ASSESSMENT OF GREEN HYDROGEN PRODUCTION IN A SELECTED OIL REFINERY IN TÜRKİYE

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Thesis for the Master's Program in Sustainable Energy

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I hereby declare that I am the sole author of this thesis and that I have conducted my work in accordance with academic rules and ethical behaviour at every stage from the planning of the thesis to its defence. I confirm that I have cited all ideas, information and findings that are not specific to my study, as required by the code of ethical behaviour, and that all statements not cited are my own.

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ABSTRACT

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Master's Program in Sustainable Energy

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Nowadays, it is undeniable that climate change, increasing temperatures beyond average temperatures is the World's most important problem. The first reason for this issue is GHG emissions emitted to atmosphere from human activities, such as energy production, industry activities, transport and so on. Among these activities, oil refineries are also responsible for large proportion of total emissions. Therefore, it is valuable to study decarbonization strategies of oil refineries, while there are some different applications to be adopted. Among them, hydrogen production is one of main important parameter to evaluate, as oil refineries use 40% of total hydrogen production that is all production is fossil-fuel based creating GHG emissions and responsible for averagely 35-40% of total refinery emissions. Because of these reasons, this thesis focused to decarbonization of hydrogen production in oil refineries. One of main important application is to introduce green hydrogen production in oil refineries, thus decreasing GHG emissions from existing conventional fossil fuel-based hydrogen production. This thesis used real oil refinery data that locate in Türkiye with approximately has 12 million tons of oil processing capacity. With help of this data, green hydrogen available production capacity, investment requirement, cost and avoided emissions from existing SMR unit is calculated, as well as, carbon tax, electricity price effects and other parameters have been evaluated supporting with existing studies about mentioned subjects.

Keywords: Green Hydrogen, Electrolyser, Oil Refinery, Decarbonization, Renewable Energy.

ÖZET

TÜRKİYE’DE SEÇİLMİŞ BİR PETROL RAFİNERİSİNDE YEŞİL HİDROJEN ÜRETİMİNİN DEĞERLENDİRİLMESİ

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Günümüzde iklim değişikliğinin, ortalama sıcaklıkların ötesinde artan sıcaklıkların dünyanın en önemli sorunu olduğu inkar edilemez bir gerçektir. Bu sorunun ilk nedeni, enerji üretimi, sanayi faaliyetleri, ulaşım ve benzeri insan faaliyetlerinden atmosfere salınan sera gazı emisyonlarıdır. Bu faaliyetler arasında petrol rafinerileri de toplam emisyonların büyük bir kısmından sorumludur. Bu nedenle, hayata geçirilebilecek birkaç farklı uygulamalar olması sebebile, petrol rafinerilerinin dekarbonizasyon stratejilerini incelemek değerlidir. Petrol rafinerileri toplam hidrojen üretiminin %40'ını kullandığından, üretimin tamamı fosil yakıt bazlı olup sera gazı emisyonları oluşturduğundan ve toplam rafineri emisyonlarının ortalama %35-40'ından sorumlu olduğundan, rafinerideki hidrojen üretimi değerlendirilmesi gereken önemli parametrelerden biridir.. Bu nedenlerden dolayı, bu tez petrol rafinerilerinde hidrojen üretiminin dekarbonizasyonuna odaklanmıştır. Önemli uygulamalardan biri, petrol rafinerilerinde yeşil hidrojen üretiminin başlatılması ve böylece mevcut geleneksel fosil yakıt bazlı hidrojen üretiminden kaynaklanan sera gazı emisyonlarının azaltılmasıdır. Bu tezde Türkiye'de bulunan ve yaklaşık 12 milyon ton petrol işleme kapasitesine sahip gerçek petrol rafinerisi verileri kullanılmıştır. Bu veriler yardımıyla yeşil hidrojen mevcut üretim kapasitesi, yatırım gereksinimi, maliyeti ve mevcut SMR ünitesinden kaçınılan emisyonlar hesaplanmış, ayrıca karbon vergisi, elektrik fiyatı etkileri ve diğer parametreler belirtilen konulardaki mevcut çalışmalarla desteklenerek değerlendirilmiştir

Anahtar Kelimeler: Yeşil Hidrojen, Elektrolizör, Petrol Rafinerisi, Dekarbonizasyon, Yenilenebilir Enerji.

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LIST OF ABBREVIATIONS

AE: Alkali Electrolyser

ANF: Annuity Factor

BoP: Balance of Plant

CAPEX: Capital Expenditures

CBAM: Carbon Border Adjustment Mechanism

CCR: Continuous Catalytic Reformer

CCS: Carbon Capture and Storage

CCUS: Carbon Capture, Utilization and Storage

COP: Conference of the Parties

ETS: Emission Trade System

ETS: Emission Trading System

EU: European Union

GHG: Greenhouse Gas Emission

GO: Guarantee of Origin

GWP: Global Warming Potential

IEA: International Energy Agency

IOC: International Oil Company

IRENA: International Renewable Energy Agency

LCA: Life Cycle Analysis

LCOH: Levelized Cost of Hydrogen

MRV: Monitoring, Reporting and Verification

MTA: Million Ton Annual

NDC: Nationally Determined Contribution

NOC: National Oil Corporation

O&M: Operating and Maintenance

PEME: Proton exchange membrane Electrolyser

POX: Partial Oxidation

PPA: Power Purchase Agreement

R&D: Research and Development

SAF: Sustainable Aviation Fuel

SMR: Steam Methane Reformer

SOE: Solid Oxide Electrolyser (SOE)

TÜİK: Turkish Statistical Institute

UNFCCC: United Nations Framework Convention on Climate Change

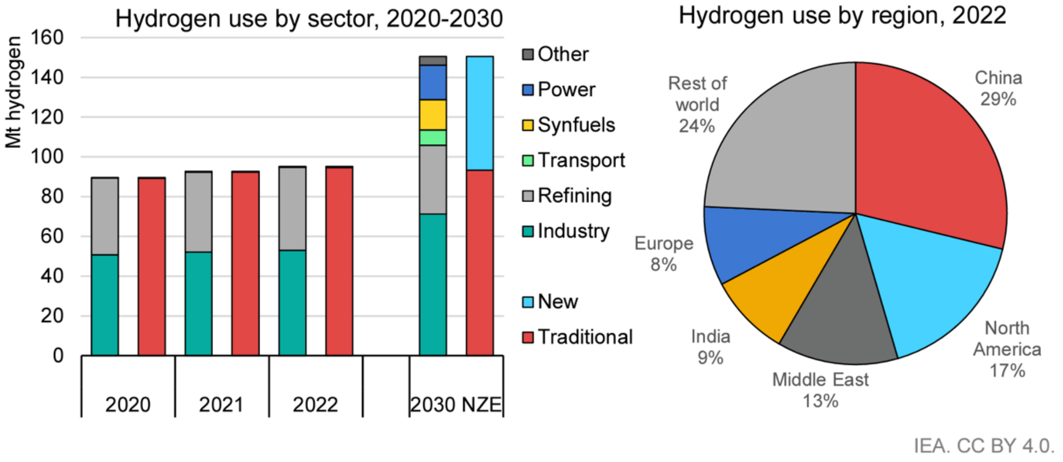
CHAPTER 1: INTRODUCTION

Due to the outcomes of global warming, it became important to reduce GHG emissions from all sectors, industry, transport, energy generation and so on. Oil refineries are main carbon emitter; therefore, it is very important to decrease GHG emissions from oil refineries. Oil refineries in Türkiye all have declared net-zero goal and actions for short-term 2035 and long term 2050 in parallel with Türkiye's Nationally Determined Contribution (NDC) affirms a 41% decrease in greenhouse gas (GHG) emissions in Turkiye by 2030, compared to the base year of 2012. The amount of greenhouse gas emissions in 2030 is estimated to be 695 million metric tons of CO_2 equivalent. In 2053, Türkiye’s key intends to achieve a net-zero level of greenhouse gas (GHG) emissions (RTMEUCC, 2023).

Paris Agreement that is a significant global treaty that was approved in December 2015 at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, France. The objective of the agreement is to address the issue of climate change and its consequences by restricting the increase in global temperatures to a level much below 2°C over the levels seen before industrialization. Furthermore, the accord also seeks to make further efforts to limit the temperature rise to only 1.5°C. At the same time, with the parallel for Paris Agreement treaty, countries, international organizations and organizations like EU started to declare net-zero emission strategy, called ‘EU Green Deal’ aiming to be first continent net-zero carbon emitter by 2050. These regulations are not only concern for EU countries, but also other countries that continuously trade with them. EU’s main goal to create fair trade while keeping fair competition with inside companies and foreign companies. Without that carbon leakages could happen. EU’s ‘Fit for 55’ program which covers actions to be taken by 2030 has comprehensive regulations which have to be followed because it has big effect on Türkiye as Türkiye has close trade with EU.

In order to meet stringent emission regulations and standards on decreasing emissions of units, as well as product specifications, growing demand for lighter, hydrogen rich products, such as gasoline increase hydrogen demand (need) in the refineries. Also, due to increased use of heavier crude oils, containing higher amount of sulphur and nitrogen, use of hydrogen in oil refineries have been increased. Environmental regulations on the oil products; limit of sulphur in diesel, allowable limits of off-gas emission to atmosphere have an increased effect on the refineries operations to be more stringent, at the same time, increasing hydrogen usage. At the same time, to increase profitability margins of refinery, refiners use poorer quality crude that has more impurities in it resulting more hydrogen demand (Ramachandran and Menon, 1998).

From the latest IEA data 2023, Global hydrogen demand reached more than 95 million tons (Mt) in 2023, that almost entirely from unabated fossil fuels, resulting more than *900 Mt CO_2 emissions*. A nearly 3% increase from IEA revised estimate for 2021 and compared to 91 Mt in 2019 (pre-pandemic level). From following graphic indicated in IEA (2023), 62% of hydrogen produced by natural gas without CCUS (Grey hydrogen), 16% of hydrogen is produced as a by-product in the refinery reforming process, Hydrogen production from coal (black hydrogen) accounts 21% (mainly in China), very few amounts of oil are used to produce hydrogen (less than 1%) in 2021. Low-emission hydrogen production was less than 0.7% (1 Mt), almost as a blue hydrogen (fossil fuel with CCUS), only 100 kt hydrogen was produced by electricity via water electrolysis. But it has to be mentioned that this amount is increased 35% compared to previous year. It is seen that approximately 43% of all of hydrogen produced is used in the oil refinery production.



IEA. CC BY 4.0.

Notes: NZE = Net Zero Emissions by 2050 Scenario. "Other" includes buildings and biofuels upgrading.

Figure 1. Hydrogen Use by Sector and Region in the World (Source: IEA, 2023).

Below, detail usage areas and production methods classification are shown (Kumar and Lim, 2022).

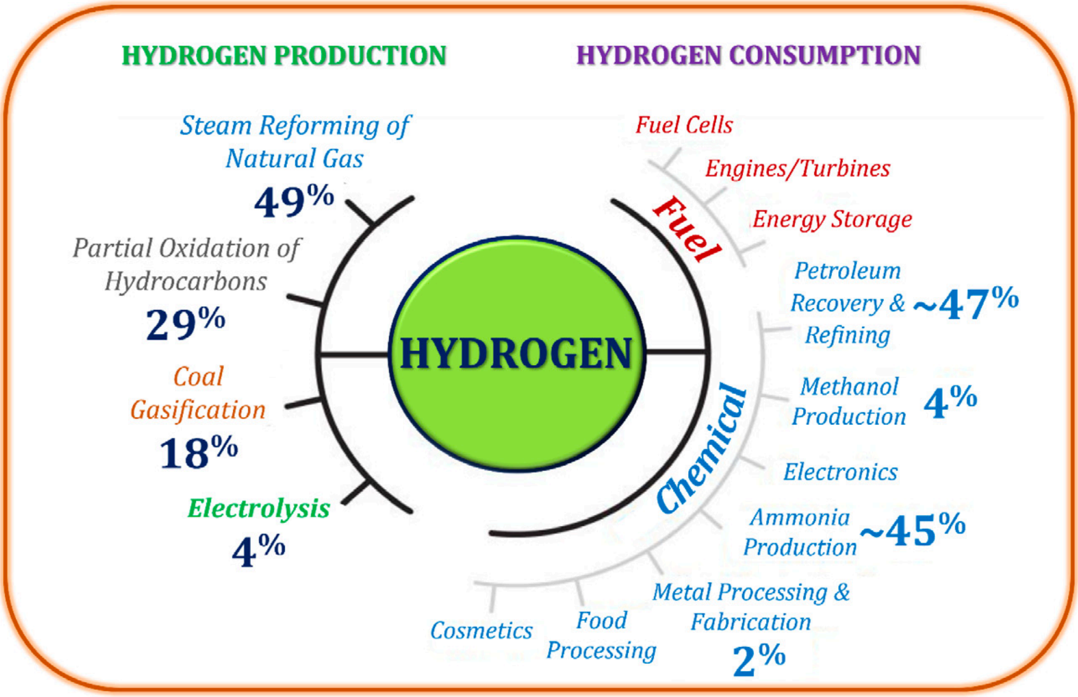


Figure 2. Hydrogen Production and Consumption Areas (Source: Kumar and Lim, 2022).

The use of hydrogen in the refining industry exceeded 41 million metric tons in 2022, exceeding its previous record set in 2018. North America and the Middle East saw the highest rise in demand compared to the previous year. Together, they contributed to over 1 million tons, which is almost 75% of the worldwide growth in 2022 (Figure 3). China was the only significant refining area that had a fall in its demand for hydrogen, amounting to around 0.5 Mt. This reduction was a result of a decline in refinery throughput caused by substantial mobility restrictions imposed during the epidemic. Approximately 80% of the hydrogen used in refineries is generated directly at the refineries, with roughly 55% being created via specialized hydrogen production and the remaining amount being a by-product of other activities, such as naphtha crackers. Only a fraction of 1% of the hydrogen used in refineries in 2022 was generated by low-emission technology. The other 20% of hydrogen used was obtained as merchant hydrogen, mostly provided externally, and predominantly derived from unabated fossil fuels. In 2022, the process of producing hydrogen for refining purposes led to the emission of *240-380 million metric tons of carbon dioxide* into the environment.

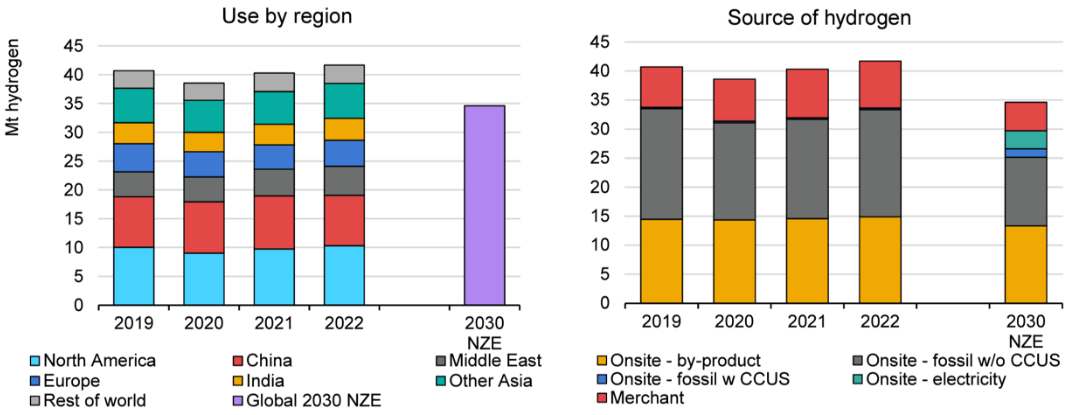


Figure 3. Hydrogen use by region and source of hydrogen for refining (Source: IEA, 2023).

From the latest TÜİK data, in 2021, Türkiye's emission amount was 564.4 Mt CO_2 eq. From the below table, data set from 1990 (TÜİK, 2023).

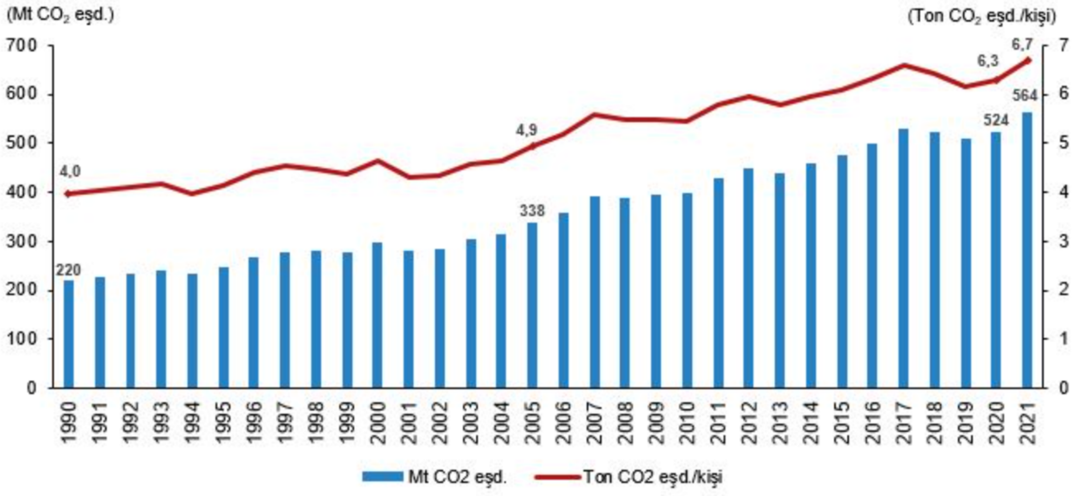


Figure 4. GHG emissions in total and per person in Türkiye between 1990-2021 (Source: TÜİK, 2023).

Below table, emissions from 1990 to 2021 are listed from reference "Turkish Greenhouse Gas Inventory 1990-2021" report by TÜİK page 80. The latest total CO_2 equivalent emission data from Türkiye's petroleum refineries are 7.764 kt (7.8 million ton) (TÜİK, 2023).

As keeping in mind that approximately 40% of total refinery scope 1 emission is related to hydrogen production, it could be said that averagely calculated in Türkiye refineries hydrogen production-based emission amount is ***3.1 Mt CO_2 eq.***

Table 1. Emissions from Turkish petroleum refining in Türkiye between 1990-2021 (TÜIK, 2023).

Year	CO_2 (kt)	CH_4 (kt)	N_2O (kt)	CO_2 eq.(kt)
1990	2289	0.07	0.014	2295
1995	2984	0.09	0.016	2991
2000	2914	0.09	0.017	2922
2005	4265	0.12	0.019	4273
2010	3531	0.08	0.012	3537
2011	4326	0.09	0.012	4331
2012	4210	0.09	0.012	4216
2013	3549	0.08	0.010	3554
2014	3424	0.07	0.009	3429
2015	5503	0.12	0.015	5510
2016	8347	0.16	0.022	8358
2017	8717	0.16	0.019	8727
2018	6224	0.11	0.013	6231
2019	8136	0.13	0.014	8143
2020	7991	0.14	0.016	7999
2021	7756	0.13	0.014	7764

Oil refineries are using large quantity of hydrogen, which is produced in the oil refinery unit areas. More than 40% of globally produced hydrogen (approximately 41 Mt) comes from refinery activities out of 95 Mt in 2023. This demand includes also hydrogen produced from the by-product of the catalytic reforming processes. But majority of hydrogen in refineries is produced through SMR process. In oil refineries, hydrogen is used in the hydro-cracking and hydro-desulfurization of crack heavier oil products to upgrade heavy oil fractions into lighter products, also to remove impurities especially sulphur from the oil products in the catalyst presence. Below, Shell Graphical scheme for hydrogen system in the petroleum refineries are drawn. This scheme is mainly general for all refinery processes. Some refineries have some plants, while others have other different plants than each other (Nazir et al., 2020).

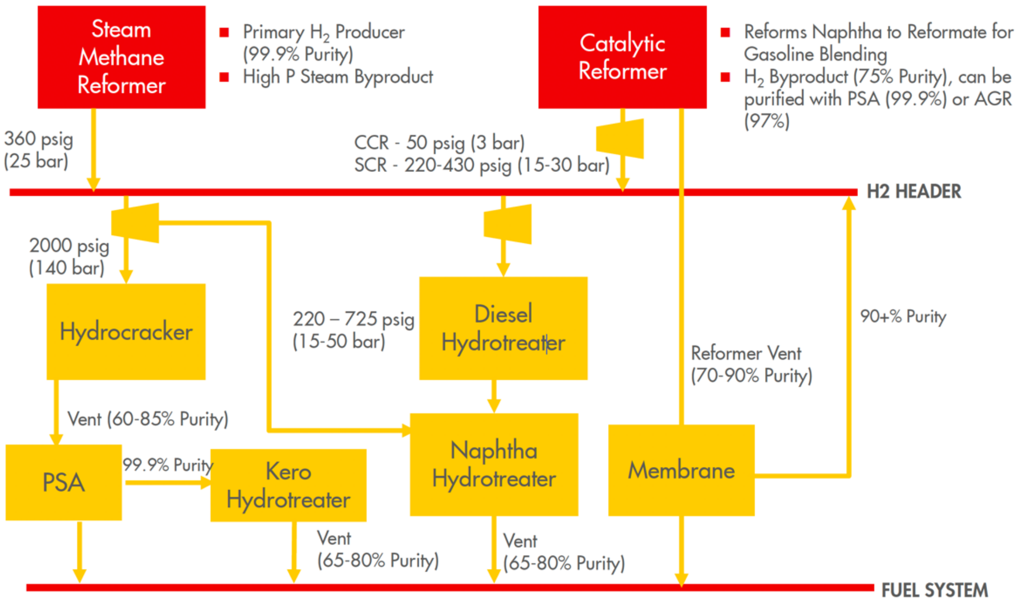


Figure 5. Oil refinery hydrogen system (SHELL, 2017).

