KADIR HAS UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF ENERGY AND SUSTAINABLE DEVELOPMENT

THE ROLE OF HYDROGEN IN THE ENERGY MIX: A SCENARIO ANALYSIS FOR TURKEY USING OSEMOSYS

HEPNUR TETİK

MASTER OF SCIENCE THESIS

ISTANBUL, SEPTEMBER, 2022

Hepnur Tetik Master of Science Thesis or Graduation Project 2022

THE ROLE OF HYDROGEN IN THE ENERGY MIX: A SCENARIO ANALYSIS FOR TURKEY USING OSEMOSYS

HEPNUR TETİK

A thesis submitted to
the School of Graduate Studies of Kadir Has University
in partial fulfillment of the requirements for the degree of
Master of Science in
Energy and Sustainable Development

Istanbul, September, 2022

APPROVAL

This thesis titled THE ROLE OF HYDROGEN IN THE ENERGY MIX: A SCENARIO ANALYSIS FOR TURKEY USING OSEMOSYS submitted by HEPNUR TETİK, in partial fulfillment of the requirements for the degree of Master of Arts / Master of Science in Energy and Sustainable Development is approved by

Assoc. Prof. Dr. Gökhan Kirkil (Advisor) …………………..
(Kadir Has University)

Prof. Dr. Volkan Ş. Ediger …………………..
(Kadir Has University)

Asst. Prof. Emre Çelebi …………………..
(Yeditepe University)

I confirm that the signatures above belong to the aforementioned faculty members.

Prof. Dr. Mehmet Timur Aydemir
Director of the School of Graduate Studies
Date of Approval: / /

DECLARATION ON RESEARCH ETHICS AND PUBLISHING METHODS

I, HEPNUR TETİK; hereby declare

- that this Master of Science Thesis that I have submitted is entirely my own work and I have cited and referenced all material and results that are not my own in accordance with the rules;
- that this Master of Science Thesis does not contain any material from any research submitted or accepted to obtain a degree or diploma at another educational institution;
- and that I commit and undertake to follow the "Kadir Has University Academic Codes of Conduct" prepared in accordance with the "Higher Education Council Codes of Conduct".

In addition, I acknowledge that any claim of irregularity that may arise in relation to this work will result in a disciplinary action in accordance with the university legislation.

Hepnur Tetik

____

03/09/2022

To My Grandmother...

ACKNOWLEDGEMENT

I would like to thank my supervisor Assoc. Prof. Dr. Gökhan Kirkil, whose expertise, understanding, generous guidance and support made it possible for me to work on a topic that was of great interest to me. I would also like to thank the OSeMOSYS community for helping to my thesis with their questions and answers and for making me remember how much importance one space character might have.

Special thanks to TÜBİTAK, for supporting me throughout my master's degree and thesis study.

Finally, to all my family, friends and my cat for always supporting me, you are the absolute best and I could not have done this without you.

THE ROLE OF HYDROGEN IN THE ENERGY MIX: A SCENARIO ANALYSIS FOR TURKEY USING OSEMOSYS

ABSTRACT

The urgent need to tackle climate change drives the research on new technologies to help the transition of energy systems. Hydrogen is under significant consideration by many countries as a means to reach zero-carbon goals. Turkey has also started to develop hydrogen projects. In this thesis, hydrogen's role in the energy system of Turkey is assessed through energy modeling in the cost optimization analytical tool OSeMOSYS (Open Source energy Modelling SYStem). The hydrogen is produced via PEM electrolysis by the use of renewable electricity. Specifically, by scenario development, potential effects of hydrogen blending into natural gas network in Turkish energy system have been displayed. As a result, by using hydrogen, a significant amount of reduction in carbon dioxide emissions is observed; however, the accumulated capital investment value has increased. Furthermore, hydrogen has the potential to reduce Turkey's energy import dependency by decreasing natural gas demand. To understand hydrogen's full potential, continued efforts in other production methods and end-uses of hydrogen are necessary.

Keywords: Hydrogen, OSeMOSYS

ENERJİ SİSTEMİNDE HİDROJENİN ROLÜ: OSEMOSYS İLE TÜRKİYE İÇİN SENARYO ANALİZİ

ÖZET

Acil bir ihtiyaç halini alan iklim değişikliğiyle mücadele, enerji sistemlerinin dönüşümüne yardımcı olacak yeni teknolojiler üzerine araştırmalarda önemli bir rol oynamaktadır. Hidrojen, birçok ülke tarafından sıfır karbon hedeflerine ulaşmanın yollarından biri olarak görülmektedir. Türkiye de benzer bir yol izleyerek hidrojen projeleri geliştirmeye başladı. Bu tezde, hidrojenin Türkiye'nin enerji sistemindeki rolü, maliyet optimizasyon aracı OSeMOSYS (Açık Kaynak Enerji Modelleme Sistemi) üzerind enerji modellemesi yoluyla değerlendirilmektedir. Hidrojen, yenilenebilir elektrik kullanılarak PEM elektrolizi yoluyla üretilir. Senaryo geliştirme yoluyla, hidrojenin doğal gaza karıştırılmasının, Türkiye enerji sistemi üzerindeki etkileri ortaya konmuştur. Sonuç olarak, hidrojen kullanılarak karbondioksit emisyonunda önemli oranda azalma gözlemlenmekte; ancak sermaye yatırım değerinde ise artış gözlenmektedir. Ayrıca hidrojen, doğal gaz talebini hafifleterek Türkiye'nin enerji ithalatına bağımlılığını azaltma potansiyeline sahiptir. Hidrojenin tam potansiyelini anlamak için hidrojenin diğer üretim yöntemlerini ve kullanım alanlarını dahil eden çalışmalar yapılması gerekmektedir.

Anahtar Sözcükler: Hidrojen, OSeMOSYS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONMYMS AND ABBREVIATIONS

BAU	Business-as-usual scenario
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
EMRA	Energy Market Regulatory Authority
EPİAŞ	Energy Markets Operations Corporation
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLPK	GNU Linear Programming Kit
GW	Giga Watt
H2	Hydrogen blend scenario
IEA	International Energy Agency
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
MENR	Ministry of Energy and Natural Resources
MoManI	Model Management Infrastructure
OSeMOSYS	Open Source Energy Modelling System
PEM	Polymeric Exchange Membrane
PJ	Petajoule
PV	Photovoltaic
TEO	Turkey Energy Outlook
TEİAŞ	Turkish Electricity Transmission Corporation
TFEC	Total Final Energy Consumption
TPES	Total Primary Energy Supply
UN	United Nations

1. INTRODUCTION

Economic growth and electrification have been leading the growth of global energy demand. To meet this demand, more fossil fuels -coal, oil and natural gas- are consumed day by day (Ozturk and Dincer, 2022). The growing use of fossil fuels which emit greenhouse gases (GHGs), such as carbon dioxide, methane, and nitrous oxide when they are combusted has resulted in disruption of the ecological balance (Abdelkareem and Olabi, 2022). This disruption named climate change refers to long-term shifts in the patterns (i.e., precipitation and temperature) of the global climate system (Acaroğlu and Güllü, 2022). The increasing amount of GHGs in the atmosphere causes global warming and the serious consequences of climate change accordingly. The most dramatic and direct impacts of climate change are extreme weather events, such as storms, droughts and floods, however further effects including reduced crop productivity and forced migration are seen in some regions (UNFCCC, 2018).

