(\frac{\$}{kWh}) * (hydrogen\ energy\ value(\frac{kWh}{kg})/(\frac{V_{Theoretical}}{V_{Operational}})(\$/\text{kg})$$

$$Electricty\ Cost = 0.039(\frac{\$}{kWh}) * (39.40(\frac{kWh}{kg})/(\frac{1.23}{1.4})(\$/\text{kg})$$

$$Electricty\ Cost = 1.7489(\$/\text{kg})$$

$$Replacement\ cost = Capital\ cost * 0.5(\$/\text{kg})$$

$$Replacement\ cost = 0.0259(\$/\text{kg})$$

$$Balance\ of\ plant = \text{CAPEX}*0.3\ (\$/\text{kg})$$

$$Balance\ of\ plant = 0.0155(\$/\text{kg})$$

$$Separation\ and\ purification\ cost = Electricty\ cost * 0.2\ \ (\$/kg)$$

$$Separation\ and\ purification\ cost = 0.3497(\$/kg)$$

$$Additional\ cost = CAPEX * 0.4\ (\$/kg)$$

$$Additional\ cost = 0.0155(\$/kg)$$

$LCOH = CAPEX + OPEX + +Maintanence\ cost\ + Electricty\ cost +$
$Replacement\ cost + Balance\ of\ Plant\ cost +$
$Separation\ and\ purification\ cost + Additional\ cost$ (\$/kg)

$LCOH = 0.0519 + 0.00519 + 0.00519 + 1.7489 + 0.0259 + 0.3497 + 0.0155 + 0.0155(\$/kg)$

$\boldsymbol{LCOH = 2.2181}$**(\$/kg)**

$$TOTAL\ CAPEX = CAPEX * m(1\ year) * year$$

$$TOTAL\ CAPEX = 6732672.57(\$)$$

AEM: Initial Cost: 10,000\$

Current density: 2 A/cm^2

Cell voltage: 1.4 V

$$Stack\ Area = Cell\ area * Cell\ number (cm^2)$$

$$System\ \ Area = Stack\ area * Stack\ number (cm^2)$$

$$System\ area = \frac{\text{Electrolyser capacity}/(J * V)}{Stack\ number}$$

$$System\ area = \frac{100{,}000{,}000(\text{W})/(2(\frac{A}{cm^2}) * 1.4)}{40{,}000}$$

System Area= 35714285.71cm^2

$$(1\ \text{hour})m = \left(35714285.71(cm^2) * 2\left(\frac{\text{A}}{cm^2}\right) * 1.4(V)\right) * \frac{\frac{1.23(V)}{1.4(V)}}{39400\left(\frac{W}{kg}\right)}$$

$$m\text{=2229.876(kg)}$$

$$(1\ \text{year})m = m(1hour) * 365 * 7.5 * 0.85$$

$$m = 5188644.398\text{(kg)}$$

$$(25\ \text{years})m = 5188644.398*25$$

$$(25\ \text{years})m = 129716110\ \text{(kg)}$$

$$Capital\ expenditure(CAPEX) = \frac{2F(C.mol^{-1})*IC(\$)}{(T*Capacity\ rate)(s)*A(cm^2)*J(A.cm^{-2})*(\frac{M}{1000})(kg.mol^{-1})}(\$/\text{kg})$$

$$CAPEX = \frac{2*96485.33\left(C.mol^{-1}\right)*10000(\$)}{(360*3600*25*7.5)(s)*0.85*35714285.71(cm^2)*2\left(\frac{A}{cm^2}\right)*0.002016(kg.mol^{-1})}$$

$$CAPEX = 0.0648\ (\$/\text{kg})$$

$$OPEX = CAPEX * 0.1(\$/\text{kg})$$

$$OPEX = 0.00648(\$/\text{kg})$$

$$Maintanence\ cost = Capital\ cost * 0.1(\$/\text{kg})$$

$$Maintanence\ cost = 0.00648(\$/\text{kg})$$

$$Electricty\ Cost = Electricty\ price(\frac{\$}{kWh}) * (hydrogen\ energy\ value(\frac{kWh}{kg})/(\frac{V_{Theoretical}}{V_{Operational}})(\$/\text{kg})$$

$$Electricty\ Cost = 0.039(\frac{\$}{kWh}) * (39.40(\frac{kWh}{kg})/(\frac{1.23}{1.4})(\$/\text{kg})$$

$$Electricty\ Cost = 1.7489(\$/kg)$$

$$Replacement\ cost = Capital\ cost * 0.5(\$/kg)$$

$$Replacement\ cost = 0.0324(\$/kg)$$

$$Balance\ of\ plant = CAPEX*0.3\ (\$/kg)$$

$$Balance\ of\ plant = 0.0194(\$/kg)$$

$$Separation\ and\ purification\ cost = Electricty\ cost * 0.2\ \ (\$/kg)$$

$$Separation\ and\ purification\ cost = 0.3497(\$/kg)$$

$$Additional\ cost = CAPEX * 0.4\ (\$/kg)$$

$$Additional\ cost = 0.0194(\$/kg)$$

$LCOH = CAPEX + OPEX + +Maintanence\ cost\ + Electricty\ cost +$
$Replacement\ cost + Balance\ of\ Plant\ cost +$
$Separation\ and\ purification\ cost + Additional\ cost\ (\$/kg)$