Hydrocracking and hydroprocessing take place in high temperature and pressure ranging from 70-150 bar and 400-800°C depending on the different feedstock. Hydrogen reacts sulphur, nitrogen removing these impurities as H_2S and NH_3 chemical form at these temperature and pressure (Nazir et al., 2020).

In Oil refineries, hydrogen is used in the below broad range processes, such as (Ramachandran and Menon, 1998).

- Sulphur compound and halides removal
- Metals removal
- Saturation of olefins, diolefins and cycloolefins,
- Aromatics saturation,
- Isomerization,
- Removal of nitrogen and oxygen from compounds,
- Decyclization or ring-opening,
- Cracking to lighter hydrocarbons.

1.1. Hydrogen Color Classification and Environmental Impact

Because of different production methods, each hydrogen production method is named colors based on their emissions, environmental effects. Below table show general colors used in literature to distinguish hydrogen production methods. Most environmentally friendly, zero carbon emission hydrogen production method is 'green hydrogen', but the biggest carbon emitter methos is 'black hydrogen'. Besides that, there are different color coding for different production methods (Kumar and Lim, 2022).

Table 2. Hydrogen colors and environmental effects (Source: Kumar and Lim, 2022).

Hydrogen Color	Technology	Source	Products	Cost (USD kg/H_2)	CO_2 Emissions
Brown Hydrogen	Gasification	Brown Coal (Lignite)	$H_2 + CO_2$	1.2-2.1	High
Black Hydrogen	Gasification	Black Coal (Bituminous)	$H_2 + CO_2$	1.2-2.1	High
Grey Hydrogen	Reforming	Natural Gas	$H_2 + CO_2$ (released)	1-2.1	Medium
Blue Hydrogen	Reforming +Carbon capture	Natural Gas	$H_2 + CO_2$ (captured 85-95%)	1.5-2.9	Low
Green Hydrogen	Electrolysis	Water	$H_2 + O_2$	3.6-5.8	Minimal

Brown hydrogen refers to process that gasification consists of coal being heated with water and releasing syngas containing a mixture of carbon dioxide, carbon monoxide, methane, hydrogen and small quantity of other gases (Kumar and Lim, 2022).

In the *grey hydrogen* production, input of the process is natural gas (mainly consist of methane). During this process, methane reacts with steam (vapor of water) on the catalysts creating hydrogen, and byproduct is carbon monoxide, then monoxide reacts again with steam creating additional hydrogen. From the reactions carbon dioxide release to atmosphere from the stack. Also, huge amount of fossil fuel used in this process to heat input materials in furnace because these all reactions happen in high temperature (approximately 700-800°C). This process is called Steam Methane Reforming (SMR) (Kumar and Lim, 2022).

Blue hydrogen production is similar to grey hydrogen production, but only main difference is that to capture carbon dioxide emissions. In grey hydrogen production, byproduct of process (carbon dioxide) and emissions from furnace is captured and stored with the Carbon Capture Utilization and Storage (CCUS) technology. Obviously, it is increasing cost of hydrogen (Kumar and Lim, 2022).

Green hydrogen is produced by splitting water molecules to hydrogen and oxygen in the electrolysers. In this production method, electrolyser is energized by the renewable energies, mainly wind and sun. Whole process nearly doesn't create emissions. Only byproduct is oxygen that either collecting in the tank for further usage or just release to atmosphere. Therefore, this production method called green hydrogen (Kumar and Lim, 2022).

Other production methods are less common, meanings of them are below;

Pink hydrogen is the same like green hydrogen, only difference is that electrolysers are powered by nuclear power. *Yellow hydrogen* is the same process only powered by solar energy. Sources could be multiple at the same time, sun, wind or nuclear power.

SMR is coded grey hydrogen that has negative environmental impact emitting too much greenhouse gases. Generally, in oil refineries grey hydrogen production is most used that is most harmful to environmental. But, some alternatives; green and blue hydrogen is least impact to environmental. Green hydrogen is relied on renewable energy to make electrolysis of water that has no any harmful damage to environment. Also, blue hydrogen is another alternative that uses CCS/CCUS technology to decrease carbon emissions from Steam-Methane Reforming (SMR) processes. This method uses natural gas to produce hydrogen, but emissions from process are captured (Kumar and Lim, 2022).

To be noted that, the International Energy Agency (IEA) does not utilize color designations to denote different hydrogen production methods. However, in instances where specific policy announcements, programs, regulations, or projects from authoritative sources employ color terminology to define a hydrogen production route (such as "green hydrogen"), they adopt that terminology to convey developments (IEA, 2023). As well as, it is important to mention that the present version of the EU explicitly prohibits the use of nuclear power for the production of green hydrogen (Moradpoor, Syri and Santasalo-Aarnio, 2023).

1.2. Hydrogen Production Methods

Table below illustrates general hydrogen production methods from different sources in general. Among these methods most used method is the steam methane reforming with fossil fuel/natural gas, whereas electrolysis and byproduct of chlor-alkali industry provide secondary source of hydrogen. In the large-scale applications, like oil refineries and ammonia synthesis unit, hydrogen is produced from hydrocarbons using Steam Methane Reforming (SMR), Autothermal reforming and methane pyrolysis (Nazir et al., 2020).

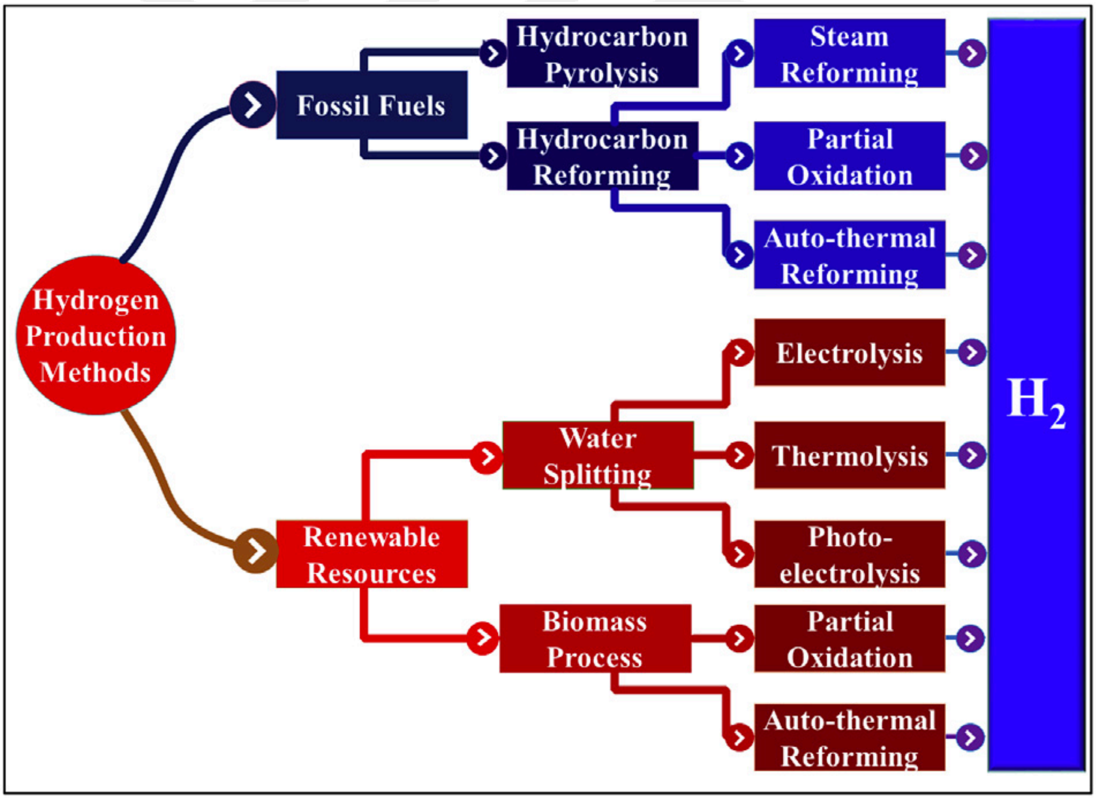


Figure 6. Various hydrogen production methods based on fossil fuels and renewable energy sources

1.2.1. Fossil Fuel Based Production

As a result of pricing being within acceptable limits, fossil fuel is the primary source of producing of hydrogen, 48% source is natural gas, 30% source is heavy oils and naphtha and 18% source is coal. Hydrogen produced from fossil fuels have two processes; one is hydrocarbon pyrolysis; other one hydrocarbon reforming.

Hydrocarbon reforming is the process that convert fossil fuel to the hydrogen with reforming techniques. Due to different reactants are used, there are 3 main methods are used. When steam used as a reactant, this process is called steam reforming, when oxygen is used, process is called partial oxidation, or both used in case process is called auto-thermal reaction (Nazir et al., 2020).

Steam Methane Reforming process involves the catalytic conversion of hydrocarbon and steam into hydrogen and carbon dioxide. This process comprises several key stages: the generation of reforming or synthesis gas (syngas), water-gas shift, and methanation or gas purification. The primary raw materials used are methane, natural gas, and other methane-containing gases, which may include various combinations of light hydrocarbons such as ethane, propane, butane, pentane, light or heavy naphtha, as well as bio-methanol or bio-ethanol reacts with steam over catalyst in high temperatures forming hydrogen and carbon monoxide. Then hydrogen is captured from the mixture. Because this process is endothermic meaning temperature decreases over reaction, continues heat must be added to the system to keep temperature at the desired level. That’s why, extra heat sources are needed, and this source is fossil fuel resulting this method has much carbon emissions. The overall chemical formula is shown below:

$$CH_4 + 2H_2O = CO_2 + 4H_2 \quad (1)$$

Steam methane reforming (SMR) is the most advanced and widely adopted method for large-scale hydrogen production, with efficiency reaching up to 85%. In a typical SMR process, steam and natural gas are reacted at temperatures ranging from 850°C to 900°C in the presence of a nickel-based catalyst to produce syngas. This syngas is then treated using pressure swing adsorption to achieve near 100% hydrogen separation (Nazir et al., 2020). Steam methane reformer basic process scheme is illustrated in figure 7.

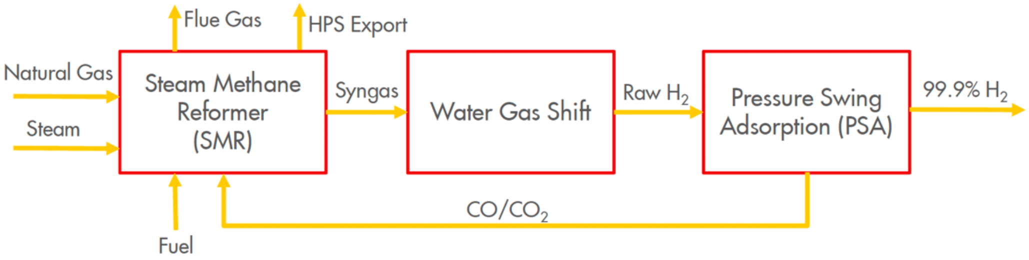


Figure 7. Steam methane reformer basic scheme (Source: LaFleur, 2017)

The partial oxidation process involves the reaction of a hydrocarbon feedstock with steam and oxygen gas to generate hydrogen and carbon dioxide. The reaction takes place at around 950°C by using various feedstocks, such as methane or naphtha, with the assistance of a catalyst. Alternatively, the process may occur at a temperature of about 1300°C without requiring a catalyst when using feedstocks such as methane, heavy oil, and coal. After the reforming process, sulfur is removed to produce pure oxygen, which is then reused to partly oxidize the hydrocarbon feedstock. This technique requires a substantial number of financial resources owing to the necessary stages involved in the recirculation of oxygen and the removal of sulfur. However, this process is the most appropriate method for producing hydrogen from heavier feedstocks such heavy oil wastes and coal. Another technique is using coal as the raw material, often known as coal gasification (Nazir et al., 2020).

Auto Thermal Reforming process is somehow similar to SMR process, but here oxygen is used, and partial oxidation happens. Feedstock, methane reacts with air and carbon dioxide in reformer to produce syngas and water. In autothermal reforming, the heat required for the endothermic steam reforming process is generated by partial exothermic oxidation, resulting in enhanced hydrogen production. Typically, a combination of steam with either oxygen or air is introduced into the reformer chamber to facilitate the simultaneous reactions of reforming and oxidation (Nazir et al., 2020).

Hydrocarbon Pyrolysis process occurs anaerobically, using the controlled pyrolysis to generate hydrogen under precise circumstances. Light liquid hydrocarbons, which have boiling points ranging from 50°C to 200°C, undergo thermocatalytic breakdown to produce elemental carbon and hydrogen. Conversely, high molecular weight hydrocarbon fractions (with boiling temperatures over 350°C) generate hydrogen by a two-step process: hydrogasification and methane cracking. This procedure has a lower carbon emission compared to the SMR process. However, because to the need for elevated temperatures, a substantial amount of electricity is necessary, mostly obtained from fossil fuel sources (Nazir et al., 2020).

1.2.2. Renewable Source Based Production

The continuous and rapid rise in atmospheric carbon dioxide levels highlights the pressing need to shift towards technologies that do not produce carbon emissions. With the depletion of fossil fuel reserves and the increasing intensity of the greenhouse effect, there will be a significant increase in the focus on renewable resources in the energy industry. The next sections will delineate several techniques for hydrogen generation using sustainable sources (Nazir et al., 2020).

Biomass-Based Production; biomass, a replenishable resource, is sourced from a variety of outlets including energy crops, crop residues, wood and wood residues, grass, industrial organic residues, animal byproducts, and municipal waste. It serves as a viable option for hydrogen production through both thermochemical and biological processes (Nazir et al., 2020).

In *Thermochemical Process,* biomass may be converted into hydrogen and hydrogen-rich gases using thermochemical methods, namely pyrolysis or gasification. During this procedure, CH_4 and CO, together with other gaseous byproducts, may be subjected to further processing to improve hydrogen generation by steam reforming and water-gas-shift processes. Biomass pyrolysis, which is a component of the thermochemical process, often takes place at temperatures of around 850K in an environment that lacks reactivity. The effectiveness of biomass pyrolysis depends on variables such as the feedstock type, catalyst choice, and operating temperature and duration. Biomass gasification is the process of converting biomass into syngas by subjecting it to temperatures between 500°C and 1400°C in the presence of a gasification medium such as air, oxygen, and/or steam. The syngas produced is subjected to a treatment procedure identical to that used in pyrolysis, with the same important parameters affecting the amount of syngas obtained (Nazir et al., 2020).

Biochemical Processes is the biological techniques used for hydrogen generation include direct and indirect bio-photolysis, as well as photo and dark fermentation. These processes are preferred due to their low energy needs and normal working conditions. In biotechnology-based hydrogen manufacture methods, microorganisms, specifically bacteria or algae, promote the splitting of water via the use of hydrogenase or nitrogenase enzyme systems, while biomass undergoes fermentative processes. Carbohydrate-rich materials undergo conversion into organic acids during these processes, which are then transformed into hydrogen gas via bioprocessing methods. Unlike algae, natural plants do not possess hydrogen catalyzing enzymes, which restricts their participation to activities involving the reduction of carbon dioxide. Algae have hydrogen-producing enzymes and can produce hydrogen under certain circumstances (Nazir et al., 2020).

Algae-based hydrogen generation shows potential since it utilizes sustainable fuel sources and carbon dioxide. However, this approach has drawbacks including a relatively low potential for producing hydrogen and the need for large surface areas to catch sufficient light. Another method of bio-photolysis includes the process of fermentation, in which microorganisms transform organic material into alcohols, acetone, and other chemicals, regardless of the presence or lack of oxygen. These technologies demonstrate the ability to produce bio-hydrogen, using waste materials for efficient energy generation and waste treatment. Nevertheless, there are some obstacles to overcome in the field of solar energy, such as the relatively poor efficiency of converting solar energy, the need for large and intricate anaerobic photo-bioreactors that occupy significant space, and the restricted supply of organic acids (Nazir et al., 2020).

Water Splitting to produce hydrogen through electrolysis, thermolysis, and photo-electrolysis methods represents the most favorable approach. This method is regarded as cleaner and more environmentally friendly.

Electrolysis is the process that uses electricity to break down of water molecule splitting to oxygen and hydrogen with the help of electrolyser that is a well-established process. Electrolysers consist of electrodes anode and cathode that electricity is given and with electricity current water molecules are splitted into hydrogen and oxygen. Electricity generated from renewable sources like wind and solar can be effectively utilized for electrolysis, yielding green hydrogen. There are various types of electrolyzers.

The most developed and widely used electrolysis methods include ***alkali (AE)***, ***proton exchange membrane (PEM)***, and ***solid oxide electrolysis cells (SOEC)***. In these electrolysis processes, pure hydrogen is generated at the cathode through various mechanisms and separated from water and oxygen. Electrolysers have the capability to convert renewable electricity into hydrogen, which can then be stored, transported, and distributed to end-users for a variety of applications. When electrolysers use renewable electricity for their operation, it is called ***green hydrogen***. While electrolysers are currently available at small scales (less than 5 MW), demonstration projects of up to 10 MW are already being considered. Alkali electrolyzers represent a well-established technology widely employed in large-scale systems owing to their extended lifespan and more economical pricing (Nazir et al., 2020).

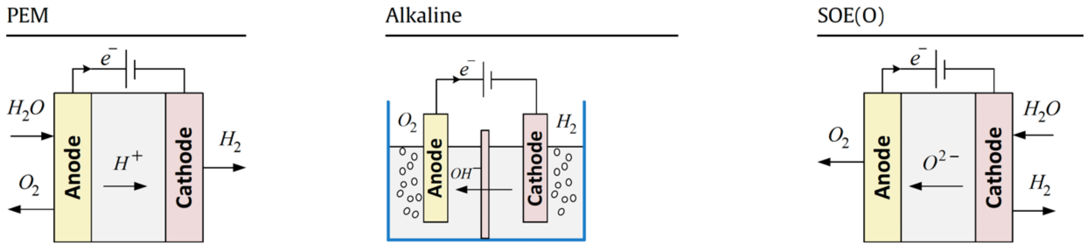


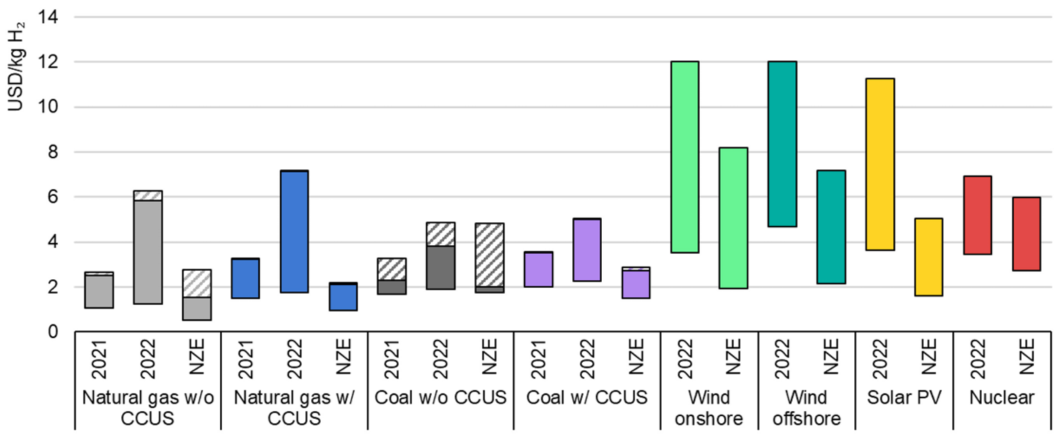
Figure 8. Water electrolysis type basic working principle (source: El-Emam and Özcan, 2019).

Thermolysis, also known as thermochemical process, involves the separation of water at very high temperatures, namely over 2500°C. In order to improve the long-term viability of this process, many thermochemical water-splitting cycles have been proposed. These cycles include the use of catalysts and may be powered by solar flux or nuclear energy (Nazir et al., 2020).