Currently, climate change is recognized as a global emergency that needs to be addressed by international cooperation. In 2015, The Paris Agreement which is the first legally binding global climate change agreement is adopted by 193 Parties (192 countries plus the European Union) including Turkey at the UN Climate Change Conference (COP21). The agreement aims to limit the global average temperature rise in this century to 2 degrees Celsius, while pursuing efforts to limit it even further to 1.5 degrees Celsius by reducing GHG emissions (Paris Agreement, 2015). The agreement presents a framework to change the global energy system and shift to a carbon-free economy. Although the aim is common for all parties, since the path to be followed by parties differs it was decided to prepare national documents called Intended Nationally Determined Contributions (INDC). Based on these facts, all nations have started to implement several strategies to mitigate negative impacts of climate change. These strategies are focusing both on energy efficiency and the use of renewable energy sources to decarbonize the economy of the country and achieve significant GHG emissions reduction and sustainable development, at the same time (Drela, 2021).

While all sectors are adapting low carbon solutions, electricity generation is experiencing a more rapid decarbonization than the other sectors, leading to scenarios where the most cost-effective way of reducing carbon intensity is increased electrification (Russo et al., 2022). In 2018, the electricity sector had the highest share of renewable energy use by 26%; however, only 17% of total final energy consumption (TFEC) was electrical end-uses. The thermal/heat energy sector including space and water heating, space cooling, and industrial process heat accounted for 51% of TFEC and 11% of the energy was supplied from renewables. The third end-use which is transport sector had the lowest share of renewable energy by only 3.3% and accounted for 32% of TFEC (REN21, 2021). However, one the major issues related to renewable energy sources is their intermittent nature, meaning they have relatively reduced capacity factor (~20–40%) and low reliability (Hjeij et al., 2022). Therefore, fossil fuel resources should be used wisely by integrating renewable energy sources and energy storage options for reducing fossil fuel dependency (Sorgulu and Dincer, 2022).

It’s clear that, a change in an energy system is slow and complex by its nature and contains many challenges. The latest report of Intergovernmental Panel on Climate Change (IPCC) states that during this century, it is likely that warming will exceed 1.5 degrees Celsius taking into account the global GHG emissions in 2030 associated with the implementation of submitted INDCs. And limiting warming to below 2 degrees Celsius requires accelerated mitigation efforts after 2030 (IPCC, 2022). The urgent need to tackle climate change drives the research on new technologies to help the transition of energy systems. Hydrogen is one of the new technologies, which is under significant consideration by many countries as a mean to reach zero-carbon goals especially for low-carbon transport, industrial decarbonization and heat provision (Velazquez Abad and Dodds, 2020). Combustion of hydrogen does not result in any harmful emissions such as carbon dioxide (CO_2) and carbon monoxide (CO). Carbon neutral hydrogen can be produced by using renewable energy sources or fossil fuels with carbon capture and storage technologies. Replacement of hydrocarbon-based fuels by hydrogen in transportation and manufacturing sectors could result in significant reduction in global carbon emissions. Moreover, hydrogen can play a key role in solving intermittency issue of renewable energy sources by being an energy carrier storing electricity that is converted back to electricity via fuel cell technology. In addition, it is considered as a low-carbon natural gas substitute that can be used in the form of blending into natural gas to further ensure energy security, while cutting emissions (Razi and Dincer, 2022).

Ratifying the Paris Agreement in October 2021, Turkey announced a net zero by 2053 target. Prior to Paris Agreement, Turkey has published the National Climate Change Strategy and the action plan for the period of 2010-2023 in line with the United Nations Framework Convention on Climate Change principle of “common but differentiated responsibilities” to increase the amount of renewables, reduce GHG emissions and increase energy efficiency. In the INDC submitted by Turkey, it was stated that the GHG emissions will be reduced by up to 21% from a business-as-usual level by 2030 (Republic of Turkey, 2015). However, this target indicates still a significant expansion of Turkey’s current emissions level (IEA, 2021). In order to achieve the zero-carbon goal, other strategies are needed. With its limited fossil fuel resources and high potential for renewable energy sources, Turkey is a viable option for hydrogen projects (Dinçer et al., 2021).

Gas decarbonization has a significant importance for developing countries like Turkey where energy policy has been influenced by fuel poverty and energy vulnerability for decades (Sandri et al., 2021). The gradual integration of low carbon gases such as biomethane and hydrogen to replace natural gas is a part of the Hydrogen Strategy of the EU. Accordingly, to rapidly scale up production and use of hydrogen within the next ten years, much attention is being given to the establishment of a market for hydrogen, in particular hydrogen produced by renewable energy sources (Bard et al., 2022). By adopting a similar approach, Turkey can benefit from hydrogen to reduce emissions and energy vulnerability, at the same time.

This thesis aims to identify the hydrogen’s role for Turkey by modeling a part of the Turkish energy system until the year 2040, and to answer following questions by scenario analysis: What are the effects of adding hydrogen to the energy mix of Turkey by blending into natural gas? And, to what extent can hydrogen help decarbonizing

Turkish energy system? The study takes into account green hydrogen that is produced by electrolysis and used for storage of excess electricity and replacement of final natural gas demand. Scenarios are analyzed with a basis of cost optimization by a tool called Open Source Energy Modelling System (OSeMOSYS).

The role of hydrogen in energy system at national level has been researched through energy system modeling. Balta-Ozkan & Baldwin (2013) presents a framework by expanding the UK MARKAL Energy System model with a spatial hydrogen module to explore the potential of hydrogen at the sub-national level. The results indicate that hydrogen related infrastructures and technologies are competitive with notable potential contributions to decarbonization pathway of the UK's energy system. Similarly, Espegren et al. (2021) looks at the role of hydrogen in the energy transition of Norway by energy system modeling with TIMES. The study concludes that the decarbonization of transport and industrial sectors depends on access to renewable power and hydrogen. Putting more focus on the hydrogen's flexibility providing aspect, Motalebi et al. (2021) has used OSeMOSYS Energy System Model to evaluate the potential of different hydrogen technologies to contribute to these emissions reduction of Canada. The study has two important conclusions. The hydrogen contributes to meet emission targets by providing significant flexibility to Canadian electricity system, but this is limited to costs and existing flexibility of the hydrogen system.