$LCOH = 0.0648 + 0.00648 + 1.7489 + 0.00648 + 0.0324 + 0.0194 + 0.3497 + 0.01946(\$/kg)$

$\boldsymbol{LCOH = 2.2479(\$/kg)}$

$$TOTAL\ CAPEX = CAPEX * m(1\ year) * year$$

$$TOTAL\ CAPEX = 8415840.713\ (\$)$$

PEM: Initial Cost: 8500$

Current density: 2 A/cm^2

Cell voltage: 1.4 V

$$Stack\ Area = Cell\ area * Cell\ number (cm^2)$$

$$System\ \ Area = Stack\ area * Stack\ number (cm^2)$$

$$System\ area = \frac{\text{Electrolyser capacity}/(J * V)}{Stack\ number}$$

$$System\ area = \frac{100{,}000{,}000(\text{W})/(2(\frac{A}{cm^2}) * 1.4)}{50}$$

System Area= 35714285.71 cm^2

$$(\text{1 hour})m = \left(35714285.71(cm^2) * 2\left(\frac{\text{A}}{cm^2}\right) * 1.4(V)\right) * \frac{\frac{1.23(V)}{1.4(V)}}{39400\left(\frac{W}{kg}\right)}$$

$$m = 2229.876\ (\text{kg})$$

$$(\text{1 year})m = m(1hour) * 365 * 7.5 * 0.85$$

$$m = 5188644.398(\text{kg})$$

$$(\text{25 years})m = 5188644.398*25$$

$$(\text{25 years})m = 129716110\ (\text{kg})$$

$$Capital\ expenditure(CAPEX) = \frac{2F(C.mol^{-1}) * IC(\$)}{(T * Capacity\ rate)(s) * A(cm^2) * J(A.cm^{-2}) * (\frac{M}{1000})(kg.mol^{-1})}(\$/\text{kg})$$

$$CAPEX = \frac{2 * 96485.33(C.mol^{-1}) * 8500(\$)}{(360 * 3600 * 25 * 7.5)(s) * 0.85 * 35714285.71(cm^2) * 2\left(\frac{A}{cm^2}\right) * 0.002016(kg.mol^{-1})}$$

$$CAPEX = 0.0551(\$/\text{kg})$$

$$OPEX = CAPEX * 0.1(\$/\text{kg})$$

$$OPEX = 0.00551(\$/\text{kg})$$

$$Maintanence\ cost = Capital\ cost * 0.1(\$/\text{kg})$$

$$Maintanence\ cost = 0.00551(\$/\text{kg})$$

$$Electricty\ Cost = Electricty\ price(\frac{\$}{kWh}) * (hydrogen\ energy\ value(\frac{kWh}{kg})/(\frac{V_{Theoretical}}{V_{Operational}})(\$/\text{kg})$$

$$Electricty\ Cost = 0.039(\frac{\$}{kWh}) * (39.40(\frac{kWh}{kg})/(\frac{1.23}{1.4})(\$/\text{kg})$$

$$Electricty\ Cost = 1.7489(\$/\text{kg})$$

$$Replacement\ cost = Capital\ cost * 0.5(\$/\text{kg})$$

$$Replacement\ cost = 0.0275(\$/\text{kg})$$

$$Balance\ of\ plant = \text{CAPEX*0.3}\ (\$/\text{kg})$$

$$Balance\ of\ plant = 0.0165(\$/\text{kg})$$

$$Separation\ and\ purification\ cost = Electricty\ cost * 0.2\ \ (\$/\text{kg})$$

$$Separation\ and\ purification\ cost = 0.3497(\$/\text{kg})$$

$$Additional\ cost = CAPEX * 0.4\ (\$/\text{kg})$$

$$Additional\ cost = 0.0165(\$/\text{kg})$$

$LCOH = CAPEX + OPEX + +Maintanence\ cost\ + Electricty\ cost + Replacement\ cost + Balance\ of\ Plant\ cost + Separation\ and\ purification\ cost + Additional\ cost$ (\$/kg)

$LCOH = 0.0551 + 0.00551 + 1.7489 + 0.00551 + 0.0275 + 0.0165 + 0.3497 + 0.0165$(\$/kg)