Photo-electrolysis is the process of dividing water by using the electrical charge produced inside a semiconductor electrode when it absorbs visible light. When semiconductor materials function as photo-catalysts, they produce pairs of electrons and holes when they absorb photons. The electrons, which have been separated, go via an external circuit towards the cathode. At the cathode, they join with protons (H^+) to create hydrogen. Simultaneously, the anode has openings that undergo a chemical reaction with water, resulting in the production of protons (H^+) and oxygen. The primary factors limiting the effectiveness of this process are the charge transfer and the absorption efficiency of visible light by the semiconductor electrode. Colloidal quantum dots are considered one of the top choices for photocatalysis. However, their toxicity presents environmental hazards, which has led researchers to investigate cleaner and ecologically friendly approaches to hydrogen generation (Nazir et al., 2020).

1.3. Hydrogen Production Costs

The cost of hydrogen generation is contingent upon the technology used and the expense of the energy source utilized, often exhibiting substantial geographical disparities. The cost of producing hydrogen from fossil-based sources without any emissions reduction measures ranged from 1.0 USD/kg to 3.0 USD/kg of hydrogen. In 2021, the most cost-effective methods for producing hydrogen were via these production pathways, as contrasted to using fossil fuels with carbon capture, utilization, and storage (CCUS) which costed between 1.5-3.6 USD/kg of hydrogen, or using electrolysis with low-emission electricity which costed between 3.4-12 USD/kg of hydrogen. The graph below illustrates each production method cost range in general (IEA 2023).



IEA. CC BY 4.0.

Notes: CCUS = carbon capture, utilisation and storage; PV = photovoltaic; NZE= Net Zero Emissions by 2050 Scenario in 2030. Solar PV, wind and nuclear refer to the electricity supply to power the electrolysis process. NZE values refer to 2030. Natural gas price is USD 5-15/MBtu for 2021, USD 6-36/MBtu for 2022 and USD 1-8/MBtu for 2030 NZE. Coal price is USD 40-180/tonne for 2021, USD 50-360/tonne for 2022 and USD 30-70/tonne for 2030 NZE. Solar PV electricity cost is USD 22-120/MWh for 2022, USD 13-80/MWh for 2030 NZE, with capacity factor of 12-35%. Onshore wind electricity cost is USD 25-130/MWh for 2022, USD 25-120/MWh for 2030 NZE, with capacity factor of 15-53%. Offshore wind electricity cost is USD 50-225/MWh for 2022, USD 30-125/MWh for 2030 NZE, with capacity factor of 32-67%. The cost of capital is 6%.

The dashed area represents the CO_2 price impact, based on USD 15-140/t CO_2 for the NZE Scenario. More techno-economic assumptions will be made available in a separate forthcoming Annex.

Sources: IEA analysis based on data from McKinsey & Company and the Hydrogen Council; IEA GHG (2014); NETL (2022); IEA GHG (2017); E4Tech (2015); Kawasaki Heavy Industries.

Figure 9. Levelized cost of hydrogen production by technology in 2021, 2022 and in the Net Zero Emissions by 2050 Scenario in 2030 (Source: IEA, 2023).

Steam methane reforming projected costs for specific components involved in hydrogen generation by steam methane reforming (SMR) are as outlined: The allocation of resources is as follows: 60.7% is dedicated to feedstock, 29.1% is allocated for capital expenditure, and 10.2% is designated for operations and maintenance. The anticipated production costs for a hydrogen plant intended to create 380,000 kg/day of hydrogen, running at a 90% capacity factor, and with a natural gas cost of 10 USD/MMBtu, are 2.27 USD/kg with carbon capture and sequestration, and 2.08 USD/kg without (Nazir et al., 2020).

Hydrocarbon pyrolysis obviates the need for waste gas sequestration or CO_2 removal protocols. As a consequence, the capital costs for large-scale hydrogen production facilities are decreased in comparison to SMR and POX technologies, leading to a reduction of roughly 30% in hydrogen expenses. Furthermore, the use of the carbon output in other sectors might lead to further cost reductions. From an environmental standpoint, the process of catalytically decomposing natural gas to generate hydrogen and carbon is more beneficial than the method of hydrogen generation using steam methane reforming (SMR) combined with carbon dioxide (CO_2) sequestration (Nazir et al., 2020).

The estimated expenses for producing hydrogen vary between 1.25 USD/kg and 2.2 USD/kg, depending on the kind of biomass used and the size of the manufacturing batch. The predicted cost of creating hydrogen for a plant that produces 139,700 kg per day using biomass, with biomass prices ranging from 46 USD/ton to 80 USD/ton, is expected to be between 1.77 USD/kg and 2.05 USD/kg (Nazir et al., 2020).

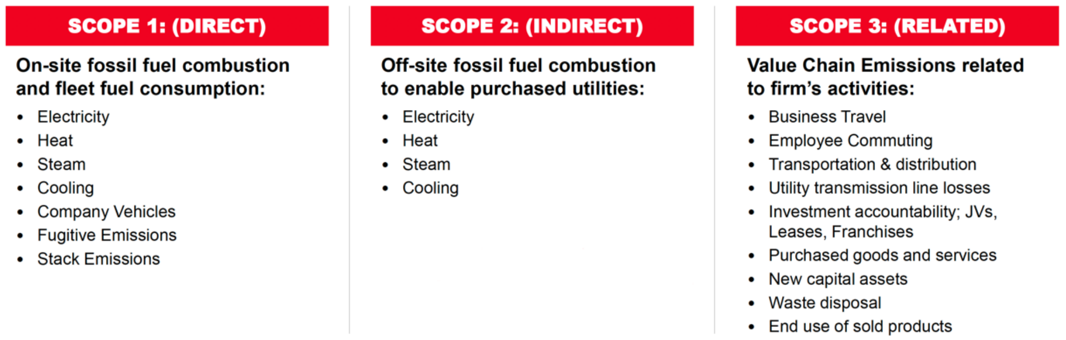
The projected expense for generating hydrogen from a photo-bioreactor, which has a cost of 50 USD/m^2 and a solar conversion efficiency of 10%, is estimated to be 2.13 USD/kg. In the context of indirect bio-photolysis, the use of both hydrogenase and nitrogenase enzymes results in a hydrogen generation rate that is similar to that achieved by the direct bio-photolysis approach. Nevertheless, this strategy is now in the early stages of development. The estimated cost of producing hydrogen is around 1.42 USD/kg, calculated using a total capital cost of 135 USD/m^2 (Nazir et al., 2020).

Blue hydrogen production includes the costs associated with capital expenditures, operational expenses, and fuel prices. Capital expenditures include the acquisition of CCUS equipment and the establishment of connections to the SMR reactors. Operating expenditures are associated with the transportation and storage of carbon dioxide. The cost of fuel includes the expenditure for the energy required for the process of carbon capture (Hammerstrom, 2022).

Currently, green hydrogen is the costliest among blue and grey hydrogen, with prices ranging from 4.5 USD/kg to 8.5 USD/kg. In order to establish green hydrogen as a viable competitor to existing methods of hydrogen generation, it is crucial to achieve substantial cost reductions in capital investments, power expenses, and electrolyzer efficiency. Capital expenditures include the acquisition of electrolyzers, power electronics, and plant infrastructure. Technological advancements in this industry are crucial for reducing the cost of green hydrogen. Renewable power prices are projected to decrease in the future, but at a slower pace. According to the International Energy Agency (IEA), it is projected that green hydrogen will be able to rival gray hydrogen by 2030, since the prices of small and medium-scale production are expected to reduce to 3.53 USD/kg. By 2050, the cost of green hydrogen might reduce to 0.80-1.38 USD/kg, owing to significant advancements in electrolyser and electricity prices between 2030 and 2050 (Hammerstrom, 2022).

1.4. Emissions Scopes

There are three types of emissions are classifying. Scope 1, Scope 2 and Scope 3. According to the Greenhouse Gas Protocol carbon accounting framework (WRI, 2004), emissions from industrial activities can be classified into three distinct categories: scope 1 emissions, referring to the direct greenhouse gas emissions originating from an organization's internal operations (such as on-site processes and activities); scope 2 emissions, which encompass the indirect greenhouse gas emissions arising from the acquisition of external energy inputs (such as electricity, heat, cooling, and off-site steam generation); and scope 3 emissions, which encompass all other indirect greenhouse gas emissions not accounted for under scope 2. Scope 3 emissions, also known as value chain emissions. The accounting technique for greenhouse gas (GHG) emissions of an oil refinery differs depending on whether the refinery runs independently or is controlled by an international oil company (IOC) or national oil corporation (NOC). When analyzing an independent refinery, the greenhouse gas (GHG) emissions associated with the raw material oil are categorized as scope 3 emissions. Nevertheless, whether the refinery is owned by an international oil company (IOC) or a national oil corporation (NOC), the emissions associated with the raw oil used are categorized as scope 1 emissions. In figure below illustrates general views of scope details.



SCOPE 1: (DIRECT)

On-site fossil fuel combustion and fleet fuel consumption:

- Electricity
- Heat
- Steam
- Cooling
- Company Vehicles
- Fugitive Emissions
- Stack Emissions

SCOPE 2: (INDIRECT)

Off-site fossil fuel combustion to enable purchased utilities:

- Electricity
- Heat
- Steam
- Cooling

SCOPE 3: (RELATED)

Value Chain Emissions related to firm's activities:

- Business Travel
- Employee Commuting
- Transportation & distribution
- Utility transmission line losses
- Investment accountability; JVs, Leases, Franchises
- Purchased goods and services
- New capital assets
- Waste disposal
- End use of sold products

Figure 10. Emissions scope details

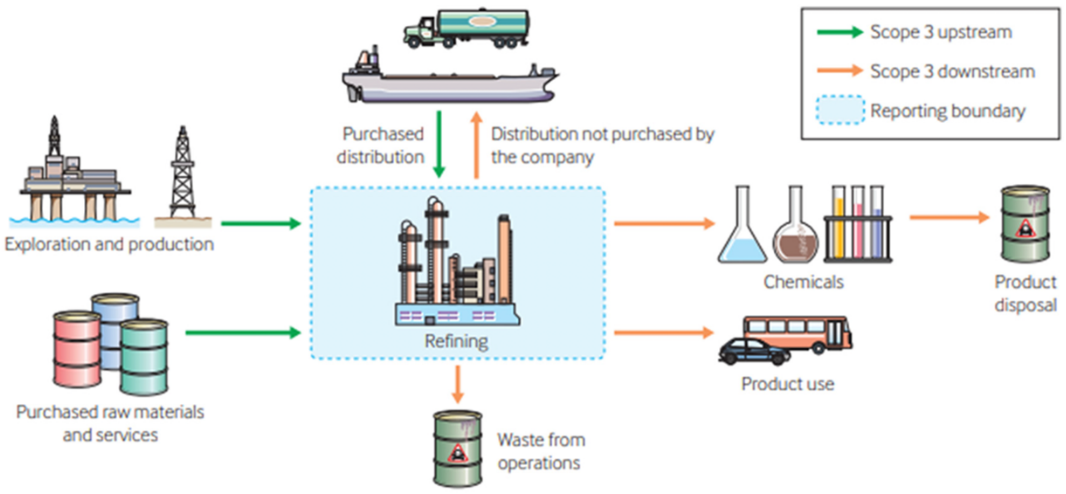
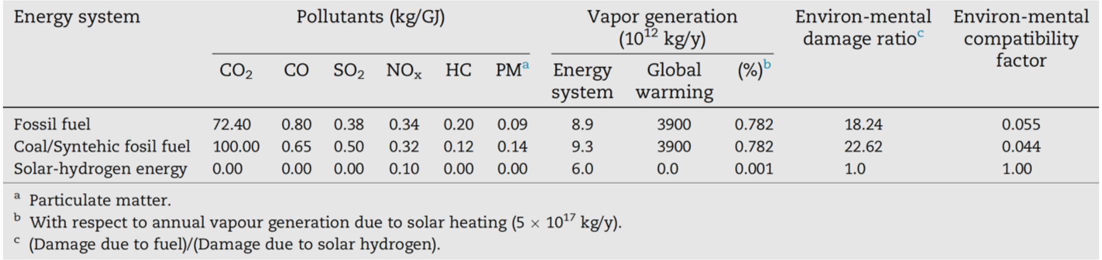


Figure 11. Scope 3 upstream and downstream emission sources of oil refinery industry (Source: Griffiths et al., 2022).

Life cycle analysis (LCA) studies have demonstrated that electrolysis processes powered by renewable energy sources yield low global warming potential (GWP), with values of less than 5 kg CO_2eq./kgH_2, with wind electrolysis being the most favorable. In contrast, electrolysis utilizing electricity from the grid can result in higher GWPs, reaching levels as high as 30 kg CO_2eq./kgH_2. Compared to other energy systems, the solar hydrogen energy system exhibits much lower levels of environmental issues such as pollution, vapor formation, and environmental harm. Table given below illustrates the drawbacks of the coal/synthetic fuel system and the benefits of the green hydrogen system. The green hydrogen system effectively eliminates emissions of CO_2, CO, SO_x, hydrocarbons, and particulates. Additionally, the formation of NO_x may be prevented by avoiding flame burning in air (Baykara, 2018).



Energy system	Pollutants (kg/GJ)						Vapor generation (10^{12} kg/y)			Environ-mental damage ratio[c]	Environ-mental compatibility factor
	CO_2	CO	SO_2	NO_x	HC	PM[a]	Energy system	Global warming	(%)[b]		
Fossil fuel	72.40	0.80	0.38	0.34	0.20	0.09	8.9	3900	0.782	18.24	0.055
Coal/Syntehic fosil fuel	100.00	0.65	0.50	0.32	0.12	0.14	9.3	3900	0.782	22.62	0.044
Solar-hydrogen energy	0.00	0.00	0.00	0.10	0.00	0.00	6.0	0.0	0.001	1.0	1.00

[a] Particulate matter.
[b] With respect to annual vapour generation due to solar heating (5×10^{17} kg/y).
[c] (Damage due to fuel)/(Damage due to solar hydrogen).

Figure 12. Environment related properties of the main energy systems (Source: Baykara, 2018).

CHAPTER 2: METHODOLOGY

2.1. Data Collection and System Description

The actual data of a petroleum refinery in Türkiye that has approximately ***12 million ton per year*** production capacity was used throughout this study. The selected refinery has two production lines actively producing hydrogen. One of them uses catalytic reformer (CCR) unit in which hydrogen is produced as a by-product; the other line is the Steam Methane Reformer (SMR) unit which is the main hydrogen source and it does not have a carbon capture system. In this study, only SMR unit production capacity has been evaluated, CCR unit production is not added due to hydrogen being by-product in its process. The SMR plant design capacity of this selected oil refinery is ***160,000 Nm^3 per hour***, it is approximately ***125,000 ton per year***. In 2023, hydrogen production obtained from the SMR unit has been ***86,400 tonnes***, with an ***average capacity utilization of 70%*** of the Hydrogen Generation Plant. Purity of the produced hydrogen in selected refinery is ***99.99%.*** Hydrogen is mainly used in hydrotreating of naphtha, kerosene, diesel and hydrocracking of heavy hydrocarbon processes. A simplified hydrogen production and consumption scheme of the refinery is shown in Figure 13.

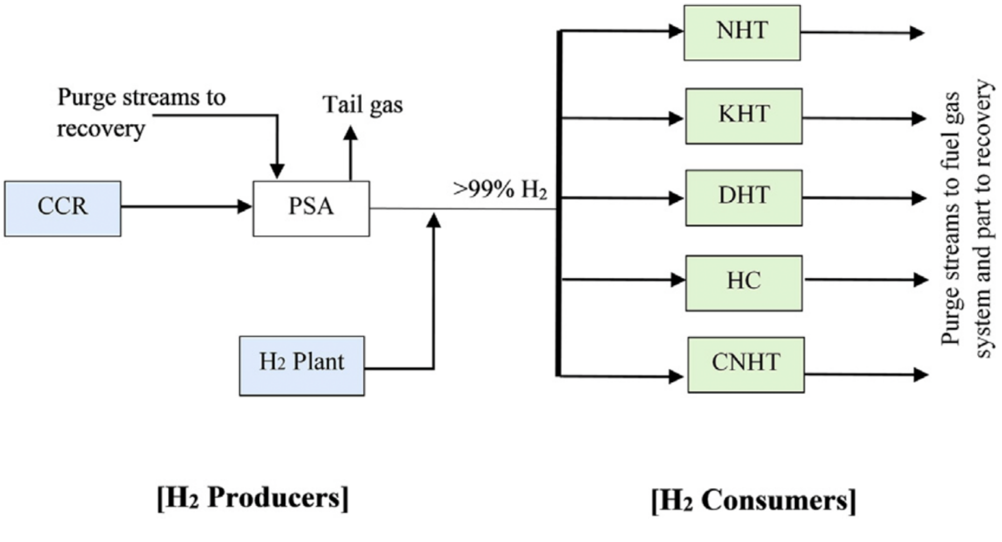


Figure 13. A simplified schematic of the hydrogen production and utilization lines currently used in the selected Petroleum Refinery

No further analysis was carried out due to lack of data inventory about hydrogen production in Türkiye. In this regard, the “Turkish Greenhouse Gas Inventory 1990-2021” report by TUİK (2023), “Ministry of Energy and Natural Resources National Energy Plan” (RTMENR, 2022), and “Türkiye Hydrogen Technologies and Strategies Roadmap” (RTMENR, 2023) reports have been evaluated but no such data have been acquired. Thus, the thesis research has been carried out with the actual data of the designated Petroleum refinery.

For the existing hydrogen production line, it is advised to install an electrolyser that could generate hydrogen from water with zero emissions. This electrolyser will be powered by the renewable electricity from the wind turbine farm of the refinery including 17 turbines ***power capacity of 51 MW***. Accordingly, the main and only renewable source of the electrolyser will be obtained from the wind turbine farm.

Analysis of the hydrogen production capacity of the electrolyser has been done by the capacity of the existing wind turbine farm capacity. Incrementing electrolyser capacities have been evaluated ranging from 10 MW to 50 MW. Accordingly, the amount of green hydrogen that will replace existing grey hydrogen production as well as the avoided emissions have been calculated. Figure 2 shows the schematic of the proposed hydrogen production units.

As mentioned previously, the existing wind turbine farm has an electricity generation capacity of 51 MW. However, it has an annual design power factor of 0.42 on average based on the wind profile of the area. (Power factor is the is the ratio of the actual energy produced in a given period, to the theoretical maximum possible, for example running full time at maximum designed power). In this study, actual data of 2023 was used for calculations. Due to changes in the weather conditions in the area, each season, each day and each hour have different power energy generation profiles. Figure 3 depicts the hourly electricity generation in 2023.