Güler et al. (2021) has designed the hydrogen supply chain of Turkey with a focus on transport sector for the next 30 years. Total operating and capital costs are minimized to meet sector demand. The results show that the supply chain starts as a centralized chain with only few number of facilities and becomes decentralized by the end of the planning horizon. SHURA Energy Transition Center has published two reports related to future of hydrogen in Turkey. In the first report, a list of priority areas was suggested for the development of a National Hydrogen Strategy for Turkey. The development of a clear plan that encompasses the costs, understanding hydrogen's business opportunities, and the contribution of hydrogen to Turkey's energy transition strategy as a domestic resource were included in the list. The report shows, hydrogen can have an equally split role in manufacturing industry, buildings (residential, commercial and public) and transport sectors in Turkey (SHURA, 2021a). The second report is a techno-economic study about green hydrogen potential of Turkey. The results indicate that green hydrogen production can help to reduce energy import dependency by substituting 10% of fossil fuel use in 2050 (SHURA, 2021b). In a recent study, Amil&Yılmazoğlu (2022) has discussed the importance of hydrogen for Turkey in the 2030 energy projection. The results obtained by EnergyPLAN code indicate that it is inevitable for Turkey to invest in hydrogen technologies until 2030 to achieve sustainable development goals.

This thesis aims to contribute to the efforts of developing a hydrogen economy in Turkey by modeling the hydrogen integrated energy system of Turkey, thus to create an understanding of the hydrogen’s role during the energy transition towards becoming zero carbon. Although Turkey has announced its net-zero goal by 2053, this study investigates 2020-2040 period, since hydrogen blending into natural gas network is considered to be a midterm solution, meaning further measures should be applied afterwards.

Following this introduction, a general explanation of hydrogen will be given in chapter 2. In chapter 3, an overview of the Turkey’s energy system will be given, analyzing past and current trends in energy supply and demand, thus peculiarities of interest. Chapter 4 will present the thesis methodology, OSeMoSYS will be briefly introduced and some special features of the modeling platform will be explained followed up by a detailed introduction of Turkey’s OSeMOSYS model. Chapter 5 will go through the data collected and assumptions made for the modeling purpose. The results are then displayed in chapter 6. Finally, a discussion around the results and the reality of a hydrogen economy in Turkey is made in chapter 7, together with a presentation of the thesis conclusions.

2. HYDROGEN

Hydrogen is a gas produced by splitting water (electrolysis) or by reacting fossil fuels with steam or oxygen and it functions as a versatile energy carrier and feedstock (Bruce et al., 2018). Currently, hydrogen is mainly used in oil refining and ammonia production for fertilizers and demand for hydrogen in its pure form was given to be around 70 million tons per year. 76% of this demand is supplied from natural gas and 23% from coal, which implies that currently almost all of the hydrogen is produced by fossil fuels (IEA, 2019).

Hydrogen technologies have been exceptionally resilient during the Covid-19 pandemic maintaining its strong momentum in 2020. It is stated as a record year for both policy action and low-carbon hydrogen production. The installed electrolysis capacity has reached to 70 MW, twice compared to previous year. Another important update was carbon capture and storage technologies implementation in two facilities producing hydrogen from fuels. However, this progress falls below of necessary level of actions for Net Zero Emissions by 2050. Moreover, low-carbon hydrogen demand for new applications is limited to road transport. On that account, more efforts are needed in demand creation. (IEA, 2021b)

Hydrogen gas is a carbon-free fuel because it only emits water when it is burned, but in fact carbon neutrality depends on how it is produced. If hydrogen is produced from fossil fuels (i.e. gasification and steam methane reforming) but emissions aren't captured using carbon capture and storage (CCS) technologies, then the hydrogen is classified as grey (produced from natural gas or coal). If CCS technologies are used, then it's called blue hydrogen, which is considered by some parties as a bridge that could facilitate the development of hydrogen market until the green hydrogen becomes more available. On the other hand, opponents of blue hydrogen claim that the methane emissions should be taking into consideration in order to not cause a delay on decarbonization actions (Howarth and Jacobson, 2021). Another alternative is called turquoise hydrogen which is produced with the pyrolysis of methane at high temperature for the co-production of hydrogen and carbon black. Turquoise hydrogen stands out with its two advantages; it is significantly less energy intensive in comparison to electrolysis and steam methane reforming and it benefits from the existing infrastructure of natural gas (Diab et al., 2022). The final alternative, green hydrogen which is produced from water electrolysis utilizing renewable electricity and other methods such as biomass gasification will be explained in the sub-section (IRENA, 2020).