$\boldsymbol{LCOH = 2.2256}$ **(\$/kg)**

$$TOTAL\ CAPEX = CAPEX * m(1\ year) * year$$

$$TOTAL\ CAPEX = 7153464.606\ (\$)$$

SOEC: Initial Cost: 12500\$

Current density: 1 A/cm^2

Cell voltage: 1.7 V

$$Stack\ Area = Cell\ area * Cell\ number (cm^2)$$

$$System\ \ Area = Stack\ area * Stack\ number (cm^2)$$

$$System\ area = \frac{\text{Electrolyser capacity}/(J * V)}{Stack\ number}$$

$$System\ area = \frac{100{,}000{,}000(\text{W})/(1(\frac{A}{cm^2}) * 1.7)}{20000}$$

System Area= 58823529.41 cm^2

$$(1\text{ hour})m = \left(58823529.41(cm^2) * 1\left(\frac{\text{A}}{cm^2}\right) * 1.7(V)\right) * \frac{\frac{1.23(V)}{1.7(V)}}{33330\left(\frac{W}{kg}\right)}$$

$$m = 2170.805\ (\text{kg})$$

$$(1\text{ year})m = m(1hour) * 365 * 7.5 * 0.85$$

$$m = 5051192.619\ (\text{kg})$$

$$(25\text{ years})m = 5051192.619 \;\; *25$$

$$(25\text{ years})m = 126279815.5\text{ (kg)}$$

$$Capital\ expenditure(CAPEX) = \frac{2F(C.mol^{-1})*IC(\$)}{(T*Capacity\ rate)(s)*A(cm^2)*J(A.cm^{-2})*(\frac{M}{1000})(kg.mol^{-1})}(\$/\text{kg})$$

$$CAPEX = \frac{2*96485.33\left(C.mol^{-1}\right)*12500(\$)}{(360*3600*25*7.5)(s)*0.85*58823529.41\ (cm^2)*1\left(\frac{A}{cm^2}\right)*0.002016(kg.mol^{-1})}$$

$$CAPEX = 0.0984(\$/\text{kg})$$

$$OPEX = CAPEX*0.1(\$/\text{kg})$$

$$OPEX = 0.00984\ (\$/\text{kg})$$

$$Maintanence\ cost = Capital\ cost*0.1(\$/\text{kg})$$

$$Maintanence\ cost = 0.00984\ (\$/\text{kg})$$

$$Electricty\ Cost = Electricty\ price(\frac{\$}{kWh})*(hydrogen\ energy\ value(\frac{kWh}{kg})/(\frac{V_{Theoretical}}{V_{Operational}})(\$/\text{kg})$$

$$Electricty\ Cost = 0.039(\frac{\$}{kWh})*(33.33(\frac{kWh}{kg})/(\frac{1.23}{1.7})(\$/\text{kg})$$

$$Electricty\ Cost = 1.7965(\$/\text{kg})$$

$$Replacement\ cost = Capital\ cost*0.5(\$/\text{kg})$$

$$Replacement\ cost = 0.0492(\$/\text{kg})$$

$$Balance\ of\ plant = \text{CAPEX*0.3 (\$/kg)}$$

$$Balance\ of\ plant = 0.0295 \text{(\$/kg)}$$

$$Separation\ and\ purification\ cost = Electricty\ cost * 0.2\ \text{(\$/kg)}$$

$$Separation\ and\ purification\ cost = 0.3593 \text{(\$/kg)}$$

$$Additional\ cost = CAPEX * 0.4\ \text{(\$/kg)}$$

$$Additional\ cost = 0.0295 \text{(\$/kg)}$$

$LCOH = CAPEX + OPEX + +Maintanence\ cost\ + Electricty\ cost + Replacement\ cost + Balance\ of\ Plant\ cost + Separation\ and\ purification\ cost + Additional\ cost$ (\$/kg)

$LCOH = 0.0984 + 0.00984 + 1.7965 + 0.00984 + 0.0492 + 0.0295 + 0.3593 + 0.0295$ (\$/kg)

$\boldsymbol{LCOH = 2.3823}$ **(\$/kg)**

$$TOTAL\ CAPEX = CAPEX * m(1\ year) * year$$

$$TOTAL\ CAPEX = 12435648.22\ \text{(\$)}$$

CURRICULUM VITAE

PERSONAL INFORMATION

Name Surname : Ayşen KÖSE

Date of Birth : 24.08.1988

Phone : 05545918283

E-mail : aysenkose0gmail.com

EDUCATION

Bachelor : Kırıkkale Unıversıty Mechanıcal Engıneerıng

Master Degree :

WORK EXPERIENCE

Mechanical Engineer at ASKİ

International Conference on Energy-Saving Construction Practices and Renewable Energy Technologies (ICESCPRET-24) (2-3 August, 2024) Istanbul

TOPICS OF INTEREST

- Hydrogen
- Green Hydrogen
- Techno economic analysis
- Thermodynamics

November,12

ANKARA

Marketability Analysis of Green Hydrogen Production in Türkiye

Ayşen KÖSE