The electricity generation capacity of the selected petroleum refinery, being 51 MWh, is the maximum capacity it could hold. This number was measured as approximately ***145.0 GWh in 2023.***

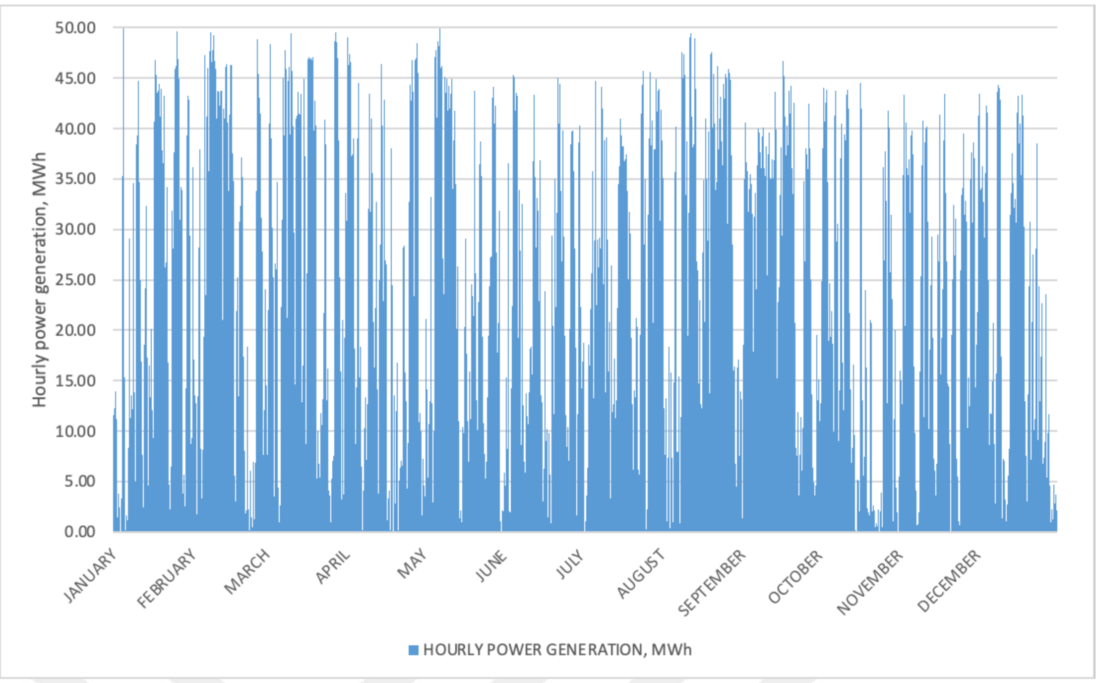


Figure 14. Hourly Electricity Generation in the Built Wind Farm during 2023

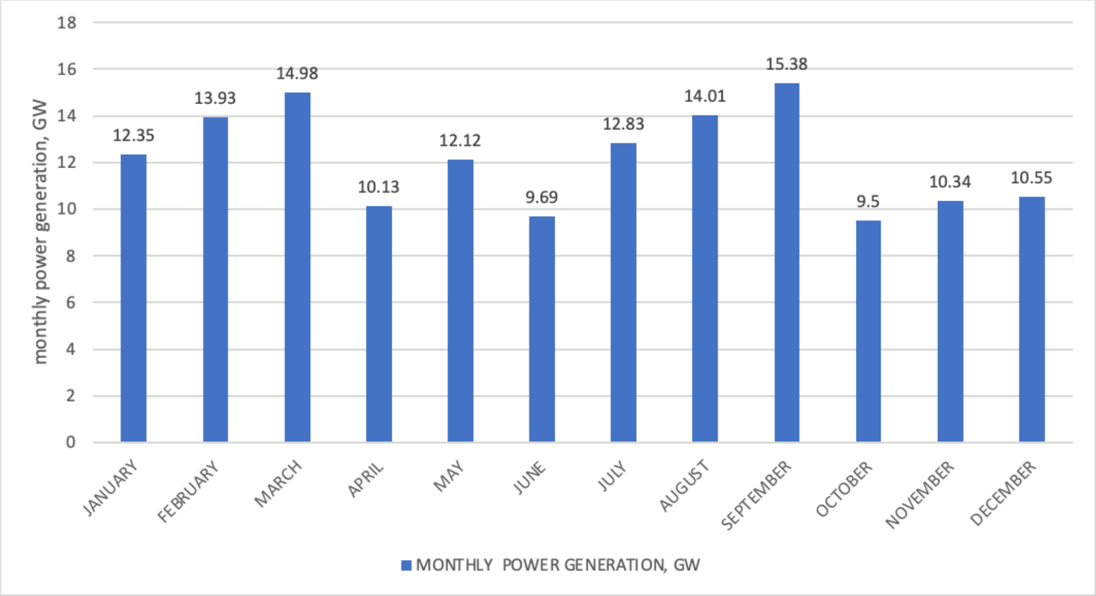


Figure 15. Monthly electricity generation in the built wind farm during 2023

In this thesis, 5 electrolysers run on wind energy with different capacities are proposed and the calculations have been evaluated accordingly;10 MW, 20 MW, 30 MW, 40 MW, 50 MW. The methodology of the calculations is reported in the following section.

2.2. Technoeconomic Analysis

The Levelized Cost of Hydrogen (LCOH) and Investment Costs have been calculated in USD/kg with the following equations to estimate the cost of green hydrogen production for the selected petroleum refinery. Investment costs for the infrastructure required for hydrogen production has been considered, but storage and land costs have not been considered in this calculation due to the sake of the installed system.

In the literature, it is seen that there are various calculation methodologies for hydrogen costs. Therefore, as a general approach, annuity method has been used for all calculations.

Lehmann (2022) and Fraunhofer ISE (2018) has described LCOH calculations only basis of yearly operational expenses and initial investment expenses. Manna et al. (2021) has applied the LCOH calculations without including replacement cost of electrolysers stacks, but added storage cost to calculations. Minutillo et al. (2021) has stated LCOH calculation equations with adding replacement cost to the other general parameters.

In this paper, the equation used was modified from all formulas as reported above Lehmann (2022), Fraunhofer ISE (2018), Manna et al. (2021) and Minutillo et al. (2021) studies. Real time renewable electricity prices at each hour for that wind turbine has been used for calculations. Equation 2 has been used for LCOH calculations in this paper.

$$\text{LCOH} = \frac{Total\ Costs(\$)}{H2\ Annual\ Production\ (kg)}$$

$$= \frac{ANF*\left(C_{inv,we} + \frac{C_{rep,we}}{(1+i)^t}\right) + C_{O\&M,we} + C_{rew.el}}{M_{H_2}} \qquad (2)$$

Where, $C_{inv,we}$ is the initial investment cost of the water electrolyser in USD, $C_{rep,we}$ and t is the stack replacement cost and related year of the water electrolyser in USD respectively. $C_{O\&M,we}$, represents the cost to guarantee the normal operation and maintenance of the water electrolysers, it is calculated on yearly basis. $C_{rew,el}$ is the total yearly electricity cost for the electrolysers for that year. M_{H2} is the total mass of hydrogen produced in kilogram annually.

Secondly, for the future forecasts, a carbon tax value has been added to the LCOH calculation. In this case, the modified equation is shown in Equation 3, deducting reduced emissions amount times carbon tax.

$$\text{LCOH} = \frac{Total\ Costs(\$) - Reduced\ Emissons\ Carbon\ Tax\ Costs(\$)}{H2\ Annual\ Production\ (kg)}$$

$$= \frac{ANF * \left(C_{inv,we} + \frac{C_{rep,we}}{(1+i)^t}\right) + C_{O\&M,we} + C_{rew.el} - T_{CO2} * Q_c}{M_{H_2}} \tag{3}$$

Where, T_{CO2} is the carbon tax per tonnes of CO_2 released, while Q_C is the reduced emission amount, calculated based on hydrogen production amount reflecting how much emissions are reduced from existing grey hydrogen generation unit.

Calculation is done with the annuity method. ANF is the annuity factor that determines cost on yearly basis and defined as shown in equation 4 (Lehmann, 2022).

$$\text{ANF} = \frac{i\ (1+i)^n}{(1+i)^n - 1} \tag{4}$$

Where, i and n are the nominal interest rate in fraction and plant lifetime in years, respectively.

2.3. Analysis of Water Electrolyser Capacities

The selected petroleum refinery owns an AE and a PEM electrolyser and the calculations have been using real data from the refinery. In the literature varying efficiencies between the AE and PEM electrolysers have been reported Table 3.

Kumar and Lim (2022) and Kumar and Lim (2023) demonstrated companies that manufacture electrolysers. The average energy efficiencies of AE and PEM electrolysers with crosscheck of above study values have been used.

The existing hydrogen system in the selected petroleum refinery pressure is 27 bar, therefore only data from companies with that has ability to work on 30 bar and more pressures for hydrogen have been used. Among these data efficiency values of each electrolyser were applied.

Table 3. Energy efficiencies of AE and PEM electrolysers reported in the literature.

AE Electricity Generation (kWh/Nm^3)	PEM Electricity Generation (kWh/Nm^3)	Considerations	Reference
4.5-7.5 kWh/Nm^3	5.8-7.5 kWh/Nm^3	Cell pressures ranges 25-80 bar.	(El-Shafie, 2023)
4.8 kWh/Nm^3			(Proost, 2019)
4.5-4.8 kWh/Nm^3		commercial values from companies	(Minutillo et al., 2021)
3.72 and 5.28 kWh/Nm^3, and 4.45 kWh/Nm^3 average			Lehmann (2022)
4,5-6.6 kWh/Nm^3 (54%-78%)	4.2-6.6 kWh/Nm^3 (54%-84%)		(Schmidt et al., 2017)
4.6 kWh/Nm^3	5.4 kWh/Nm^3		(Matute, Yusta and Correas, 2019)
8.3 and 5.3 kWh/Nm^3			(Manna et al., 2021)
62-82%,	67-82%.		(Wang, Cao and Jiao, 2022)
		Maximum efficiency was obtained value of 82.4% in the operating conditions of 60 A, 65°C (maximum temperature) and 5 bar (minimum pressure)	(Ursúa et al., 2013)
		highest efficiency of 78.52% was captured at 120°C and 10 bar for 1 A/cm2 operation.	(Jang et al., 2023)

In this study calculations on the defining hydrogen production amount, it has been used minimum, maximum and average efficiencies of AE and PEM electrolysers to give different results in different efficiencies as there is not exact efficiency value for the electrolyser for now as the electrolyser technology are developing. It is better to see numbers in each efficiency to compare results.

In this study, to calculate of AE and PEM Water Electrolysers capacity, it has been used following efficiency data; PEM Electrolyser is more efficient than Alkali Electrolyser. It is seen from table is that maximum efficiency for Alkali Electrolyser is 78.6%, while 82.3% for PEM Electrolyser. Sarno and Ponticorvo (2019) stated that more innovative technology development, efficiency could be increased to 3.8 kWh/Nm^3, efficiency at 93% for PEM Electrolysers.

Kumar and Lim (2023) stated that, at present, the primary expense in the PEM water electrolyser system remains the cell stack, constituting about 45% of the overall cost, while the balance of plant comprises the remaining 55%. The balance of plant encompasses expenses such as electricity and water costs, as well as the engineering components related to hydrogen processing and cooling systems.

Because, efficiencies are used in the stack efficiencies, but, in this study, to calculate hydrogen production amount, system efficiency is used. As knowing that there is average 7-10 % difference depending on size of the plant. When plant capacity is increased, BoP (Balance of Plant) is becoming more feasible rather than less capacity electrolyser system. Therefore, the selected below values for the calculation is more accurate for this study.

Table 4. Chosen efficiencies of AE and PEME for this study

WATER ELECTROLYSERS	**MAXIMUM EFFICIENCY**	**AVERAGE EFFICIENCY**	**MINIMUM EFFICIENCY**
AE	78.6 % (4.5 kWh/Nm^3)	72.2 % (4.9 kWh/Nm^3)	65.5 % (5.4 kWh/Nm^3)
PEM	82,3 % (4.3 kWh/Nm^3)	73,8% (4.8 kWh/Nm^3)	65.5 % (5.4 kWh/Nm^3)

In this paper, assessment of five different capacity electrolyser according to existing wind farm capacity profile have been done. Minimum capacity is 10 MW electrolyser, Maximum is 50 MW electrolyser. And between these capacities, 20 MW, 30 MW and 40 MW for Alkali Electrolyser and PEM Electrolyser have been evaluated, too. Output data for each electrolyser at each capacity, and calculated values of each capacity electrolysers have been revealed in results section.

2.4. Electrolyser Cost Literature Review and Selection of Data for Calculation

To find the most accurate LCOH values, literature review has been reviewed to find electrolyser system prices. Below table shows literatures about cost of water electrolysers, some of them are cost including BoP prices, some of them are only electrolyser prices. Decision prices for this study calculations based on these literature data comparing each literature has been made.

Table 5. Cost of AE and PEME reported in the literature.

AE prices	PEME prices	Considerations	Reference Study
640 USD/kW	587 USD/kW		(Kumar and Lim, 2023)
830 EUR/kW in 2017, 600 EUR/kW is expected in 2025.	1300 EUR/kW in 2017, 900 EUR/kW is expected in 2025.	CAPEX of the system including stack, balance of plant and power supply unit	(Matute, Yusta and Correas, 2019)
1000-1200 EUR/kW$_{el}$	1860-2320 EUR/kW$_{el}$	Cell pressures ranges 25-80 bar	(El-Shafie, 2023)
830 EUR/kW	1300 EUR/kW	it is expected to decrease to 600 EUR/kW and 900 EUR/kW, respectively	(Schmidt et al., 2017)
1000 USD/kW		Electrolyser specific cost dependent on the rated power which	(Genç, Çelik and Genç, 2012)

		varies according to producer company of electrolysers	
1200 USD/kW.			(Minutillo et al., 2021)
550 EURO/kW (data from NEL)	750 EURO/kW (data from “ITM Power”)	Cheapest values of electrolyser cost, *Detailed cost graphic added additionally	(Proost, 2019)
750 EUR/kW for 20MW and above electrolysers, 830 EUR/kW for 5 MW electrolysers, 1200 EUR/kW for 1 MW electrolysers.			Lehmann (2022)
1200 USD/kW			(Holm et al., 2021)
700 EUR/kW		“NEL” data	(Saba et al., 2018)
270 USD/kW		Electrolyser cost	(León et al., 2023)
242-388 EUR/kW	384-1071 EUR/kW	Stack cost	(Krishnan et al., 2023)
700 EUR/kW			(Janssen et al., 2022)
500-1400 USD/kW	1100-1800 USD/kW	Direct CAPEX	(Hurtubia and Sauma, 2021)
270 USD/kW for stack-only, 500-1000 USD/kW	400 USD/kW for stack-only, 700-		IRENA (2020)

for the entire system	1400 USD/kW for the entire system		
		Which is held in Shell Petroleum Refinery in Germany 20 million euro for 10 MW PEM Electrolyer project fot the total investment.	REFHYNE (2021)

Proost (2019) demonstrated that using multi-stack systems has an effect on the reduced CAPEX. In this study, below graph shows the correlation between number of stacks and capex.

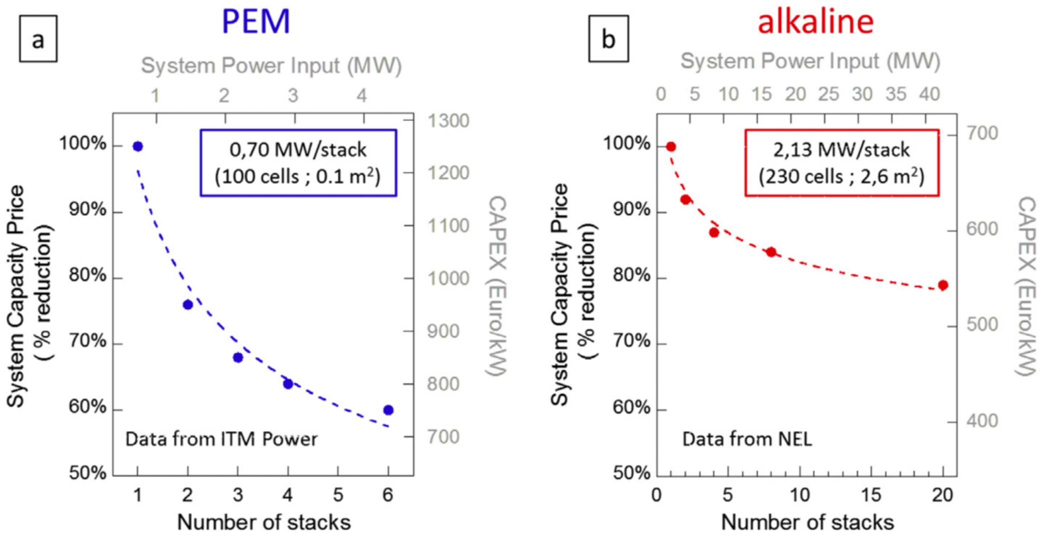


Figure 16. Reduction in CAPEX upon use of multi-stack systems, both for PEM (a) and alkali (b) electrolysers (Source: Proost, 2019).

Below graph shows correlation between annual operating hours of electrolysers and LCOH in different CAPEX prices with the comparison of steam methane reformer hydrogen price, while operating hours increase, LCOH value reaching its minimum value (Proost, 2019).

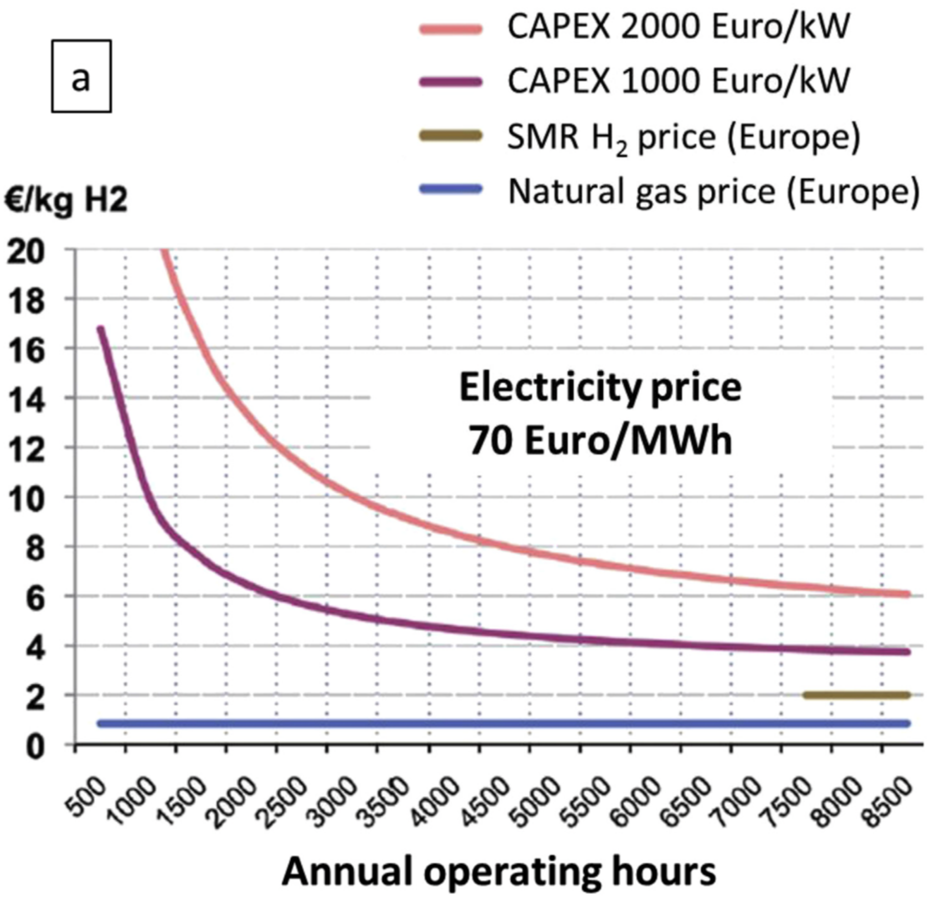
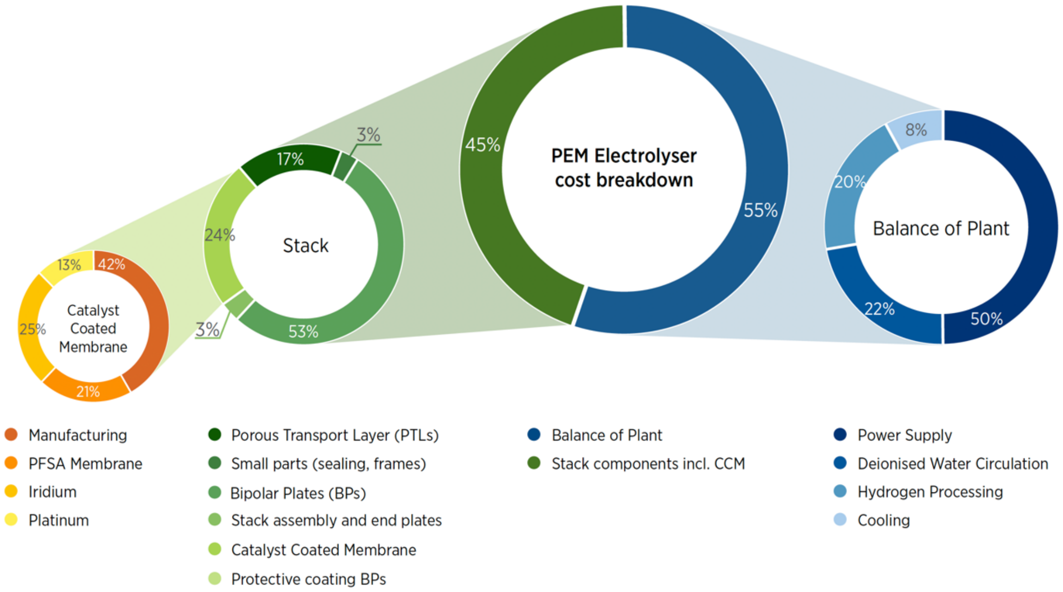


Figure 17. Electrolytic H_2 production cost (in Euro/kg) as a function of electrolyser operational time for different electroyser CAPEX values (Source: Proost, 2019).

All the main parameters of above points from different study's reveals that for this study LCOH values should be minimum. Because, in this study minimum electrolyser capacity is chosen 10 MW, minimum CAPEX requirement values in this study has been used. Beyond electrolyser capacity, BoP capital cost is also reducing for the entire system, as a result, this also effects on the general capital reduce. Even, when scaling up to 100 MW electrolyser, CAPEX could be as low as 400 Euro/kW.

AE and PEME system cost prediction is very difficult. To find out total investment cost of each system, other costs to the direct CAPEX cost have been added. According to Hurtubia and Sauma (2021), installation CAPEX is the 10% of the direct CAPEX, and indirect CAPEX cost is the 33,8% of direct CAPEX.