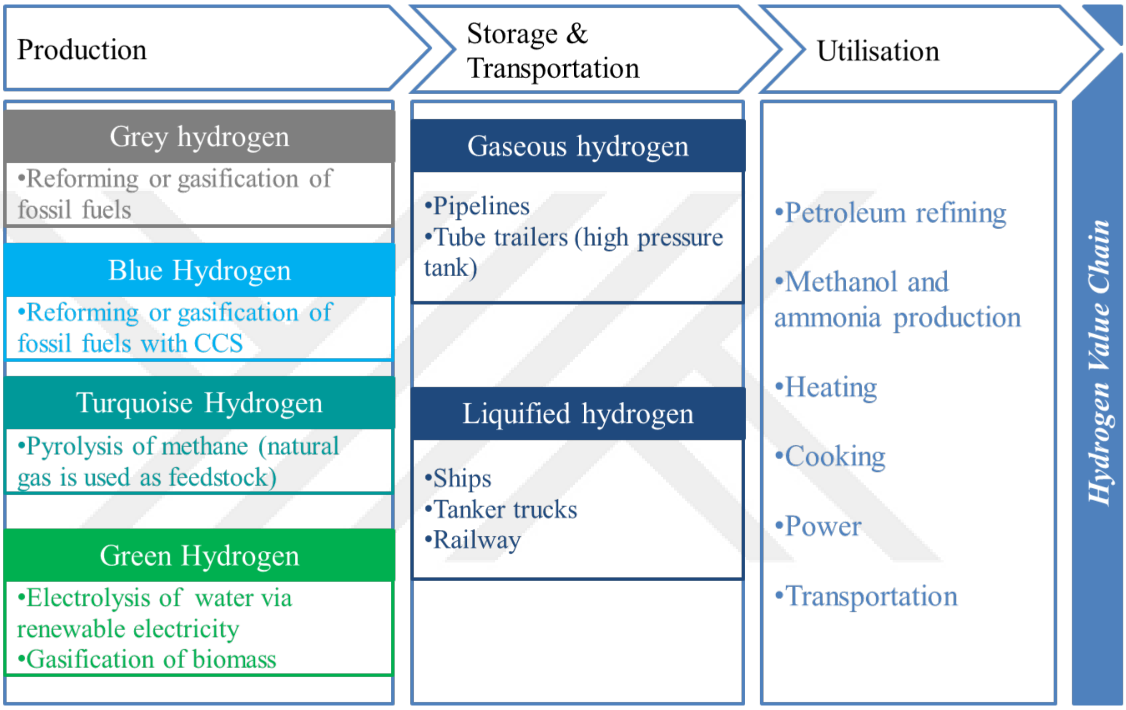

Figure 2.1 Hydrogen value chain (Bruce et al., 2018 ; IRENA, 2020 ; Hjeij et al., 2021)

Figure 2.1 represents the hydrogen value chain; as mentioned above hydrogen can be produced both by fossil fuels and renewable energy and its types are color coded according to the production method. Hydrogen can be stored in different forms such as compressed gas, liquid or chemical forms. Geological storage is acknowledged as the best option for large scale and long term storage of hydrogen. Salt caverns, depleted natural gas or oil reservoirs, and water aquifers could serve as geological storage for storing hydrogen (Elberry et al., 2021). Depending on the form of hydrogen (gas or liquefied) and the transportation distance, it can be transported via pipelines or other vehicles. For example, to transport hydrogen gas to longer distances, pipelines would be ideal; whereas for shorter distance transportation of liquefied hydrogen, tankers or railway can be used (Güler et al., 2021). The hydrogen potential extends to the electricity, transport and heating (e.g. blending hydrogen to natural gas). Additionally, it can be used as a feedstock in industrial sectors as it has been mainly utilized until today.

Power to gas (PtG), a sector-coupling technology, that is defined as a process that uses electricity to produce gas (i.e. hydrogen) can play a crucial role in energy transition by offering flexibility to the system and acting as a GHG neutral energy carrier (Jarosch et al., 2022). Being an excellent energy carrier, relation of hydrogen with electricity is double sided. While electricity can be used to produce hydrogen; excess renewable power can be stored in the form of hydrogen, then to be transformed back to electricity by the fuel cell technology. The power that is generated by fuel cells can be used for stationary and portable power and transportation. Vehicles operating on hydrogen as a fuel are called fuel cell vehicles (FCV) or fuel cell electric vehicles (FCEV) and are currently being produced by several automobile manufacturers. Compared to battery-electric vehicles, FCEVs are evaluated to have lower costs. The cost advantage stems from hydrogen storage becoming cheaper than batteries at a capacity of 55 kWh, equivalent to a range of about 300 km (Hjeij et al., 2021). For heating sector, blending hydrogen into the natural gas network offers a midterm solution for decarbonization while maintaining similar combustion performance with pure natural gas.

Hydrogen offers benefits to end users such as increased stability and security of energy supply, while not causing carbon emissions (Sandri et al., 2021). Hence, hydrogen has been an attractive research subject for decades, and has become more relevant in the past years with the rapid cost reductions in renewables and technical advancements (e.g. electrolyzers). A recently published bibliometric analysis of the research on hydrogen economy indicates that the related literature has been increasing, particularly in the last decade. Pipeline transportation, risk assessment and blending are included in the aspects that will be important in the future of hydrogen studies (Kar, Harichandan & Roy, 2022).

2.1 Green Hydrogen

Green hydrogen is the type of hydrogen that is produced from renewable energy sources. It does not emit GHGs when used and can be used in its pure form or can be transformed into other chemicals such as ammonia. End use of green hydrogen is as follows; industry, transport, heating and power generation. Among other types of hydrogen, it is considered to be the most suitable option for decarbonization pathway. The most known production method is water electrolysis powered by renewable electricity, which is consistent with the net-zero efforts, allowing the use of synergies from sector coupling, hence reducing technology costs and making the power system more flexible. There are other renewables-based production methods, but these are not mature technologies at commercial scale yet, except for biomass gasification (Taibi et al., 2018; IRENA, 2020). According to a comparative analysis, green hydrogen production from biomass provides approximately similar results as electrolysis based hydrogen production. In addition, biomass-based production has the advantage of lower operating costs and higher efficiency (Amin et al., 2022). Despite biomass having these advantages, electrolysis-based production is the selected method for this study. The reason behind this choice is that it offers to ability to include different renewable energy sources.

Currently, green hydrogen production is only limited to demonstration projects, without significant production by comparison to brown and grey hydrogen (Gielen et al., 2019). The reason why green hydrogen has acquired currency now is that it is becoming more available. Continuously decreasing costs of renewable power generation, scaling up electrolysis technologies, carbon neutral government policies, benefits that hydrogen can supply to power systems and presentation of broader end uses for hydrogen are factors that have been affecting the availability of green hydrogen (IRENA, 2020).

Decreasing renewable energy and electrolyzer costs, as well as increasing need for decarbonization of all economic sectors, will be the driving factors of the emergence of a global market for green hydrogen (Ministry of Energy, Government of Chile, 2020). In spite of offering opportunities for economic growth, green hydrogen is still in need of a well-defined and stable policy framework to reduce uncertainty and risks for producers. Future international hydrogen trade will be able to fulfill its economic growth potential if only consistent rules and regulations for green hydrogen standards are agreed across regions or globally (Velazquez Abad and Dodds, 2020). Moreover, it is impossible to determine embedded emissions, meaning emissions released during the production of hydrogen, by examining the end product. Some buyers will be even willing to pay a higher price for green hydrogen; therefore a certification of embedded emissions will play a key role in the future of green hydrogen (White et al, 2021).

2.2 Hydrogen blending into natural gas network

In comparison to other fossil fuels, natural gas emits the less carbon dioxide into the air when combusted, making natural gas the bridge fuel of the energy transition towards decarbonized energy system. As a result, the further expansion of natural gas infrastructure (e.g. long distance pipelines) is observed in many regions of the world. Natural gas dominates the pipeline development mix according to Global Energy Monitor’s report (2021), accounting for 82.7% of global pipelines in pre-construction and construction. This dominance demonstrates current shift from oil to gas in the global energy system. While the share of the oil in global primary energy consumption has been falling since its peak in 1978, share of the gas has been steadily increasing (BP, 2020). However, in order to reach zero-carbon goals, natural gas should also be eliminated from the energy mix in the near future. Natural gas demand is expected to peak in this decade and decline after 2030 by being replaced by hydrogen and biomethane gases in the period of 2020-2050 to eventually become zero-carbon (Stern, 2019).