Total system cost of electrolysers includes BoP Price which corresponds 55% of the total cost, while 45% of the total cost is stack cost with its detail assembly parts. As aforementioned, in this study, because electrolyser capacity is chosen bigger, this cost breakdown is changing to lower representing BoP price less than that percentage. In this mind, total system cost has been used for calculations (IRENA, 2020).



Note: The specific breakdown varies by manufacturer, application and location, but values in the figure represent an average.

Figure 18. Cost breakdown for a 1 MW PEM electrolyser (Source: IRENA, 2020).

For the calculation of this study, cost prices of 1000 USD/kW for the Alkali Electrolyser system including BoP and 1400 USD/kW for the PEM Electrolyser system including BoP has been applied.

2.5. Stack Replacement Cost and Selection of Data for Calculation

For LCOH calculation, another important parameter is the stack replacement cost and replacement year. Stack life is changing depending on different factors, such as usage, energy intensity. In this thesis calculation, stack life has been chosen 10 years, referenced from Minutillo et al. (2021). In studies, there is limited sources about stack replacement cost. Below table, the reference studies have been investigated to find more appropriate value to use in this paper calculation.

For this study calculation, costs of 340 USD/kW for AE stack and 420 USD/kW for PEME stacks has been applied.

Table 6. AE and PEME stack replacement cost in literatures

AE stack replacement cost	PEME stack replacement cost	Reference Study
380 EUR/kW in 2017, 270 EUR/kW in 2025	470 EUR/kW in 2017, 250 EUR/kW in 2025	(Matute, Yusta and Correas, 2019)
15% of the total CAPEX	15% of the total CAPEX	(Fraunhofer ISE, 2018)
340 USD/kW	420 USD/kW	(Nguyen et al., 2019)

2.6. Carbon Tax Estimation

In this study calculations, future probabilities of carbon emission tax for the Turkish Petroleum Refineries have been included. For this purpose, different sources have been researched to find out how much would be this cost.

Türkiye has launched Emission Trade System (ETS) and starts pilot applications in 2024. This system includes industries and energy sectors. Therefore, it is crucial to address refinery emissions. Also, As of January 1, 2026, the EU requires the carbon footprint of all products to be imported into the union in 6 sectors to be measured and a carbon tax to be collected for each ton released into the environment. In this first period, refinery products are not included to the CBAM system. But it is obvious that in the recent future refinery products will also be included to the carbon pricing system. In this case, refineries are more engaged with the emissions.

As the carbon tax price in Türkiye has not been defined yet, and if price will be defined in the market, assumption has been used from World countries examples. According to World Bank (2023) data, countries' carbon tax prices are shown for 2023 in figure 19. Therefore, different carbon tax price has been applied to my calculation. These values are *10, 20, 30, 40 and 50 USD dollars per ton of CO_2 emissions*. Including this amount to the LCOH calculations, deducting this amount from yearly cost have been decreased green hydrogen cost, hence leading to be competitive to the existing grey hydrogen. After calculation, it is demonstrated how much hydrogen cost decreases with applying different carbon taxes.

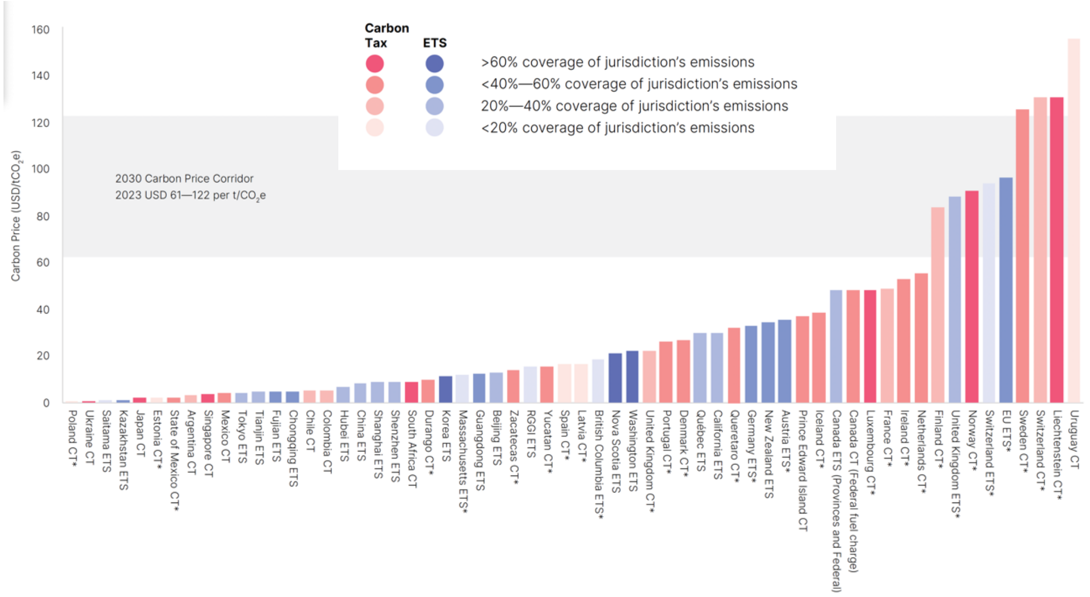


Figure 19. Prices across ETSs and Carbon Taxes in the World (Source: World Bank, 2023).

CHAPTER 3: RESULTS

3.1. Electrolyser Capacity and Power Factor

For producing green hydrogen with the electrolysis powered by the renewable electricity, the electrolyser capacity is determined, calculations are done and results are shown below. Electrolyser capacity is calculated based on only renewable energy input, not to replace whole existing hydrogen production.

Electrolyser capacities are calculated based on chosen values of efficiencies of AE and PEM electrolyser with different capacities. It is low/minimum efficiency (65.5% for both AE and PEME), average efficiency (72.2% for AE and 73.8% for PEME) and best/maximum efficiencies (78.6% for AE and 82.3% for PEME). And electrolyser capacities are chosen in 5 different capacities based on the wind farm production profile. Therefore, electrolyser capacities of 10, 20, 30, 40, and 50 MW are used. Because of maximum electricity generation of existing wind farm is 49.98 MW, electrolyser maximum capacity is chosen 50 MW. With this values, below green hydrogen production amounts are calculated.

Table 7. Results of Electrolysers Hydrogen Production amounts

ELECTROLYSER	EFFICIENCIES (kW/Nm^3)	10 MW (ton H_2)	20 MW (ton H_2)	30 MW (ton H_2)	40 MW (ton H_2)	50 MW (ton H_2)
AE	4,5	1,165.4	1,948.1	2,503.4	2,811.7	**2,867.8**
	4,9	1,070.2	1,789.0	2,299.1	2,582.1	2,633.7
	5,4	**971.1**	1,623.4	2,086.2	2,343.1	2,389.8
PEME	4,3	1,219.6	2,038.7	2,619.9	2,942.4	**3,001.2**
	4,8	1,092.5	1,826.3	2,347.0	2,635.9	2,688.5
	5,4	**971.1**	1,623.4	2,086.2	2,343.1	2,389.8

Capacity factor of each electrolyser is calculated according to existing wind farm real-time values. It also reveals existing wind farm real electricity production profile that in which range it is most efficient.

Table 8. Electrolysers capacity factors in each design capacity

Electrolyser Design capacity, AE, PEME	10 MW	20 MW	30 MW	40 MW	50 MW
Electrolyser Yearly Capacity, MW	87,600	175,200	262,800	350,400	438,000
Amount of Yearly Available Renewable Electricity, MW	58,922	98,497	126,578	142,162	145,000
Electrolyser Power Factor	0.67	0.56	0.48	0.41	0.33

In the below graph that shows us correlation between power factor of electrolysers and electrolyser capacity. From this graph, it could be seen how power factor are decreasing when choosing bigger capacity electrolysers.

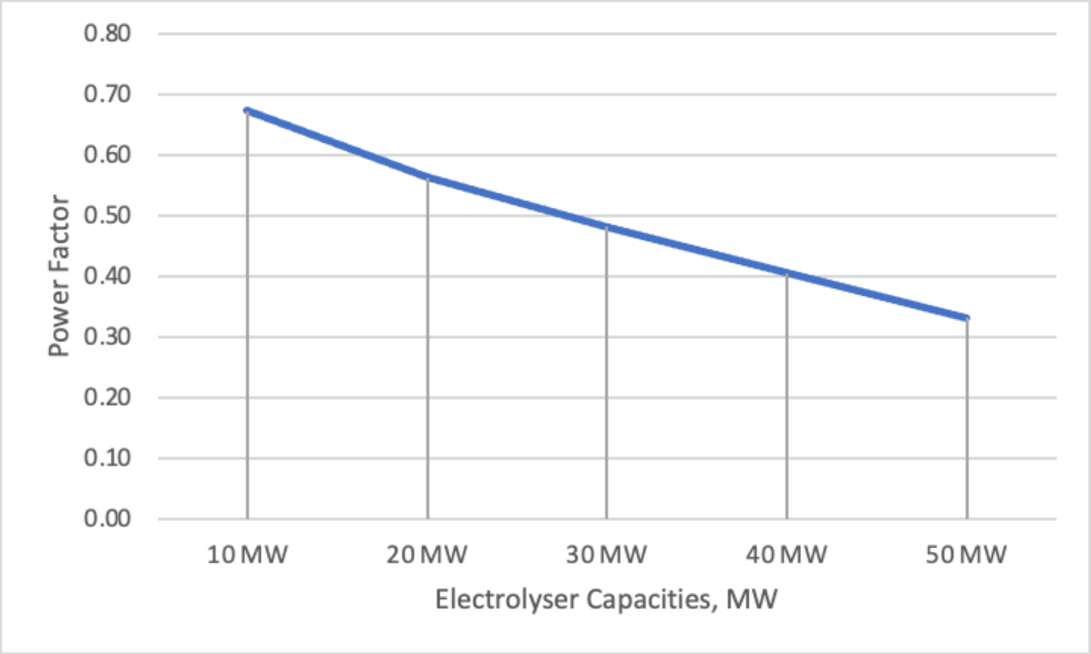


Figure 20. Graph of electrolysers capacity factors in each design capacity

3.2. Investments required for green hydrogen production

Investment is needed for the establishment of the electrolyser system and its BoP. Investment amount is calculated based on these parameters. The calculated initial investment costs for AE and PEME system are shown below table, as it is changing with the capacity of each electrolyser type. For AE system cost of the total system is chosen 1000 USD/kW, and for PEME system cost of total system is chosen 1400 USD/kW. As a result, total investment costs are calculated based on these costs of each capacity electrolysers.

Table 9. Calculated total investment cost for AE and PEME

ELECTROLYSERS	TOTAL INVESTMENT COST, USD
AE system, 10 MW	10,000,000
AE system, 20 MW	20,000,000
AE system, 30 MW	30,000,000
AE system, 40 MW	40,000,000
AE system, 50 MW	50,000,000
PEME system, 10 MW	14,000,000
PEME system, 20 MW	28,000,000
PEME system, 30 MW	42,000,000
PEME system, 40 MW	56,000,000
PEME system, 50 MW	70,000,000

3.3. Levelized cost of Hydrogen (LCOH) in the selected petroleum refinery

From the equation 2, LCOHs are calculated in different capacity electrolysers. Values of useful life and O&M cost in terms of percentage of initial capital cost for each sub-system are shown in table 10.

Table 10. Critical Parameters of electrolysers used in calculations

Parameter	Unit	Value	Reference
Plant life time (n)	years	25	Lehmann (2022)
Nominal interest rate (*i*)	%	3	(Minutillo et al., 2021)
AE System Investment Cost (Including BoP)	USD/kW	1000	Averagely assumed from other studies
PEME System Investment Cost (Including BoP)	USD/kW	1400	Averagely assumed from other studies
O&M Cost (Wind Farm)	USD/year	1.1M	This study
O&M Cost (Electrolyzer)	% of CAPEX (electrolyser)	2	(Minutillo et al., 2021)
Time for replacement (*t*)	Years	10	(Minutillo et al., 2021)
AE Replacement cost	USD/kW	340	(Nguyen et al., 2019)
PEME Replacement cost	USD/kW	420	(Nguyen et al., 2019)

Table 11. LCOH for each electrolysers in each capacity

ELECTROLYSER	EFFICIENCIES, %	10 MW	20 MW	30 MW	40 MW	50 MW
AE	HIGH (78.6%)	**5.63**	5.72	5.85	6.08	6.40
	AVERAGE (72.2%)	6.13	6.23	6.37	6.62	6.96
	LOW (65.5%)	6.76	6.86	7.03	7.30	**7.68**
PEME	HIGH (82.3%)	**5.66**	5.80	5.99	6.28	6.68
	AVERAGE (73.8%)	6.32	6.48	6.68	7.01	7.46
	LOW (65.5%)	7.11	7.29	7.52	7.89	**8.39**

Below, results are shown in the graphic version. In these graphs, it is seen how LCOH increases with the increasing capacity of electrolysers. As capacity increase, LCOH between following capacities are becoming much bigger.

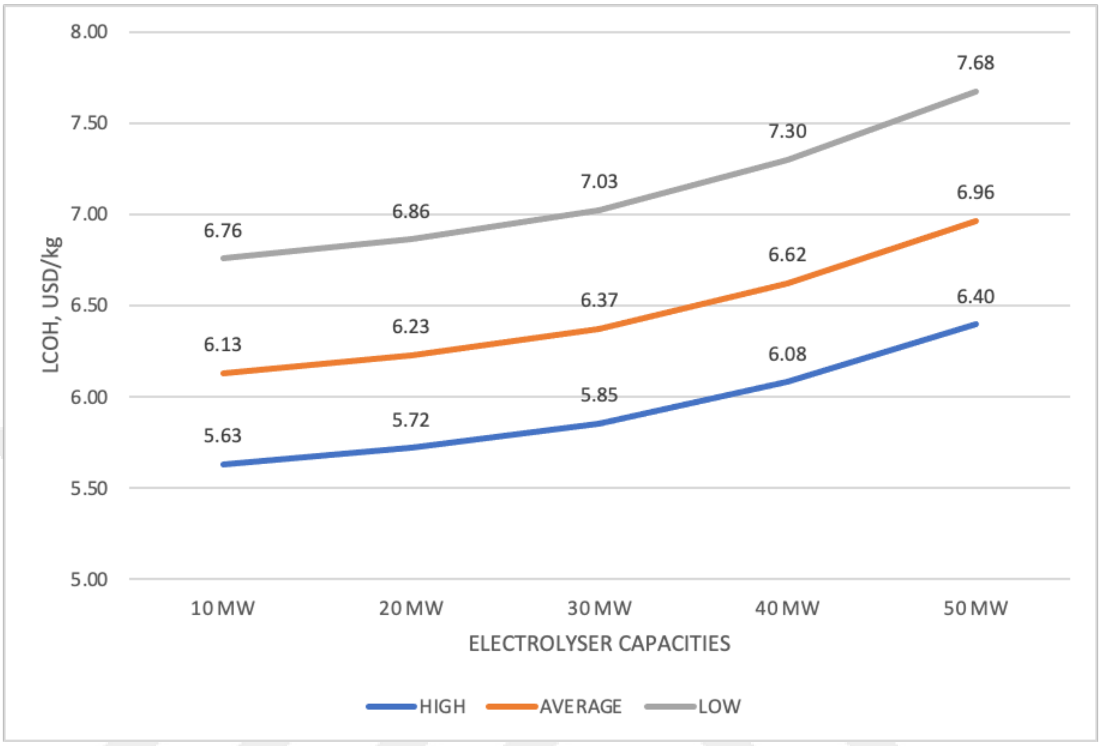


Figure 21. Alkali Electrolyser LCOH in each capacity and efficiency

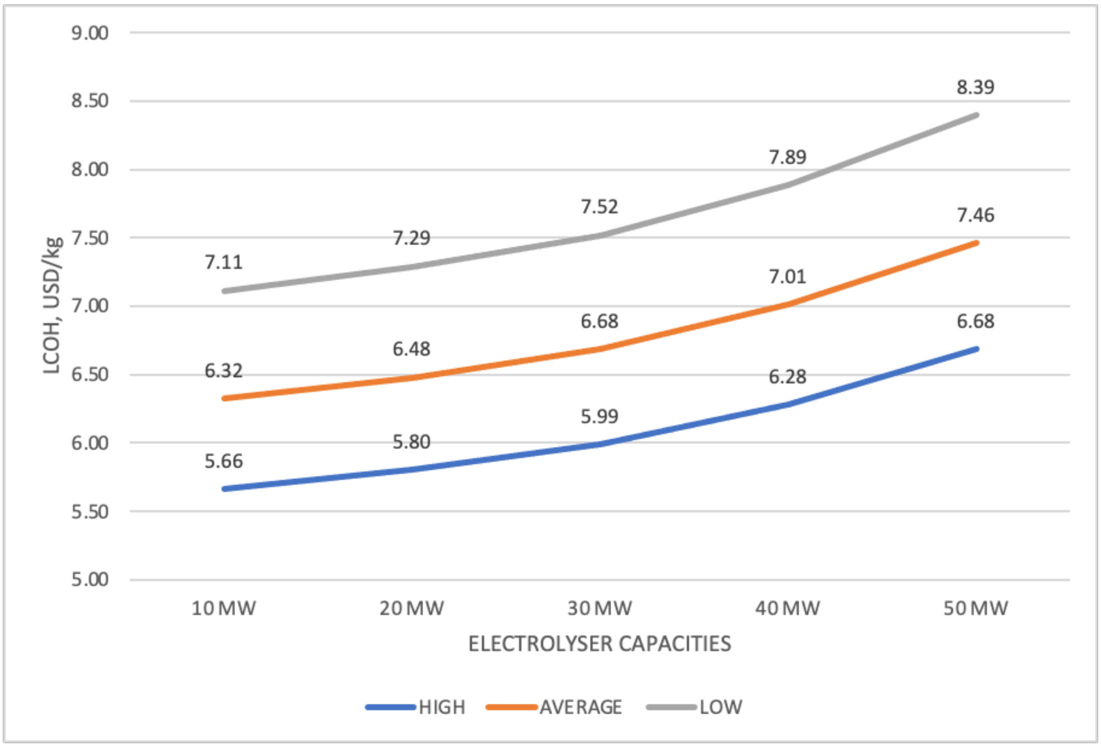


Figure 22. PEM Electrolyser LCOH in each capacity and efficiency

3.4. Water requirement

Water is needed for electrolyser operation as input. Electrolyser breaks water molecule into hydrogen and oxygen. For 1 kg hydrogen production, between 18 kg and 24 kg of water is required (IRENA, 2020). As the refinery produces hydrogen with the SMR that uses water, that means there is not extra water requirement. Also, this selected refinery has its water purification plant that could feed to electrolyser. While SMR capacity decrease, that amount of water could be used in electrolysers. Only some pipeline connections infrastructure works have to be done to bring that water to the electrolyser plant. When checked selected refinery water quality, it is seen that this quality is in limits that electrolysers could directly use without any extra purification works. It brings cost effectiveness of the new system, as there is not any extra operational water production cost, either.

In this study, it was estimated that ***270 m^3 to 800 m^3*** daily purified water is needed for electrolysers depending on the efficiency of the electrolysers from minimum efficiency with minimum capacity to maximum efficiency with maximum capacity.

Another important consideration is water that is used in hydrogen production via electrolysis. Water prices can reach very high levels in some areas that has water shortages. In oil refineries where there is hydrogen manufacturing, extra water systems may be required. Depending on the technology an electrolyser requires, added amount of ultra-pure water may be needed in oil refineries, thus new facilities for water desalination and purification may be required. The reduction of impurities from electrolyser stacks creates largest cost than purification and desalination of water. Thus, overall, it is important to install water purification systems as per electrolyser demand.

For large-scale hydrogen production, IRENA (2020) concludes that “the overall water demand would be relatively small compared to the global water consumption”.

3.5. Reduced emissions from existing SMR unit

In SMR processes, approximately 9 kilograms of CO_2 are emitted per kilogram of hydrogen, as reported in Muradov (2015). Normally, this quantity of CO_2 is released into the air during the extraction of valuable hydrogen gas. Nevertheless, in contemporary SMR plants that integrate SMR with CCS, there is a potential for significant reduction in CO_2 emissions. Shifting to green hydrogen production as an alternative to current SMR processes could be a substantial step in mitigating CO_2 emissions.

1,050,000 ton per year (750,000 ton from directly process and 300,000 ton from furnace emission) emissions from SMR unit is generated in selected refinery. Total amount of emissions from the refinery is approximately ***2,500,000 ton per year***, meaning approximately ***42%*** of total refinery emissions are responsible of SMR hydrogen production. These data show the importance of decarbonization of hydrogen production, so it has great effect on the petroleum refinery overall decarbonization.

The hydrogen production from electrolysers and how much emission that it would reduce existing HGU hydrogen production and thus ratio of the emissions from SMR unit for the proposed configuration were calculated. The result of the calculations of AE system is shown in table 12 and figure 23.

Table 12. Results table of avoided emissions and its percentage of refinery emissions in Alkali Electrolyser application

EFFICIENCIES OF AE, (%)	ALKALI ELECTROLYSERS CAPACITIES, (MW)	EMISSIONS AVOIDED, (ton/year)	PERCENTAGE OF TOTAL REFINERY EMISSONS, (%)
HIGH EFFICIENCY (65.5%)	10 MW	33,719.8	1.3%
	20 MW	56,367.6	2.3%
	30 MW	72,437.4	2.9%
	40 MW	81,355.9	3.3%
	50 MW	**82,979.7**	**3.3%**
AVERAGE EFFICIENCY (72.2%)	10 MW	30,967.2	1.2%
	20 MW	51,766.2	2.1%
	30 MW	66,524.2	2.7%
	40 MW	74,714.6	3.0%
	50 MW	76,205.8	3.0%
LOW EFFICENCY (78.6%)	10 MW	28,099.8	1.1%
	20 MW	46,973.0	1.9%
	30 MW	60,364.5	2.4%
	40 MW	67,796.6	2.7%
	50 MW	69,149.7	2.8%

Below, to visualize of the data the graphical trend of the high efficiency AE system shown.

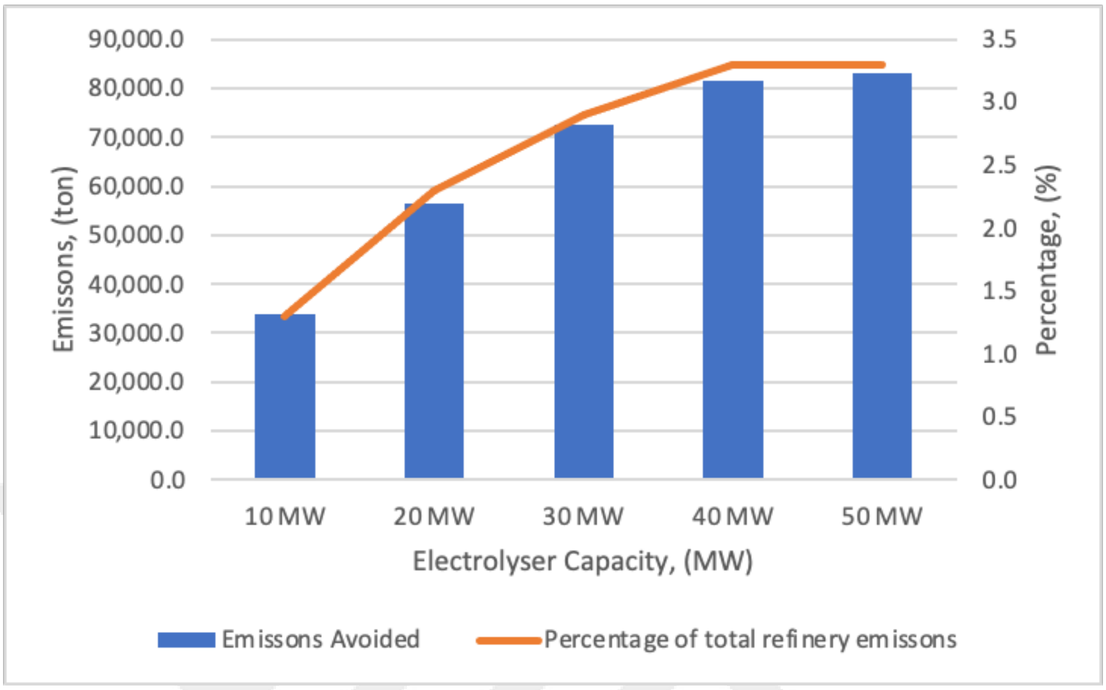


Figure 23. Results graphic of avoided emissions and its percentage of refinery emissions in Alkali Electrolyser application

The result of the calculations of PEME system is shown in table 13 and figure 24.

With this data, the maximum emissions are reduced by *82,979.7 ton (3.3% of total refinery emissions)* with the AE system, while *86,839.2 ton are reduced (3.5% of total refinery emissions)* with PEME system.

Table 13. Results table of avoided emissions and its percentage of refinery emissions in PEM Electrolyser application

EFFICIENCIES OF PEME, (%)	PEM ELECTROLYSERS CAPACITIES, (MW)	EMISSIONS AVOIDED, (ton/year)	PERCENTAGE OF TOTAL REFINERY EMISSONS, (%)
HIGH EFFICIENCY (65.5%)	10 MW	35,288.2	1.4%
	20 MW	58,989.3	2.4%
	30 MW	75,806.6	3.0%
	40 MW	85,139.9	3.4%
	50 MW	**86,839.2**	**3.5%**
AVERAGE EFFICIENCY (73.8%)	10 MW	31,612.3	1.3%
	20 MW	52,844.6	2.1%
	30 MW	67,910.1	2.7%
	40 MW	76,271.2	3.1%
	50 MW	77,793.5	3.1%
LOW EFFICENCY (82.3%)	10 MW	28,099.8	1.1%
	20 MW	46,973.0	1.9%
	30 MW	60,364.5	2.4%
	40 MW	67,796.6	2.7%
	50 MW	69,149.7	2.8%

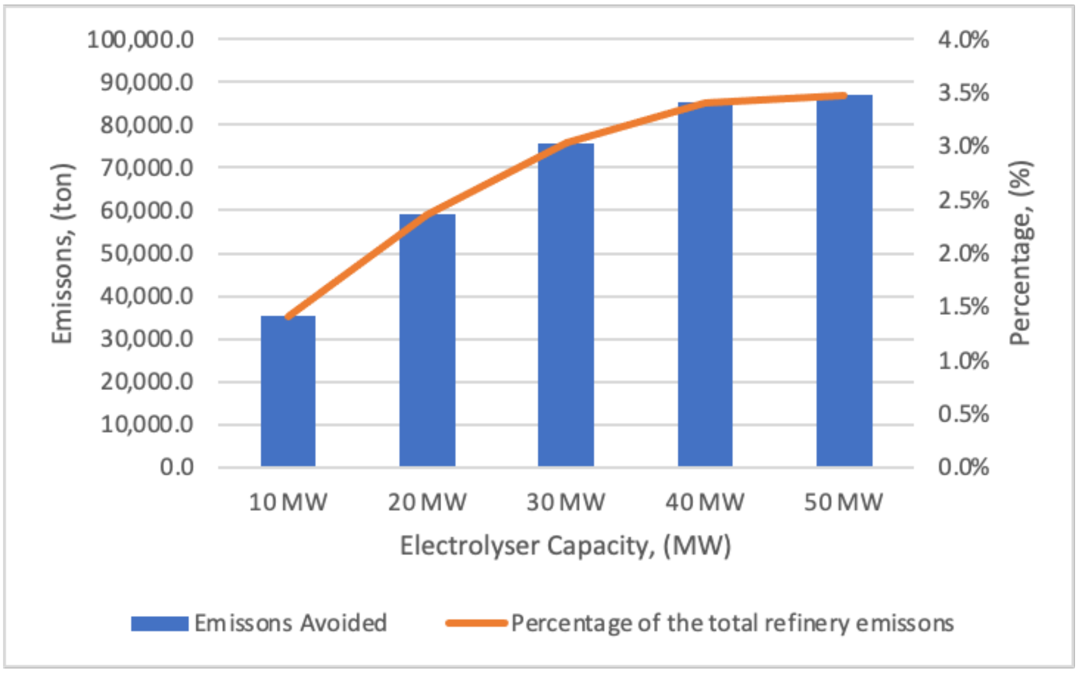


Figure 24. Results graphic of avoided emissions and its percentage of refinery emissions in PEM Electrolyser application

3.6. The Effect of Carbon Tax on LCOH

Another calculation is done with including carbon tax prices to the reduced emissions amount for each capacity of electrolysers. Five different carbon tax price is applied and LCOH calculation equation 3 results are shown below.

Table 14. Carbon tax effect on LCOH

Carbon Tax Price, (USD/ton)	LCOH price decrease, (USD/kg)	AE, 10 MW High efficient, LCOH, (USD/kg)	PEME, 10 MW High efficient, LCOH, (USD/kg)
10 USD/ton	0.29	5.34	5.37
20 USD/ton	0.58	5.05	5.08
30 USD/ton	0.87	4.76	4.80
40 USD/ton	1.16	4.47	4.51
50 USD/ton	1.45	4.19	4.22

It is seen from table 14 that each 10 USD/ton carbon price effects on LCOH decrease 0.29 USD per kg, and could decrease 1.45 USD/kg of LCOH by applying 50 USD/ton carbon tax.

3.7. The Effect of Electricity Prices on LCOH

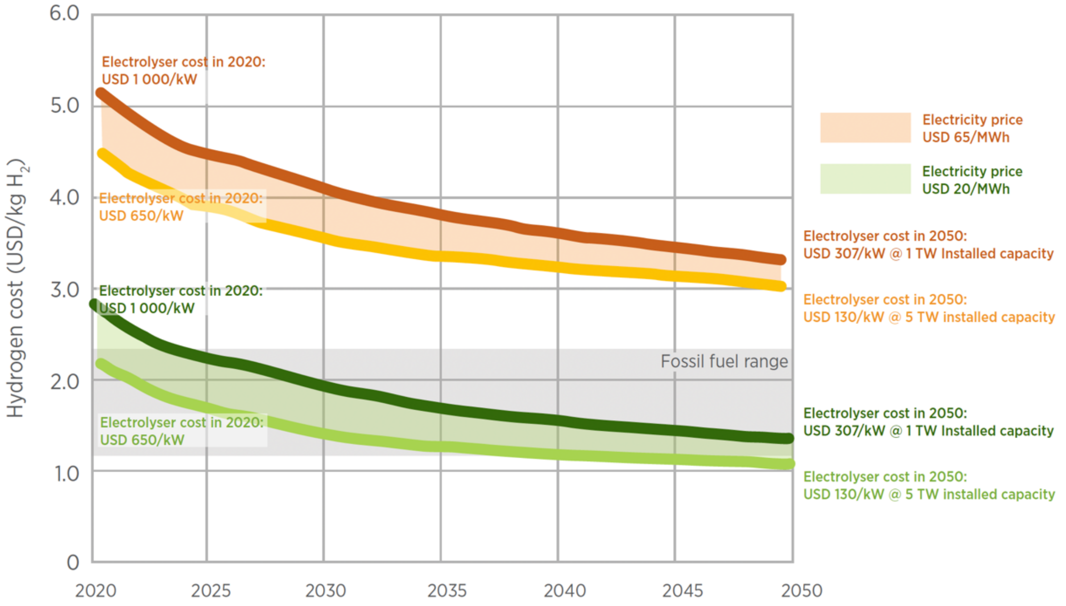
Further calculations were made with different electricity prices as 20 USD/MWh, 40 USD/MWh, 60 USD/MWh and 80 USD/MWh, to find out how electricity prices effects on LCOH All calculations were done by real-time data, electricity price was used as 5 USD/MWh. Table 15 shows that in order to make feasible of green hydrogen projects, electricity prices should be 20 USD/MWh and below.

These results do not include carbon tax prices. If carbon tax prices are included for this values, 0.29 to 1.45 USD/kg from the last value should be deducted.

Figure 25 shows that 40 USD/MWh and below values for electricity price make green hydrogen more feasible and compatible as grey hydrogen cost is approximately between 1-3 USD/kg, generally 2 USD/kg. The best scenario electricity price for green hydrogen is 20 USD/MWh as mentioned in IRENA (2020).

Table 15. Electricity price effect on LCOH

ELECTRICITY PRICE, (USD/MWh)	DECREASE on LCOH Value, (USD/kg)	AE LOWEST LCOH, (USD/kg)	PEME LOWEST LCOH, (USD/kg)
20 USD/MWh	3.82	1.81	2.02
40 USD/MWh	2.79	2.84	3.00
60 USD/MWh	1.77	3.86	3.97
80 USD/MWh	0.74	4.89	4.95
95 USD/MWh (real-time data)	0 (base case)	5.63	5.66



Note: Efficiency at nominal capacity is 65%, with a LHV of 51.2 kilowatt hour/kilogramme of hydrogen (kWh/kg H2) in 2020 and 76% (at an LHV of 43.8 kWh/kg H2) in 2050, a discount rate of 8% and a stack lifetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

Figure 25. Cost of green hydrogen production as a function of electrolyser deployment, using an average (65 USD/MWh) and a low (20 USD/MWh) electricity price, constant over the period 2020-2050 (Source: IRENA, 2020).

CHAPTER 4: DISCUSSION

4.1. The Role of Green Hydrogen in Oil Refinery Decarbonization Efforts

There are limited studies regarding green hydrogen usage in oil refineries to decrease GHG emissions. It is also considered in Da Silva, Rochedo and Szklo (2022) study, as well.

Manna et al. (2021) assessed green hydrogen production capacities in alkali electrolyser powered with solar panels in all India. To make calculations, study used hydrogen demand data of all Indian oil refineries and ammonia synthesis plants and came up with the calculations how much solar panel and electrolyser capacity is needed to meet all Indian refinery and ammonia synthesis plants. LCOH is calculated in each efficiency parameter, too. Total refinery hydrogen generation capacity in all India is 2.92 MTA. To replace this amount of fossil-fuel based hydrogen with green hydrogen, scholar calculated that 62.24 billion dollars are required, while initial investment cost for alkali electrolyser is assumed 850 USD/kW, and SPV initial investment cost is 543 USD/kW. And optimal efficiency for AE system is assumed 66,5%. In this case, total 25.7 MTA emissions could be avoided in all Indian refineries.

Kakoulaki et al. (2021) examined green hydrogen capacity powered by solar, onshore and offshore wind, hydropower in European Union and UK together in a matter of regional and national level. Study mainly focused to what extend green hydrogen could be adopted, for this reason, surplus renewable electricity potential assessed in accordance with technical potential, environmental issues and land usage restrictions to produce electrolysis hydrogen. Results show that, European countries has huge potential to be enough energy power, though 88 regions out of 109 have the excess renewable electricity potential after all electricity demand is met. Particularly, 84 regions have 50% surplus renewable electricity capacity. With this knowledge, to alter grey hydrogen production amount of 9.75 Mt to electrolytic renewable hydrogen in Europe, 290 TWh of electricity is needed. Renewable electricity capacity shows that this number can easily be met by surplus capacity and even some extra capacity would be available after that. Study concludes that green hydrogen transformation is possible in EU countries and will help to decarbonization, and strategies could be aligned in this matter.

Yáñez et al. (2022) studied oil refinery decarbonization strategies, Colombia as a case study. Study suggested chose 40 measures for oil refinery decarbonization with the five adoption areas. Green hydrogen is shown emissions mitigation option with 6% in Colombian study, following 60% mitigation of bio-oil co-processing, next 23% CCS and 7% green electricity. Study reveals PEM electrolysers are more functional for oil refineries than Alkali electrolysers due to quick response and higher current densities. Study findings show that oil refineries could reach carbon zero operation only when not including final use emissions.

Griffiths et al. (2022) studied oil refining industry strategies by using sociotechnical analysis to evaluate key technical, economic, political, as well as, social factors that effects to oil refining industry. After evaluation, study gives examples of opportunities and barriers for policy makers, researchers how oil refinery sector could be decarbonized and which lacking points are there to clear. This study chose to evaluate six main decarbonize strategies, including improved energy efficiency, waste heat recovery, upgraded unit operations design; especially heaters and furnaces, increasing renewable energy use, CCUS technology use, and low-carbon hydrogen technology adoption. It is seen that clean hydrogen is one of the main strategies in this study. Low-carbon hydrogen is assessed in three options; first, is blue hydrogen; second, low-temperature green hydrogen production; and lastly, low-carbon hydrogen from high-temperature electrolysis via nuclear energy generated heat.

Griffiths et al. (2022) also talked about barriers and enablers to decarbonize oil refinery industry. Technological, organizational and managerial, as well as, political, market and consumer barriers are the main constraints in deploying low-carbon hydrogen to the oil refinery industry. In study, enablers have been included, too; such as carbon pricing, R&D investment, geography-based emission intensity reduction targets, branding, labelling and market awareness for ‘low-carbon products’, access to electricity markets. Among these enablers, carbon pricing system is the major driver that have the greatest effect towards decarbonization efforts, especially to speed up decarbonization projects in near future, otherwise, oil refineries emissions could continue rise. In this study, carbon pricing, both form carbon tax or emissions trading system has been seen economic incentives, without these system decarbonization projects would not be economically feasible. It would be the best if carbon prices high enough to make costly, not feasible but environmentally friendly projects happen.

Al-Subaie et al. (2017) made evaluation about utilizing Ontario province electricity grid that is mostly fed by renewable energy sources to produce renewable hydrogen. Study examines use of this produced hydrogen in oil refineries instead of conventional steam methane reformer. To do this, 1 MW PEM electrolyser are being conducted, thus producing 1180 m3/h hydrogen. Study assesses production costs and life cycle emissions based on five different scenarios with the help of Aspen HYSYS program and mixed integer linear programming. Although known that steam methane reformer is efficient and cost effective even when stringent carbon pricing policy, this study shows renewable hydrogen potential to decrease from steam methane reformer emissions equal to approximately 34893 gasoline passenger vehicles. Production costs of SMR was 1.1 USD thanks to low natural gas prices, compared to 2.5 USD for PEM electrolysis. Study concludes that hydrogen from renewable energies is good alternative to existing ones in oil refineries decarbonization targets.

Da Silva, Rochedo and Szklo (2022) worked on the renewable hydrogen production from surplus wind power, hence eliminating GHG emissions from existing refinery steam-methane reformer. Scholar used Rio Grande do Sul State oil refinery located in Brazil as a case study in six different scenarios. Two scenarios are related to as a reference, steam methane reformer with and without CCS, other four is about to use wind energy to produce hydrogen via electrolysis. Study evaluates the produced renewable hydrogen in the hydrotreating units in place of existing steam-methane reformer, in a result helping to decrease GHG emissions from refinery. Study demonstrates that electrolysis is only competitive only when electrolyser prices and system capital cost decline and when there is surplus electricity is available. The results show that there is potential that from 10.4% to 22.1% emissions reduction could be realized from real oil refinery with the help of renewable hydrogen usage energized by wind surplus. About 52,000 Nm3/h 99.9% pure hydrogen is produced from SMR that is base case for this case. Study calculated that approximately 218 MWh in order to produce this amount of hydrogen via electrolysers. But study calculated that 621 MW electrolyser capacity is needed to use of all renewable power from wind power, that three times more than hourly electricity demand. It is because of intermittent nature of renewable energy that some time there is peak wind electricity generation, other time low generation. This situation obviously increases investment cost. In study it is stated that alkali electrolysers can operate under a partial load of at least 20% of their maximum capacity and maximum capacity is 2.7 MW (Götz et al., 2016), (Schiebahn et al., 2015). Therefore, to reach capacity of 621 MW, 230 electrolysers are required. In renewable energy fluctuations because of seasonal weather condition change, electrolysers could be adjusted to the generated renewable electricity. In low generation, sufficient electrolysers will work, while others stopped. This operation increases integrity of equipment and boost efficiency of the system.

Peláez-Samaniego et al. (2014) evaluated production and usage of electrolysis hydrogen in Ecuador from two sources either only hydropower or mixed with other renewable power. This produced hydrogen discussed 3 main usage points could be; first; in production of ammonia, second; hydrotreaters in oil refiners, and third; energy storage as a stabilizer of the instability of renewable energy systems. Study results show that if electrolysis plant run at full capacity while consuming low-cost electricity, low-cost renewable hydrogen could be produced at approximately 3.0 US $/kgH$_2$. They also discussed the possibility of using hydrogen in hydrotreating units in oil refineries, among other uses, and determined that this application has the potential to be implemented.

Nurdiawati and Urban (2022) studied three main decarbonization tool for oil refineries in Sweden conducting interview with sector professionals. Three tool includes advanced biofuels, green hydrogen and carbon capture and storage (CCS). Study brings some challenges and opportunities of each technology adoption to oil refineries. Among these three technology adoption, advanced biofuels is shown great potential for its technology maturity, legislation framework and market function. Later, green hydrogen and CCS technologies show strong motivation although they have lack of market formation because of insufficient policy regulations.

Moradpoor, Syri and Santasalo-Aarnio (2023) focused on the green hydrogen production for oil refining in the two scenarios; one is in power purchase agreement-based, second is pay as produced power purchase agreements (PPA). Investment-based scenarios generate green hydrogen with a reduced operational cost, but a higher breakeven price compared to power purchase agreement-based scenarios. The most cost-effective method to produce green hydrogen is by using an alkali electrolyser with a baseload power purchase agreement. Since wind power is not directly owned by the oil refining business, it is more probable that power purchase agreements will be used to get it.