Blending hydrogen into the natural gas network is expected to have an important role in energy transition by being a midterm solution for decarbonization while maintaining similar combustion performance with pure natural gas. Moreover, it can decrease the supply-demand contradiction between the electricity and natural gas by integrating both systems. In recent years, the gas-electricity integrated energy system has received notable attention; hydrogen can solve the problem of energy storage shortage of the traditional integrated energy system (Zhou et al., 2022). Current studies on hydrogen blending into the natural gas network include the production of hydrogen, transportation of the mixture, end use of the mixture (i.e. combustion of the hydrogen blend) and modes of blending.

For instance, Ozturk and Dincer (2021) have investigated an integrated system which consists of a geothermal-based power and hydrogen generation and blending of produced hydrogen into the natural gas pipeline to use for household applications with Aspen Plus software. The offered system was comprised of geothermal plant, electrolyzer, blending unit and the reactor of combustion. In a more recent study, same authors have analyzed another integrated system where hydrogen is uniquely produced from waste heat obtained from the cement slag and blended with natural gas for domestic use which is a new concept (Ozturk and Dincer, 2022). The cement industry is one of the major emitters of GHGs in industrial sectors. The study aimed to reduce emissions in domestic appliances by blending hydrogen with natural gas.

Various literatures have demonstrated that when the hydrogen blending ratio is kept lower than a certain value, the existing natural gas pipelines can safely transport the mixture , which means they do not need to be readjusted (Tabkhi et al, 2008; Miao et al., 2021; Sorgulu and Dincer, 2022). For example, in Germany, hydrogen related research and development is focused on the natural gas pipeline blending hydrogen technology, for now. If the demand for hydrogen raises in the future, the natural gas pipelines are planned to be converted into hydrogen pipelines, or even some independent domestic hydrogen pipelines might be built (Pingkuo and Xue, 2022). Zhou et al. (2022) have focused on another aspect of hydrogen blending which is the analysis of hydrogen blending modes such as single node hydrogen blending, multi node hydrogen blending, and centralized hydrogen blending. All modes cause different energy losses; in comparison to single and multi note hydrogen blending, centralized hydrogen blending has found to be more advantageous and causing smaller energy loss.

The concept of hydrogen blending into natural gas network has been investigated by many countries through execution of several long-term projects with trials of hydrogen-blending in small communities (Mahajan et al., 2022). Different blend ratios ranging from 1% to 100% are implemented in projects for various sizes of residential areas between 100 and 40.000 residentials. Europe and Australia has demonstrated many projects; while there have been fewer such projects in the United States and Canada, thus far. In Europe, the UK has the majority of projects; HyDeploy project which has started in 2019 being the first and largest project.

3. ENERGY SYSTEM OF TURKEY

Turkey is a country at the crossroads of Asia and Europe, with most of the country located in south-western Asia and a small part in south-eastern Europe with a population over 80 million. Its central geographic position gives the country a strategic importance in international relations including energy sector. Following the economic crisis in 2001, Turkey has developed rapidly both in economic and social aspects. In 2018, Turkey almost doubled its gross domestic product (GDP) per capita in 2011, and became the 19th largest economy in the world (World Bank, 2019). However, the currency and debt crisis in 2018 has resulted in high inflation and decrease in the annual GDP growth rate (IEA, 2021).

Energy consumption is imperative to maintain economic growth. The shift in its economy from agriculture to one based on industry and services, is another reason for increase in energy demand of the country. Turkey relies on fossil fuels for about 83% of its energy supply. Even though Turkey has significant coal deposits, remains dependent to imports for oil and gas. Turkey has deployed several measures including oil and natural gas exploration activities in the Black Sea and the Mediterranean and bilateral agreements between countries to secure its supply by diversification of sources. Moreover, the government aims to increase the use of domestic energy sources, including renewables, nuclear and coal. Renewables have already made a significant progress in recent years, particularly unlicensed production and rooftop solar energy applications, wind and geothermal energy investments have drawn attention. In addition, by incorporating energy efficiency in energy regulations, it is aimed to reduce energy intensity and energy import dependency (Amil and Yılmazoğlu, 2022).

This chapter describes the energy system of the study, in this case, the energy system of Turkey, analyzing past and current trends in energy supply and demand, thus peculiarities of interest. Additionally, it serves as a basis for many assumptions related to this work.

3.1 Total Primary Energy Supply (TPES)

Turkey is a developing country with a fast-growing economy; as a result its energy supply has showed a steady increase. As seen in Figure 3.1, between 2000 and 2020, TPES has almost doubled itself, despite a recent decline in 2018 caused by the economic slowdown. TPES is dominated by fossil fuels and their share has been around 90% in the past two decades. But, in recent years, their share has started to decrease. In 2020, fossil fuels accounted for 82.8% of TPES (IEA, 2021).

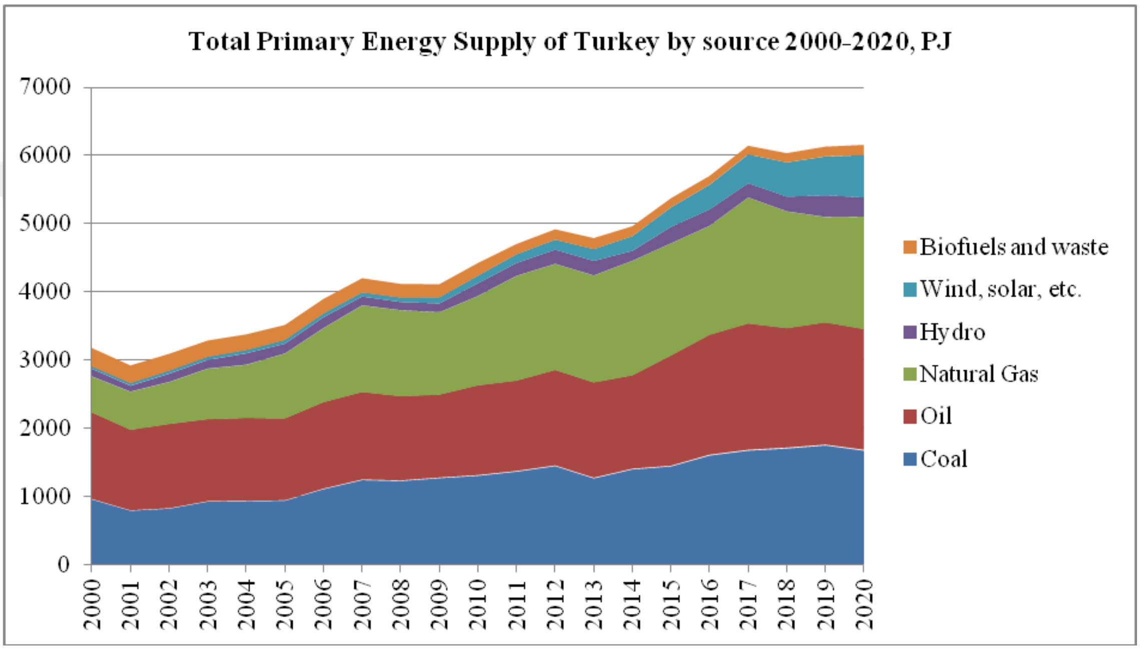

Figure 3.1 TPES of Turkey by source, 2000-2020, PJ (IEA, 2021)