In this thesis, 5 different electrolyser capacities have been evaluated, and it is seen that when electrolysers capacity is increasing from 10 MW to 50 MW, power factor of electrolysers is decreasing. Using knowledge of Da Silva, Rochedo and Szklo (2022) study, adjusting electrolyser working operation in accordance with renewable energy power, power factor and system efficiency could be increased.

In this paper, both AE and PEM technology has been assessed, with this aforementioned knowledge, it could be said that PEM technology is advised to our case study refinery.

In these studies, carbon pricing mechanism is seen as a main enabler of decarbonization efforts. In this thesis, this point is also demonstrated in different carbon tax prices showing how cost of green hydrogen is decreasing.

Most of studies has focused to decrease emissions rather than price of hydrogen, it is seen that studies forecast green hydrogen prices will decrease in near future with the help of new technology development, more renewable electricity adoption and introducing some legislations on these sectors.

Surplus renewable power is studied more surprisingly. Therefore, it deserves to work on this topic in future studies. Green hydrogen is cheaper when there is surplus renewable electricity. Therefore, green hydrogen is generally more feasible in the places that have abundant renewable power capacity.

Because of renewable energy intermittency, in off-grid operations, electrolysers capacity factors becoming low. This creates increasing investment and cost of hydrogen. Therefore, on-gird operations should be prioritized.

Studies indicate the usage of green hydrogen in direct usage in oil refinery operation for hydrotreating.

4.2. Green Hydrogen Production Projects

International Energy Agency (IEA, 2023) lists hydrogen projects that under development or planned all around the world. Some important valuable projects are mentioned following with its main parameters.

The most interesting and comparable real Project with this study is the BP's Lingen Refinery Green Hydrogen Project. Lingen refinery capacity is about five million tonnes of crude oil per year. BP and Ørsted have partnered in 2022 to build zero-carbon green hydrogen Project that has a capacity of 50 MW. This new plant will produce one ton of hydrogen, approximately 9000 tonnes per year which is 20% of total refinery hydrogen demand starting in 2024. Project capacity could be expended up to 500 MW that this capacity will able to remove all fossil fuel-based hydrogen emissions consequently. And it is planned to increase capacity more than 500 MW upcoming years. Electrolysers will be powered by the wind turbines located in the North Sea provided by Ørsted. In this regard, 80,000 tonnes of GHG emissions a year will be avoided from current steam methane reforming unit (BP, 2020).

The REFHYNE project is the first green hydrogen initiative now operational in a European oil refinery. This project started in 2018 and be operational in 2021. This project cost is 20 million euros, which 10 million euro granted by European Commission. The plant built by ITM Power and be in charged by Shell Rhineland Park in Wesseling, Germany. Project includes 10 MW PEM electrolyser which is approximately producing 1300 tonnes of green hydrogen a year that is fully integrated with the refinery processes, mainly in hydrotreating units to desulphurization of conventional fuels, as well as testing of the PEM technology at the greatest scale ever done and investigating use of in other sectors such as industry, transport, heating, power generation. Shell's goal is to increase green hydrogen capacity to 100 MW to develop more sustainable fuels in their plants, such as sustainable aviation fuels (SAF) using green hydrogen and biomass. Following graph show project development milestones in each year (REFHYNE, 2021).

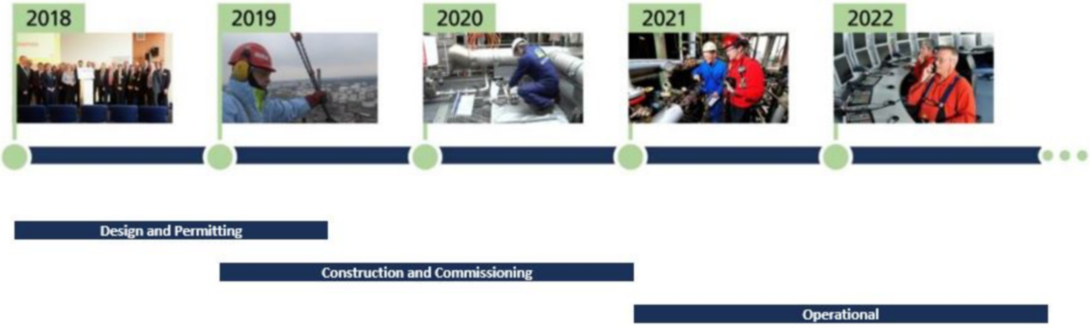


Figure 26. REFHYNE project development milestone basic scheme (Source: REFHYNE, 2021).

Germany's H&R Group has started renewable hydrogen plant to feed its refinery with its own hydrogen that before hydrogen had been purchased from industrial suppliers. 5 MW PEM electrolyser has been projected by H&R Ölwerke Schindler cost about 12 million dollars, and built by Siemens. Spokesperson for H&R said that, this new configuration not only does it save money, but it also simplifies logistics and reduces emissions from refineries. by 2500 ton per year. Additionally, it is added that this is the first phase of the forthcoming 'Green Refinery' initiative (Clark, 2017).

Shell with the cooperation of Everfuel has installed 20 MW electrolyser green hydrogen plant in Fredericia in Western part of Denmark to feed hydrogen to existing oil refinery. The project cost is approximately 20 million euros. Partners are having plan to increase capacity of the plant to 1 GW. Project also includes container to hold up 10 tons of hydrogen named HySynergy to use as a green fuel to for heavy transport (Plechinger, 2019).

Creating the first net zero carbon area in the United Kingdom by the year 2040 is the goal of Zero Carbon Humber, a partnership consisting of the most prominent energy and industrial firms as well as academic institutions. As well as other infrastructures, the primary objective of the Project is to construct low-carbon hydrogen production facilities and carbon capture, utilization, and storage (CCUS) systems in order to decarbonize the part of the nation that produces the greatest emissions. This region is making totally 18-billion-pound economy with the help of refining, petrochemicals, manufacturing and power generation facilities and this makes 37% of CO_2 emissions out of total UK's biggest six industry clusters. With this Project it is expected 10 million ton of CO_2 emissions avoided by 2030. Below general picture show how Zero Carbon Humber project will look like (Zero Carbon Humber Partnership, 2019).

Silver Frog project with the Hydrogenics, Meyer Burger, Ecosolifer, European Energy partnership as modular production site in Italy announced in 2019 with the starting date of 2030. Project includes 100% green hydrogen production facility to be built and transported to chemical and refinery use. For this purpose, 10 GW water electrolyser will be built with the 10 GW solar and 5 GW wind power plants. After project become available, 800 kt per year hydrogen production is expected along with reduction of 8 Mt CO_2 emissions (FuelCellsWorks, 2019).

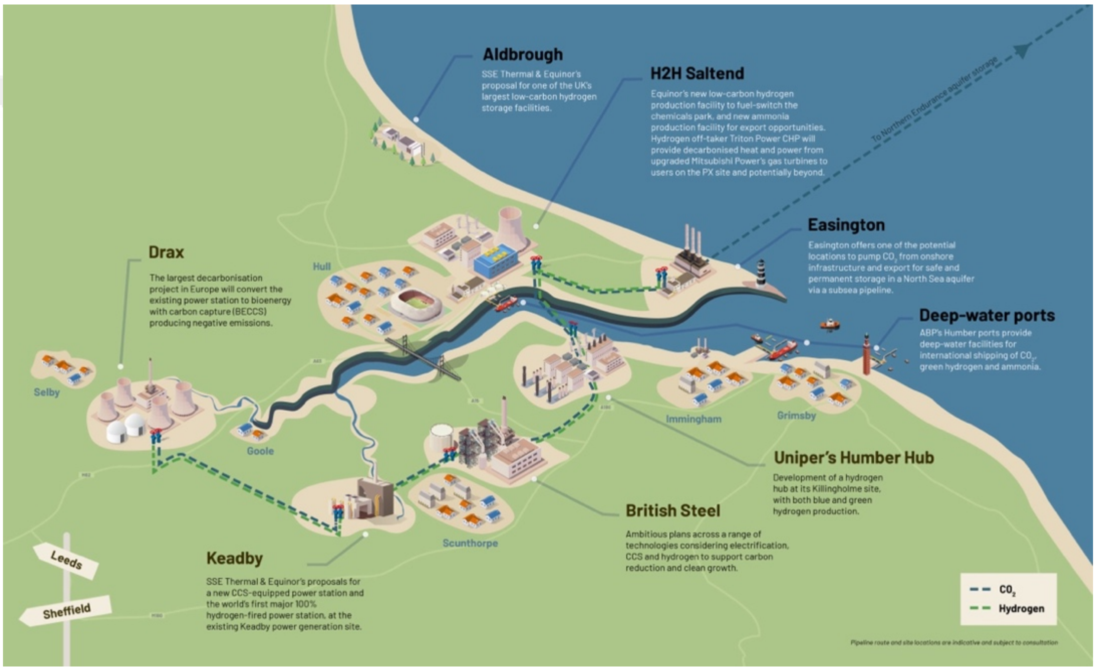


Figure 27. Zero Carbon Humber project basic layout (Source: Zero Carbon Humber Partnership, 2019).

In the Netherlands, the NortH2 green hydrogen project has been initiated by a collaboration consisting of Gasunie, Groningen Seaports, and Shell Nederland companies. This is a project that aims to create green hydrogen in the Netherlands and establish a linked network in order to transport green hydrogen to all countries and regions in Northwest Europe, where hard-to-abate sectors are placed including oil refineries. As part of the project, three to four gigawatts of wind energy will be generated by the year 2030, and ten gigawatts will be generated by the year 2040 in order to generate 800 kt/year of green hydrogen. The North Sea is seeing the construction of these wind energy turbines. Therefore, there will be a reduction of 7 million tons of carbon emissions per year. The project has to be operational by the year 2027 (Gasinue, 2020).

Acorn Hydrogen Project is the UK’s first clean hydrogen Project to be built in Sn Fergus with the joint venture of companies Storegga, Shell UK, Harbour Energy and North Sea Midstream Partners. According to the Project, in the first step 2% of hydrogen will blend to the natural gas grid by 2025, and eventually this number will be 100%, in the result 400 kt CO_2 emissions will be reduced (Acorn, 2024).


NortH2

KICKSTARTING THE GREEN HYDROGEN ECONOMY

A cross-border consortium working together on the large-scale production, storage and transport of green hydrogen, which is supplied to hard-to-abate industry sectors in major demand centers in Northwest Europe.

- 1 GW offshore wind in 2027, 4 GW by 2030 and 10+ GW by 2040
- GW-scale electrolysers to convert green power to green hydrogen
- Annual green hydrogen production of 1.0 mln tonnes by 2040, cutting CO_2 emissions by 8 to 10 megatons a year

Approximately **20% lower societal costs by 2030** compared to a smaller scaled and segmented approach

700 to 1,200 permanent jobs in the province of Groningen and additional jobs during the construction phase

Figure 28. NortH2 project basic layout (Source: Gasinue, 2020).

GreenHydroChem Central Germany Project consortium based on Siemens AG, Linde AG and the Fraunhofer Institute for Microstructure of Materials and Systems IMWS. Project aim is to build 100 MW PEM electrolyser operation by the fed with wind and sun energy available by 2024, resulting decrease of 91% of CO_2 emissions from general processes. This project will be large industrial green hydrogen usage demonstration with the industrial and academia partnership, as well as, being first in the Middle German Chemical Triangle Region, creating potential for the use of oil refineries (Fraunhofer IMWS, 2019).

These projects show the importance of future of green hydrogen. Place of green hydrogen in the decarbonization efforts is in the top. Countries, organizations, industries change their operation to carbon-zero in dedicated places that could be used hydrogen. Therefore, this thesis results are important to work on and making comparison between projects. These projects are also valuable to learn the challenges and opportunities during project, design, operation phases, thus increasing efficiency making this kind of projects.

From aforementioned projects, it is noticed that most of the projects in green hydrogen are based on European Union rather than other part of the World. It creates an opportunity for Türkiye to make collaboration with those projects, as well as, creating hydrogen market with the neighbourhood countries and in result, making chances to profit in hydrogen market.

4.3. Green Hydrogen Production Availability in Oil Refineries

Dolci (2018) reviewed the green hydrogen opportunities in the hydrogen-intensive industries, including ammonia production, steelmaking, as well as oil refining with the gaining knowledge from mentioned sector industry experts, associations and governmental organizations. This document reveals technical limitations and potential benefits of direct using green hydrogen in these sectors. In this document, it is noted that there are not too many studies on this subject as mentioned in Da Silva, Rochedo and Szklo (2022) study, while there is more study about carbon capture.

BP, PREEM and total representatives took part in oil refining session and Concawe gave presentation. Green hydrogen is seen as a main decarbonizer tool in the oil refining sector with the easiest application to direct use in oil refineries replacing SMR produced hydrogen and its associated emissions. But, of course, some technical points have to be taken into considerations. Since hydrogen demand and production stable in oil refineries, green hydrogen production has to be constant, too. Otherwise, it couldn’t feed refineries only by itself. To use fluctuated green hydrogen in oil refineries flexible, it has to be coupled with existing hydrogen generation plant. Hydrogen storage is positive option to remove this obstacle, too. But this option adds cost to the project CAPEX. Moreover, safety issues have to be included to assess in this work.

Price of hydrogen generated from electricity (assuming electricity price is 35 EUR/MWh) is approximately two times expensive than produced with fossil fuels. For that reason, industry willing to take incentives from governments to make green hydrogen projects happen. Assumptions for the near- and long-term future in this workshop appear that it is not expected too much penetration in near future, but in long term, it is seen possible to reach sufficient penetration.

In this workshop, legislation aspects of green hydrogen penetration are mentioned, too. Saying that, it should be better to bring different support mechanisms to the places that near to the abundant renewable energy sources. Additionally, refineries may not be in places near renewable energy sources, therefore, Guarantee of Origin (GO) and Power Purchase Agreements (PPA) should be applied to such sites.

According to study, four main drivers are concluded for deployment of green hydrogen (Dolci, 2018).

1) Insufficient availability of cheap CO_2 storage options
2) Accessibility of renewable electricity
3) Hydrogen technologies cost reduction
4) Limited biomass introduction

Griffiths et al. (2021) assessed low-carbon or zero-carbon hydrogen production options for industrial applications with affecting factors like technical, economic, social or political. Study found some barriers and its impacts on deployment in large scale for industrial applications. One barrier is green hydrogen in policy documents are not well-defined, so it creates uncertainty on investments, especially when electricity is sourced from existing grid instead of renewable sources. Another point is electricity tariffs for the hydrogen production while it is remaining same like other users, it continues to be expensive than other conventional hydrogen production methods. Emerging technologies like high temperature electrolysis is not reached desired level of TRL (technical readiness level). In this condition, without defeating this barriers, green hydrogen adoption in large-scale applications will not easy.

Study also assessed carbon pricing mechanism effect on green hydrogen production methods and recognize it as a key enabler to decrease emissions, as well as, investors decisions.

Nurdiawati and Urban (2022) studied policy recommendations for decarbonization efforts of oil refineries. In the technological readiness level, CCS most matured technology than advanced biofuels and green hydrogen. While cost of green hydrogen cost is double than conventional hydrogen, its cost-competitiveness improvement is most important issue. In study, it is discussed, given some advices for decreasing of cost through improvement of manufacturing of electrolysers, economic incentives, as well as improving efficiencies of systems. At the same time, tax reduction for electricity used in electrolysers is a good option to decrease cost. In order to increase investments on green hydrogen production, government support, such as loans, incentives are important. Legislation could adopt Guarantees of Origin (GO) to help industries use renewable energy for their hydrogen production. In general, policy improvements, standardization and network building are critical to change fossil-fuel based hydrogen to low-carbon hydrogen.

Karayel, Javanı and Dinçer (2022) demonstrated Türkiye's solar energy potential to produce green hydrogen with three different electrolysers types; Alkali, PEM and Solid Oxide Electrolysers. Study revealed total 415, 406 and 427 million tons of hydrogen potential from alkali, PEM and SOE electrolysers respectively in all Türkiye. This amount is produced by electrolysers powered by SPV that is excess energy after meeting all electricity demand of that area. Study results demonstrated that Erzurum, Konya, Sivas and Van are featured as the biggest potential areas of Türkiye.

From aforementioned studies, it is seen that in near-future it is not real to adopt large scale green hydrogen production. To make this happen, there are few obstacles have to removed, some encouragement incentives have to be introduced and some disincentivize actions have to be taken. But, in medium and long-term, future green hydrogen has huge potential with the help of adoption of legislations such as Power Purchase Agreements (PPA) and Guarantee of Origin (GO) to green hydrogen systems.

According to Dolci (2018) findings, it should be noted that in this study, hydrogen from electrolysers have to work in line with existing SMR plant as aforementioned in methodology section.

4.4. Green Hydrogen Production Cost Studies

There are some studies on green hydrogen production costs, summarized some important ones below.

Panah et al. (2022) worked on green hydrogen prices. Main findings in this study are to focus how to decrease green hydrogen cost. If tax is removed from electricity price that used for hydrogen production, green hydrogen production price could decrease below 3 EUR/kgH_2. Hydrogen price could decrease to 2 EUR/kg if technology developments continue. At the same time, study expects hydrogen connected to grid price could decrease to 1 EUR/kg if electricity price decrease to half. LCOH of Alkali, PEM and Solid Oxide Electrolysers could decrease 33%, 34%, and 50%, respectively after advancing technology. This numbers could increase more to 56%, 59% and 70%, respectively with the help of giving subsidies to electricity. Additionally, carbon regulations, such as carbon tax and emission trading system are essential to compete with grey hydrogen.

Tang, Rehme and Cerin (2022) demonstrated the importance of on-grid application in green hydrogen systems. Off-grid operation hydrogen cost is two times higher than on-grid operation. Wind speed is important parameter, while solar radiation has less effect on cost of green hydrogen. Wind and sun energy mix is the best in off-grid scenario. In this study the most promising hydrogen cost is 3.5-7.2 EUR/kg, which is competitive other European countries, and this value does not include any governmental support.

Manna et al. (2021) revealed highest LCOH was 8.64 USD/kgH_2 when capacity utilization is 30% and electrolyser cost is 1000 USD/kW. The minimum LCOH value is found 2.2 USD/kgH_2 when capacity utilization of 90% and electrolyser cost 700 USD/kW. Following figure from study shows correlation between capacity factor and LCOH values for Jamnagar (SEZ) refinery.

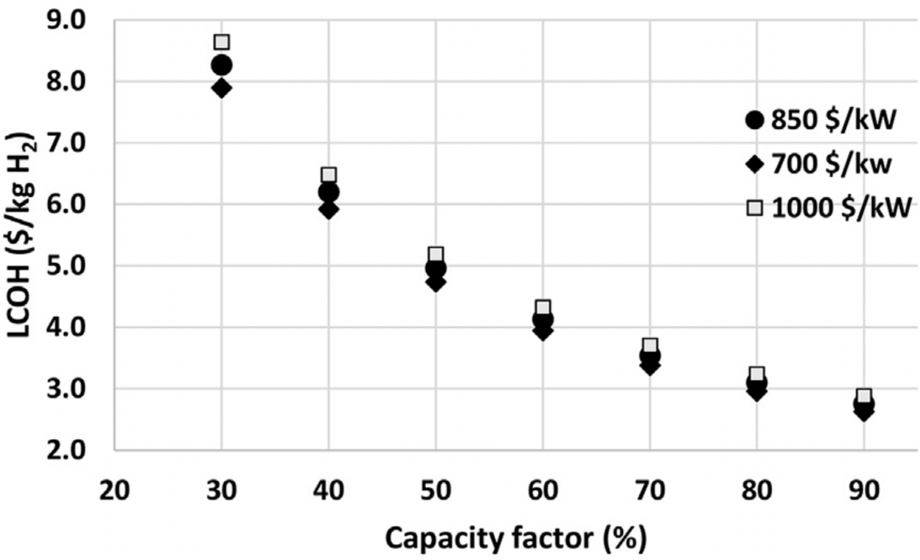


Figure 29. LCOH value for Jamnagar refinery depending on the capacity factor and electrolyser cost (Source: Manna et al., 2021).

El-Emam and Özcan (2019) worked on analysis of clean hydrogen production by different aspects in mainly cost basis. This study reveals hydrogen production cost is affected by solar and wind intermittency, too.

Macedo and Peyerl (2022) studied on green hydrogen production based on two largest wind and solar farm. Available electricity influences the cost of hydrogen. Hydrogen production is feasible when plants run at least 3000 hours and electrolysers CAPEX is 650USD/kW. Study also shows that produced hydrogen is feasible when it is directly used, not converting back to energy.

Siyal, Mentis and Howells (2015) studied that in off-grid wind power operation, with the increase of wind speed from 4.5 to 5 m/s, LCOH declines by 17-19%.