Only 30% of TPES is covered by domestic production in 2020, mostly by the coal and all types of renewable sources (MENR, 2020). Due to its geographical characteristics, there is abundance of renewable sources in Turkey; thus Turkey has adequate potential for solar, wind, hydro and geothermal energy (Ediger and Kentel, 1999; Kırtay, 2010; Apak et al., 2017). Evrendilek and Ertekin (2003) have estimated in their study that Turkey has a total 495.4 TWh/year of potential energy in total, with the 196.7 TWh/year of biomass, 124 TWh/year of hydropower, 102.3 TWh/year of solar, 50 TWh/year of wind, and 22.4 TWh/year of geothermal. Thanks to the technological developments in the renewables and investment opportunities, the share of renewable energy (geothermal, hydro, wind and solar) in TPES has more than doubled in the last decade. Although to this day, there was no operating nuclear power generation in

Turkey, within the scope of the nuclear power programme, the first unit of a nuclear power plant in Mersin province with a capacity of 4.8 GW scheduled to be operational by the end of 2023.

Fossil fuel imports are an important element of foreign trade deficit for Turkey. Almost all natural gas is imported and domestic production has only covered 7% of total oil demand. Despite the larger domestic coal production, 58% of the coal demand is still supplied by imports. Berk and Ediger (2011; 2018) have assessed Turkey's oil and natural gas import vulnerability. Although both fossil fuel types have large shares in the country's energy mix, natural gas import vulnerability is of greater significance because, unlike oil and coal, the share of natural gas in Turkey's energy mix is increasing, and it has become the dominant energy source. Therefore, substitution of natural gas and other fossil fuels is important for Turkey.

3.2 Total Final Energy Consumption (TFEC)

After the economic crisis in 2001, energy demand of Turkey has increased across all sectors, except for 2018 due to the economic slowdown (Figure 3.2). From 2009 to 2019, energy consumption in transport increased by 89%, in industry by 38%, and in services and residential 27% and 14% respectively.

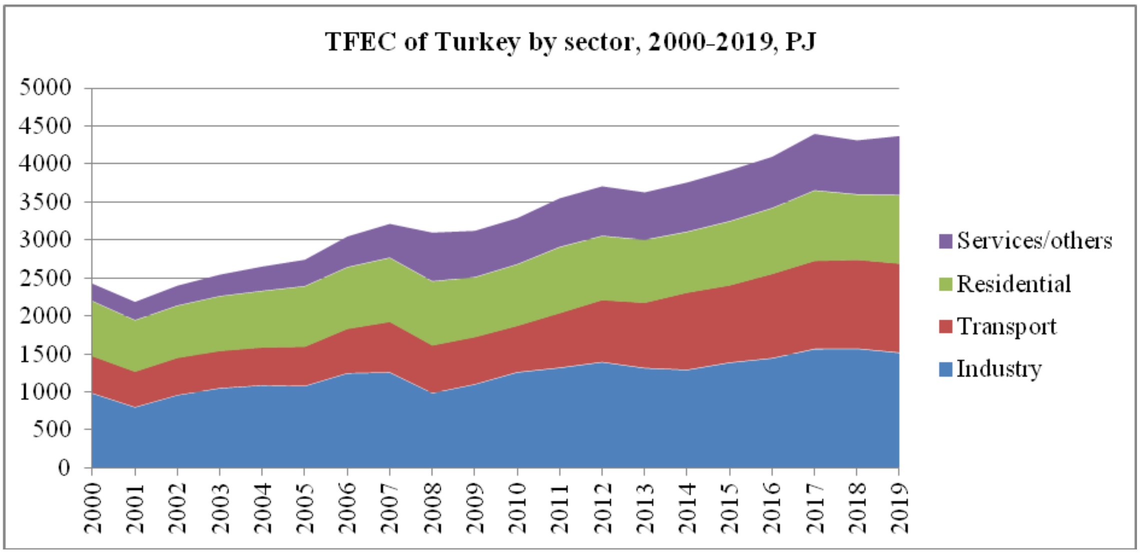

Figure 3.2 TFEC of Turkey by sector, 2000-2019, PJ (IEA, 2021)

In 2019, Turkey's TFEC was 4365 PJ, accounting for 71% of TPES. The largest energy consuming sector is industry with a share of 35%, followed by transport (27%), residential (21%) and services including agriculture and fishing (17%).

Figure 2.3 gives a more detailed look of TFEC in 2018. The transport sector is dominated by oil with 97% of TFEC in 2018. Industry sector uses a mix of all sources, consuming mainly oil, natural gas and electricity. Half of total residential demand is covered by natural gas, followed by electricity with more than a quarter of the TFEC. Electricity covers almost half of the demand in services sector.

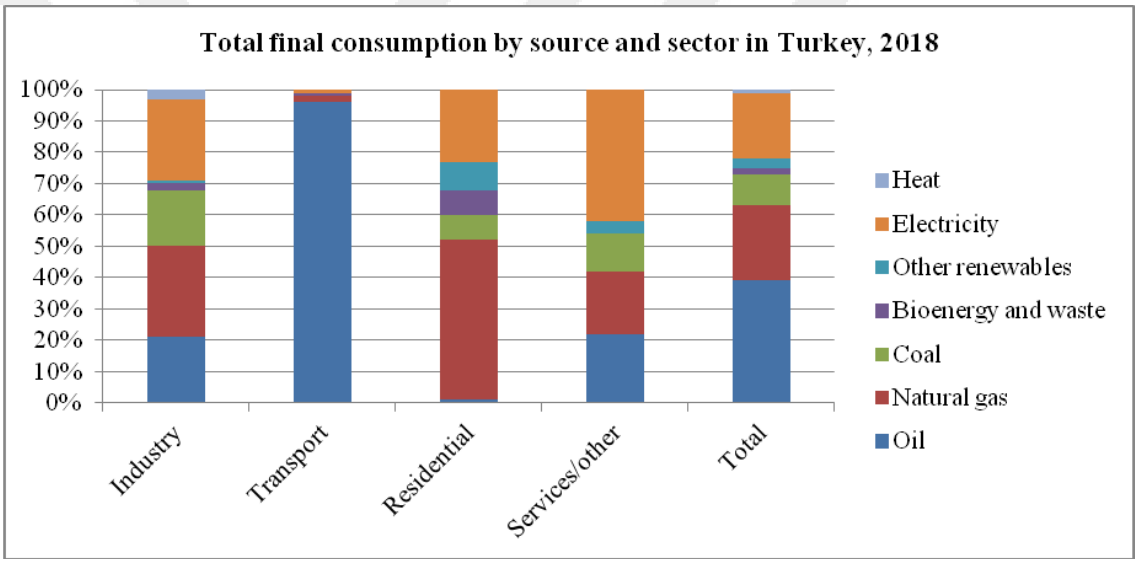

Figure 3.3 TFEC by source and sector in Turkey, 2018, % (IEA, 2021)

3.3 Hydrogen Related Developments in Turkey

Combination of current high energy dependency and high renewable energy potential gives hydrogen a significant role in the future of energy in Turkey. In this context, United Nations Industrial Development Organization (UNIDO) has taken the first initiative in November 2011 by building the Bozcaada Hydrogen Island project that produces hydrogen via electrolysis powered by solar and wind energy (Apak et al., 2017).

For the aim of reducing energy imports as a national strategy, the Turkish government allocates its energy related research, development and demonstration budget mainly to renewables and energy efficiency. In 2018, 5% of this budget was spent on hydrogen and fuel cells (IEA, 2021). Although hydrogen is not yet a direct contributor to energy generation in Turkey, it is used as a raw material in industrial sector. Currently, 1.6% of total energy consumption is supplied by hydrogen that is used as feedstock to produce ammonia (Amil and Yılmazoğlu, 2022). The preparation of a law and a roadmap on hydrogen is of great importance for the developments of this technology in the country.

The preparations for a national hydrogen strategy is kick started with the international conference that organized by the Ministry of Energy and Natural Resources (MENR) on 15 January 2020 to discuss the future of hydrogen in Turkey. The priorities of Turkish government related to hydrogen are as follows, to include more renewable energy in the system, to make the heat sector carbon-free, to produce hydrogen from domestic coal and to increase the use of boron in hydrogen storage (TSKB, 2021).

Hydrogen is seen as a key by MENR to decarbonize the heating sector through the blending of hydrogen into distribution system (Yalçın, 2020). The Renewable Gas Project within the scope of the funds given by the Energy Market Regulatory Authority (EMRA) is conducted by the Turkish Natural Gas Distributors Association (GAZBIR). The project was initialized at the beginning of 2020 with the installation of the Clean Energy Technologies Center in Konya. Hydrogen that is mixed with natural gas at different rates (5-10-15-20%) for the tests was obtained in the laboratory environment via electrolysis of water by using renewable electricity. As a result of the tests, it was stated that there is no obstacle to use of hydrogen (up to 20%)-natural gas mix in the current transmission lines and combustor devices. In addition, the produced hydrogen can be stored directly without the need for pressurized cylinders, liquefaction or metal hydrides, since the length of natural gas transmission lines are enough to store hydrogen (GAZBİR, 2022). Based on the ongoing study on 20% hydrogen blending to the natural gas system, Özçelep et al. (2021) have investigated a photovoltaic hydrogen system using a real house consumption data in Turkey, and found that by increasing the solar panel area with a rate of 14.28%, 20% of the natural gas need of the house can be replaced by green hydrogen. Thanks to the PV-hydrogen system, the carbon footprint of the house was 67.5% less than the system implementation.

In recent years, there have been several studies on production of hydrogen by different methods in Turkey. Concerning the hydrogen energy potential in Turkey, there are continuous efforts on the production of hydrogen from the chemically stored hydrogen in the Black Sea base in the form of hydrogen sulfide (H2S). However, the utilization of the said potential depends on further technological developments (Apak et al., 2017). In a recent study, Karayel et al. (2022) have investigated the utilization of hydroelectric power for green hydrogen production in Turkey and have estimated that Turkey's hydro-based green hydrogen production potential is 2.26 megaton.

Dinçer et al. (2021) has developed a hydrogen farm concept for Turkey, where renewable energy sources are deployed to produce green hydrogen using several processes, ranging from electrolysis to thermochemical cycles. According to study results, creating a hydrogen hub in Turkey has the potential to compensate for the total energy consumption of the country. In addition, the extra hydrogen production can improve the economy of the country by becoming an export commodity. Furthermore, the EU could become an importer of Turkish hydrogen considering current pipelines and availability of funds in the concept of the European Green Deal. Even though 2030 Hydrogen Roadmap of the EU doesn’t include Turkey as a potential exporter, growing hydrogen demand in Europe will create new opportunities in later period. Hydrogen Europe (2020) has underlined the importance of establishing hydrogen as the key component of ongoing Euro-Mediterranean partnerships that includes Turkey.

In February 2022, a cooperation protocol has been signed by 5 energy companies (the South Marmara Development Agency, Enerjisa Üretim, Eti Maden, Turkey's Scientific and Technological Research Council's Marmara Research Center and Aspilsan Energy) to establish Turkey’s first green hydrogen plant (Heynes, 2022).

4. METHODOLOGY

This study is based on a cost optimization made with a tool called OSeMOSYS to estimate hydrogen's role in energy system of Turkey. The tool tries to find the solution with the lowest cost to meet Turkey's energy demand. By the use of different scenarios based on the current energy data of Turkey, OSeMOSYS has been utilized to understand potential effects of hydrogen.

4.1 Open Source Energy Modeling System (OSeMOSYS)

Energy system models are widely used in the world for energy planning purposes and have been around for almost 50 years, dating back to the first oil crisis in 1973. Today, several well-known energy modeling tools are available, such as MARKAL, TIMES, PRIMES and MESSAGE. However, unlike OSeMOSYS, these tools require a long learning curve, expensive licenses and provide restricted insight to the code (Howells et al., 2011).

OSeMOSYS is developed by KTH Royal Institute of Technology in collaboration with United Nations Industrial Development Organization (UNIDO), United Nations Department of Economic and Social Affairs (UNDESA), International Atomic Energy Agency, Stockholm Environmental Institute (SEI) and North Carolina State University to support teaching by its simple, open and flexible nature (Howells et al., 2011). Its educational background was one of the reasons why it was chosen for this study. Other reasons for this choice include OSeMOSYS being freely available, offering a quick turnaround time to build a model that functions as planned, and having an active online support community.