Studies demonstrate some findings in cost reductions for green hydrogen. Among them, tax reduction from electricity price, being connected to the grid, carbon pricing regulations and giving incentives are the main contributor to decrease green hydrogen price to lower level that could compete conventional fossil-fuel based hydrogen. Technology development is also important parameter except those mentioned parameters. Power factor of renewable electricity sources and electrolysers affects cost of hydrogen, too. In this thesis result, the best LCOH value obtained was 5.63 USD/kg for AE and 5.66 USD/kg for PEME that these values are near to the results of aforementioned results.

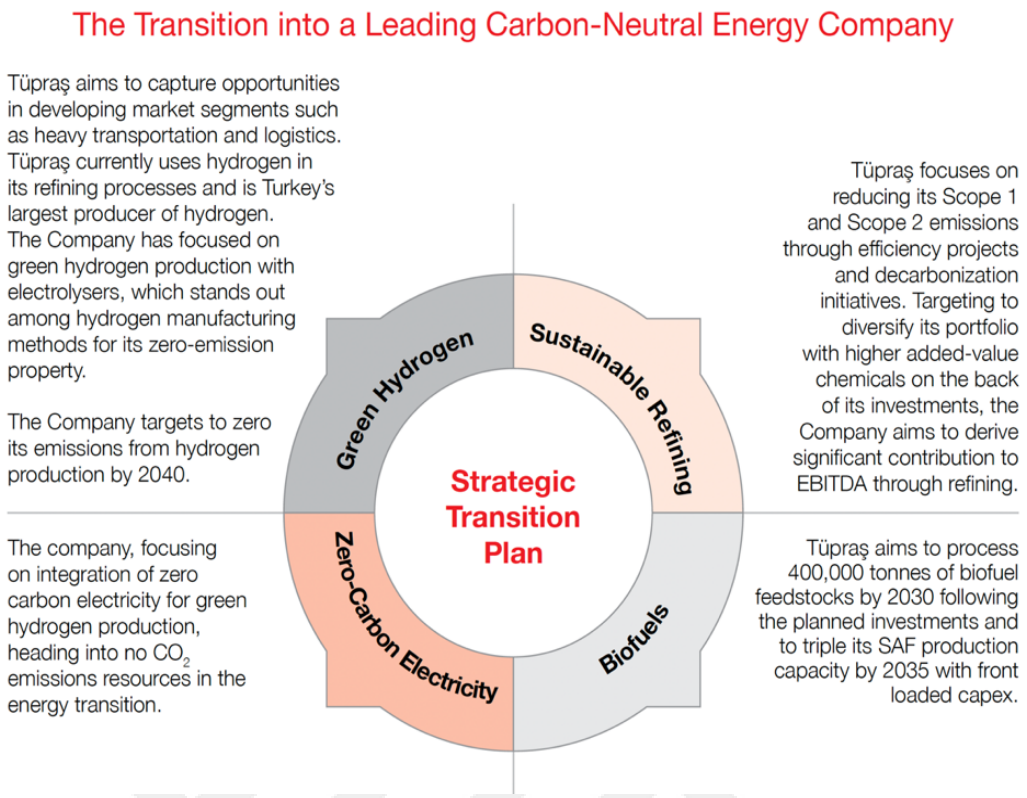
4.5. Türkiye's Refineries Sustainability Goals

There are 5 operating oil refineries in Türkiye, four is being operated by TÜPRAŞ company, and one is being operated by SOCAR company. As of January 2020, total five refinery capacity is about 860 kb/d. Average capacity utilization is 90%. Following lists of refineries are shown in table 15 (IEA, 2021).

Tüpraş is the 36th largest oil refinery company in the Worlds, and 7th largest in Europe, and first place in Türkiye with the total 30 million tons of oil processing capacity that represents 75% of total Türkiye refining capacity, this makes Tüpraş biggest hydrogen producer in Türkiye, too. While checking the latest 2023 Tüpraş Sustainability Report, decarbonization targets and selected tools are defined to go net-zero future as Tüpraş declared its goal to net-zero by 2050. The four main directions of decarbonization targets of company are the sustainability refining, biofuels, net-zero carbon electric production and lastly green hydrogen. Tüpraş plans to reach 400 MW electrolyser capacity by 2030, and then continuing to increase to 1 GW by the year of 2035, and lastly by 2040, emissions resulted from production of hydrogen will make zero. In 2023, Tüpraş scope 1 and scope 2 emissions was reduced by 15% in comparison to 2017 while in 2023 total emissions from Tüpraş refineries was approximately 6.2 MTA (Tüpraş, 2023).

Table 16. Türkiye oil refineries list and data (IEA, 2021).

Refineries	Capacity (barrels/day)	Location	Company	Year of Construction
Izmir refinery	257000	Izmir	Tüpraş	1972
Izmit refinery	244000	Körfez/kocaeli	Tüpraş	1961
STAR refinery	214000	Aliağa/Izmir	SOCAR	2018
Kırıkkale refinery	115000	Kirikkale	Tüpraş	1986
Batman refinery	30000	Batman	Tüpraş	1955


The Transition into a Leading Carbon-Neutral Energy Company

Tüpraş aims to capture opportunities in developing market segments such as heavy transportation and logistics. Tüpraş currently uses hydrogen in its refining processes and is Turkey's largest producer of hydrogen. The Company has focused on green hydrogen production with electrolysers, which stands out among hydrogen manufacturing methods for its zero-emission property.

The Company targets to zero its emissions from hydrogen production by 2040.

Tüpraş focuses on reducing its Scope 1 and Scope 2 emissions through efficiency projects and decarbonization initiatives. Targeting to diversify its portfolio with higher added-value chemicals on the back of its investments, the Company aims to derive significant contribution to EBITDA through refining.

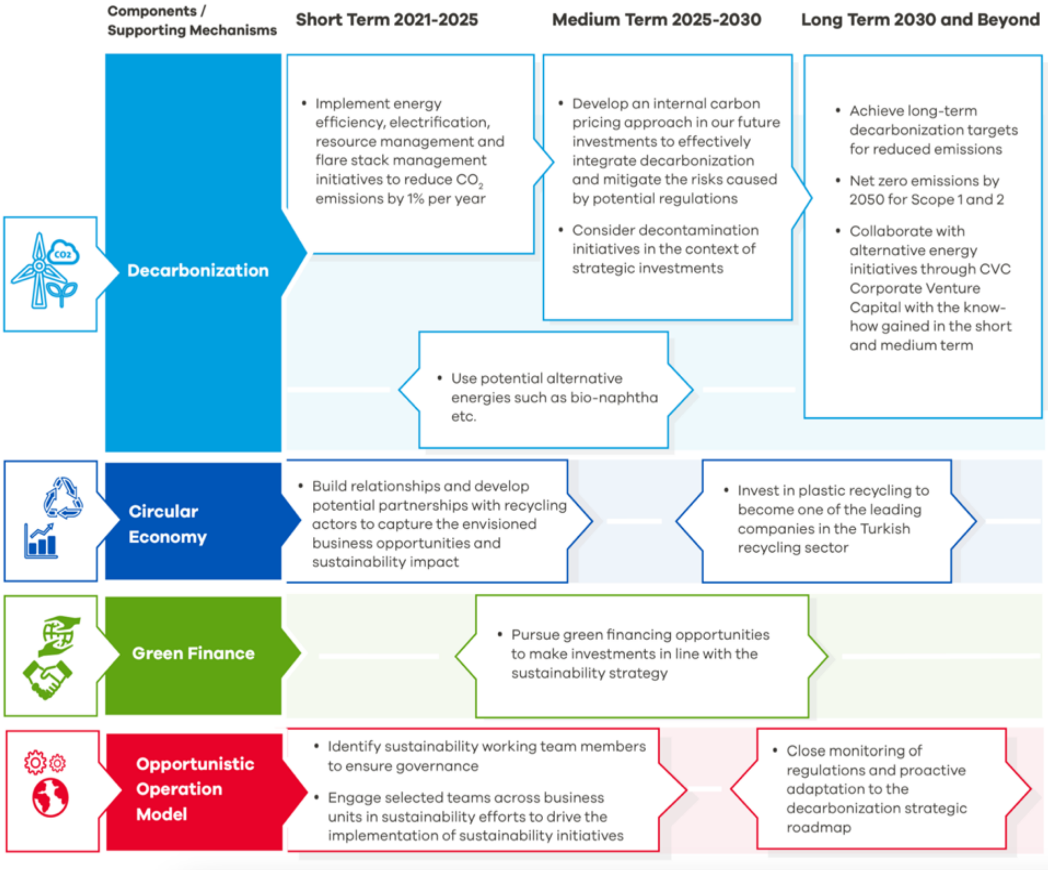
The company, focusing on integration of zero carbon electricity for green hydrogen production, heading into no CO_2 emissions resources in the energy transition.

Tüpraş aims to process 400,000 tonnes of biofuel feedstocks by 2030 following the planned investments and to triple its SAF production capacity by 2035 with front loaded capex.

Figure 30. Tüpraş Decarbonization strategies (Source: Tüpraş, 2023).

In the latest 2022 Sustainability report, SOCAR Türkiye has declared its net-zero emission goal by the year 2050, and 40% emissions decrease from its operations by 2035. Company also targeting to improve energy efficiency to decrease emission by 1% each year by 2025. STAR Refinery had 12,1 million tons of crude oil processed (113% capacity) in 2022 that is 25% of all Türkiye's crude processing capacity. STAR Refinery had approximately 2.4 MTA of scope 1 emissions, while scope 2 emissions amount was 0.4 MTA in 2022. Company has different projects mentioned in sustainability report to help to decrease GHG emissions, such as; CARMOF, CO2Focus, LOUISE, NEFERTITI projects (SOCAR Türkiye, 2023).

SOCAR has declared its sustainability goals in four main focus points; operational improving, projects to be invested, strategic new areas and carbon off-setting. In this manner, SOCAR made 3 term goal setting in titles of future decarbonization, circular economy, green finance and opportunistic operation model. Below graphic shows details of short term, medium term and long-term planning (SOCAR Türkiye, 2023).



Components / Supporting Mechanisms	Short Term 2021-2025	Medium Term 2025-2030	Long Term 2030 and Beyond
Decarbonization	- Implement energy efficiency, electrification, resource management and flare stack management initiatives to reduce CO_2 emissions by 1% per year - Use potential alternative energies such as bio-naphtha etc.	- Develop an internal carbon pricing approach in our future investments to effectively integrate decarbonization and mitigate the risks caused by potential regulations - Consider decontamination initiatives in the context of strategic investments	- Achieve long-term decarbonization targets for reduced emissions - Net zero emissions by 2050 for Scope 1 and 2 - Collaborate with alternative energy initiatives through CVC Corporate Venture Capital with the know-how gained in the short and medium term
Circular Economy	- Build relationships and develop potential partnerships with recycling actors to capture the envisioned business opportunities and sustainability impact		- Invest in plastic recycling to become one of the leading companies in the Turkish recycling sector
Green Finance		- Pursue green financing opportunities to make investments in line with the sustainability strategy	
Opportunistic Operation Model	- Identify sustainability working team members to ensure governance - Engage selected teams across business units in sustainability efforts to drive the implementation of sustainability initiatives		- Close monitoring of regulations and proactive adaptation to the decarbonization strategic roadmap

Figure 31. SOCAR Türkiye decarbonization strategies (Source: SOCAR Türkiye, 2023).

4.6. EU Green Deal and Türkiye's Hydrogen Strategy

Türkiye's Nationally Determined Contribution (NDC) confirms 41% reduction of GHG emissions in Türkiye by the year of 2030 in comparison to 2012 year which is accepted as a base year. It is equivalent to 695 Mt CO_2 GHG emissions in 2030. And in 2053, Türkiye plans to decrease GHG emissions to net-zero. To make these goals happen, Türkiye has some mitigation policies and more improving. One is monitoring, reporting and verification (MRV) system which creates opportunities to make carbon tax or trading system. This system includes more than 700 facilities from key sectors including oil refineries corresponding approximately 50% of total GHG emissions is monitored starting from 2015. It will serve as a key instrument for reducing costs and improving efficiency in the manufacturing and energy sectors. In mid-term goal is to create emission trading system, and it is foreseen to start late 2024. NDC included to prepare hydrogen strategy roadmap and implementation plan of Türkiye (RTMEUCC, 2023).

Türkiye's Hydrogen strategic plan has mainly two important vision goals; one is to lower the green hydrogen cost to 2.4 USD/kg by the year 2035, and 1.2 USD/kg by the year 2053. Second is to increase capacity of electrolysers to 2 GW by 2030, 5 GW by 2035 and 70 GW by 2053. Plan also includes to examine and make required changes in the hydrogen legislations, as well as developing national electrolyser technology by the supporting Research and Development activities, at the same time, creating cooperation with international stakeholders for this purpose, promoting partnerships between the public and private sectors to stimulate commercial demand and investment of green hydrogen in all sectors. The report also emphasizes the industrial utilization of green hydrogen including oil refineries, proposing the establishment of production centres to increase usage and reducing prices to facilitate surplus sales to Europe (RTMENR, 2023).

Document prepared by Ministry of Energy to declare Türkiye's Energy Plan covering by 2035 year. To make this happen, too many different strategies has been assessed that each has its own difficulties and opportunities. Among them, the most important goal in Türkiye National Energy Plan for this study is about electrolysers that plan includes 5.0 GW electrolysers capacity by the year 2035. In this Plan, hydrogen production is planned to use in direct usage and to meet industry needs (RTMENR, 2022).

European Union has set the goal to be first continent in carbon-zero emissions by 2050. For the first step of this program, is called 'Fit For 55 Package' that aims to reach 55% reduction in GHG emissions compared to 1990 levels. To reach this goal, EU has set too many binding applications for European countries and its member states from different sectors, for example industry, energy, transport and so on. Important point to this study about hydrogen applications. The program includes EU hydrogen market and building infrastructure, as well as hydrogen network operator system creation and facilitating hydrogen with non-EU countries. In this context, EU plans 40 GW of renewable hydrogen electrolyser capacity and 10 million tonnes of renewable hydrogen production (EU, 2019).

Program outlines reform of the EU Emission Trading System, while existing EU ETS system have reached 41% emission reduction since it is started from 2005. New approach is aiming 62% decrease in emissions, 4.3% reduction annually corresponding 2024-2027 years, and 4.4% corresponding 2028-2030 years, while current value is 2.2%. Also new ETS adds new sectors such as maritime transport, and independent ETS for buildings, road transport and fuels for additional sectors. In this context, EU is focusing also outside of EU countries, as not creating carbon leakage which could create unfair competition. Therefore, EU created Carbon Border Adjustment Mechanism (CBAM) for trading with non-EU countries. CBAM system require CBAM certificates from companies that import goods from non-EU countries to cover price difference coming from ETS allowances. In first step, CBAM will cover the sectors that high risk for carbon leakages including hydrogen production. Other sectors are iron and steel, cement, fertilisers, aluminium and electricity (EU, 2019).

While newly created emission trading system in Türkiye includes oil refining sector, it means emissions related production of hydrogen will be paid. Therefore, green hydrogen is very good option for the oil refineries to keep away from cost of emissions.

As it is seen in EU Green Deal Program hydrogen is important milestone for making Europe net-zero emission continent. For this program trade with non-EU countries is included.

Though hydrogen included CBAM, in the near future, it is not seen possible to export hydrogen to EU countries. Therefore, in this phase, hydrogen production could not be affected negatively.

CHAPTER 5: CONCLUSIONS AND FUTURE SUGGESTIONS

Petroleum refineries and ammonia synthesis units stand out globally as the primary generators and consumers of hydrogen across diverse industrial applications—a pattern that include Türkiye as well. The adoption of green hydrogen, produced through the electrolysis of water using renewable energy sources (RES) is rapidly emerging as a viable approach to decarbonize these industries. As Türkiye's petroleum refinery companies has set decarbonization targets for the 2035-2040-2050 years, it stands out as an opportunity to contribute to these targets. Results of this paper demonstrated that, the maximum emissions are reduced by *82,979.7 ton (3.3% of total refinery emissions)* with the AE system, while *86,839.2 ton are reduced (3.5% of total refinery emissions)* with PEME system in selected oil refinery.

In the near future, hydrogen generated from renewable energy sources may gain competitiveness, not only because of the gradual decline in the costs of renewable technologies but also due to the implementation of carbon dioxide taxes in specific regions, such as EU ETS and CBAM. As Türkiye is planning adoption of Emissions Trading System (ETS) by the end of 2024, green hydrogen will even become more acceptable starting from the petroleum refinery industries. In this thesis, carbon tax effect is calculated and result show that if 50 USD/ton carbon tax is applied, cost of green hydrogen declineby 1.45 USD/kg.

It is agreed from major group of authors that first market for green hydrogen will be for industrial applications, following power generations, and then, mobility sector (Maggio, Nicita and Squadrito, 2019). Currently the existing electrolyser technologies are capable to reach 30 bar pressures. In comparison, the selected refinery has 27 bar hydrogen ring headers, indicating the applicability of AE and PEM technologies for use.

It is discussed in all literatures in discussion section that nowadays main obstacle to speed up green hydrogen projects is being costly than conventional grey hydrogen. Therefore, two important parameters, one is electrolysers cost and other is renewable prices should have to decline to make green hydrogen applicable in large scale in all areas, as well as in oil refineries.

Another important point is that making green hydrogen ‘green’. For this reason, it is important to use renewable energy that’s additional to what is used. Otherwise, it could be seen energy directed from direct use to the converting energy to the hydrogen. Therefore, the best case for producing green hydrogen is to use surplus renewable energy and incrasing deployment of renewable energy power in the places that has abundant sources.

The SMR hydrogen production cost is between 1-3 USD/kg (IRENA, 2020), the results of this thesis were calculated to be above this value. Best LCOH value was achieved 5.63 USD/kg for AE, and 5.66 USD/kg for PEME. This could be explained due to the different factors as revealed in IRENA (2020), including electrolyser technology maturity and developing factors, stack costs and other technical issues. However, the obvious main contributor to the high rate of LCOH is the electricity price. In this study, real average renewable electricity price was 95 USD/MWh. Overall, the best electricity price for the proposed scenario is the maximum 40 USD/MWh. Going to 20 USD/MWh is bringing LCOH value lesser being compatible than fossil-fuel based hydrogen, even at about 2 USD/kg.

Assumptions for the near future of constant and large-scale utilization of green hydrogen in oil refineries is not expected. At first, small scale adoption of green hydrogen to the refineries will be available. Subsequently by the 2050, it has a potential to reach maximum utilization in accordance with expected technological and economic developments, increasing renewable energy penetration, boosting system efficiencies in all system parts.

To make green hydrogen production fluctuations more stable, electrolysis hydrogen plant could be coupled existing hydrogen production plant. This is the main short-term challenge for the proses operation. Hydrogen storage option could be added to the system, but this adds extra cost to the system based on its holding capacity.

Considering main enabler of modern trade is the cost basis, it is difficult to compete with the existing conventional hydrogen, as prices of green hydrogen is at least two times expensive than fossil fuel-based hydrogen. Hence, introducing additional cost, with the different mechanisms, like carbon pricing to existing hydrogen production will add extra cost, thus pushing industry to low carbon economy. Without these mechanisms, industry could not reflect accordingly itself. Therefore, Legislation aspects should have to be considered. Power Purchase Arrangements (PPA) and Guarantee of Origin (GO) systems help more adoption of renewable energy usage on hydrogen production.

Yáñez et al. (2022) reveals that PEM electrolysers is more functional for using in oil refineries than Alkali Electrolysers because of limited current densities (0.2-0.4 A/cm2) and low system response of alkali electrolysers. In contrast, PEM electrolysers response quickly in milliseconds and current densities is relatively high ranging 0.6-2.0 A/cm2 making PEM electrolysers more promising for larger industry productions, like oil refineries.

Since Solid Oxide Electrolyser (SOE) operates at higher temperatures, it can be good alternative for the refineries because of refineries has excess heat streams available. knowing that SOE is not mature technology, it is in development phase and cost is oblivious high, it will be good suggestion to study SOE technology adaptation to oil refineries.

In different literatures (Tang, Rehme and Cerin, 2022), (El-Emam and Özcan, 2019), it is mentioned that off-grid green hydrogen production is more expensive than on-gird applications. In this study, off-grid application is studied and calculated, for future considerations on-grid application could be studied and could be make discussion on difference between two applications.

As it is seen that both Türkiye refinery company; Tüpraş and SOCAR goal is to be net-zero emission company by the mid of the century. Tüpraş set clear target green hydrogen for their important milestone for transition to carbon-zero operation, while STAR Refinery has not declared green hydrogen for its decarbonization efforts. From this study, it could be appeared that green hydrogen is the good option for Türkiye's oil refineries to reach their decarbonization targets.

In sum, this thesis conducted through some calculations based on real oil refinery data, literature reviews from international and national studies, governmental and other technical reports, ongoing projects data and other similar studies. Thesis has reached its goal with results of calculations and successfully made recommendations for future studies. This thesis is valuable to use in future studies as it is backed real oil refinery data in Türkiye.

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