OSeMOSYS is characterized by its modular structure that consists of multiple blocks of functionality (Figure 3.1). These lego-blocks are compatible and potentially replaceable with new blocks with careful and consistent set, variable and parameter definitions. The blocks contain specifications of the objective function (1), costs (2), storage (3), capacity adequacy (4), energy balance (5), constraints (6), and emissions (7). OSeMOSYS minimizes the cost of total system for a given and set of available technologies. The optimization process aims to meet the given energy demands, while fulfilling several exogenous constraints in the analysis period. These constraints allow taking into account the availability of resources (i.e. coal, oil, and natural gas), the performance indicators and costs of various conversion technologies (i.e. power plants, electrolyzer, and fuel cell), domestic and imported energy resources such as fuel prices (Fonseca and Gardumi, 2022).

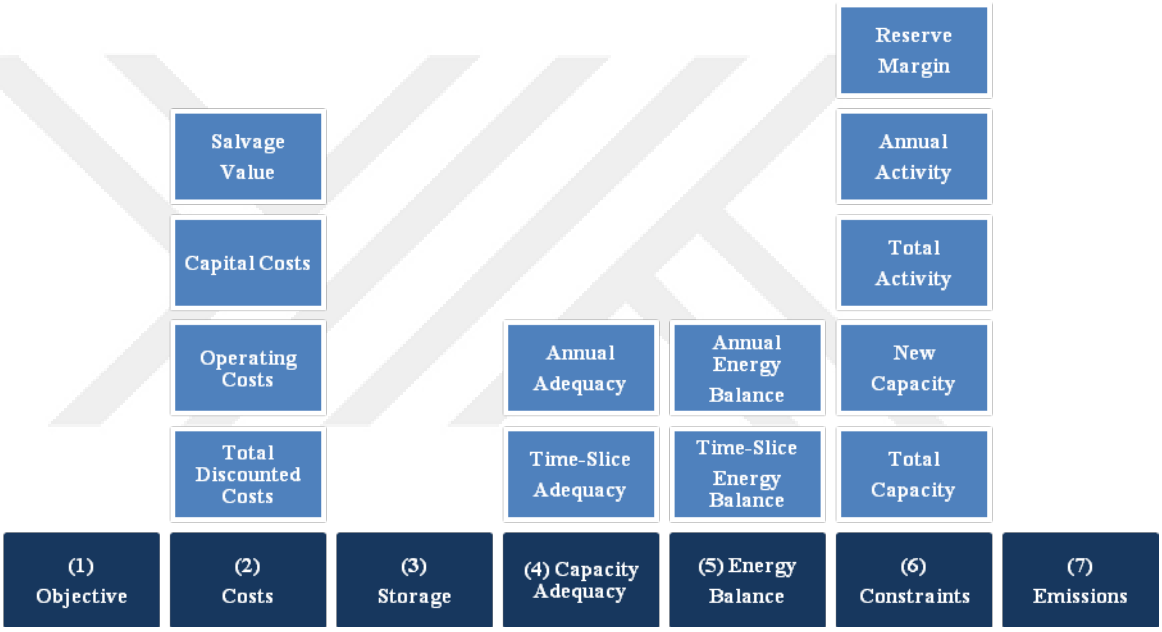

Figure 4.1 Blocks of functionality of OSeMOSYS (Howell et al., 2011)

Since its launch in 2008, OSeMOSYS has been used to analyze energy systems for areas as large as continents and countries down to regions as small as cities and villages (Motalebi et al., 2021). As an example for how it can be used for large scale analysis, it was adopted by Löffler et al. (2017) to develop a decarbonization path for the global energy system (GENeSYS-MOD) up to 2050. The model calculations shows that to achieve the 1.5–2 degrees Celsius target, the lowest cost solution is obtained by a combination of renewable energy sources, solar photovoltaic (PV) being the dominant source. On the other hand, Novo et al. (2022) used OSeMOSYS to explore decarbonization path of a smaller area, Pantelleria Island, by 2050, examining vairous adoption trends of distributed PV systems and electric vehicles by the local population. Similarly, OSeMOSYS was used by Timmons et al. (2019) to investigate renewable energy combination for the island of Mauritius offering minimum cost and by Vargas-Ferrer et al. (2022) to find the share of renewables in the Chilean power system by 2050.

Currently, there are six OSeMOSYS interfaces presented on the OSeMOSYS webpage that are available to users who want to create their energy model. Depending on their level of needs (i.e. beginner, intermediate, and advanced), users can make a choice among these interfaces. Model Management Infrastructure (MoManI) is a browser-based open source interface developed to run OSeMOSYS which is promoted for intermediate users. The interface can be used to create and run a model, store its input data of different scenarios, and visualize its results. MoManI is available both online and standalone versions. In it required constraints and equations are defined upfront. To create a model, the user expected to enter the needed dataset and values according to reference energy system. Moreover, its novel structure allows simultaneous collaboration of different teams around the world (Almulla et al., 2017). For this study, MoManI is used because of its straightforward structure simplifying energy system modeling and rapid results visualization feature helping to get immediate feedback on the work.

4.2 Reference Energy System of Turkey

Reference energy system is an analytical tool that represents the relationships between the energy supply and the total demand as a network. The scope of an analysis using reference energy systems may range from micro to global scale and the analysis can focus on the entire energy market or a specific part of the system (Mutluel and Sulukan, 2017). In this study, the focus is determined depending on several factors. While the hydrogen’s potential use areas extend to electricity, heating and transportation sectors, this thesis has chosen to look only at the electricity and heating (natural gas) sectors. Hydrogen’s role in decarbonization efforts of Turkey is researched through creation of a demand for hydrogen replacing natural gas demand. Therefore, the model boundaries are chosen so that the other use of energy such as transportation fuels, other heating fuels have been left out of the system. Importation of fuels, power plants, as well as hydrogen storage, electrolyzer and fuel cell are included in the model boundaries. The national grid for electricity and natural gas transmission and distribution are included in the model but no costs related to them are defined. The reason behind this assumption is that, they already exist and their further potential expansion is not considered in this model. Hydrogen uses natural gas transmission and distribution grid up until 20% blending, higher concentration rates requires an improved or dedicated grid.

Figure 3.2 shows the simplified reference energy system that is created for the business-as-usual (BAU) scenario. In order to have a simple model, energy end use sectors (industrial, residential etc.) and appliances (gas boiler, lighting etc.) haven't been included.

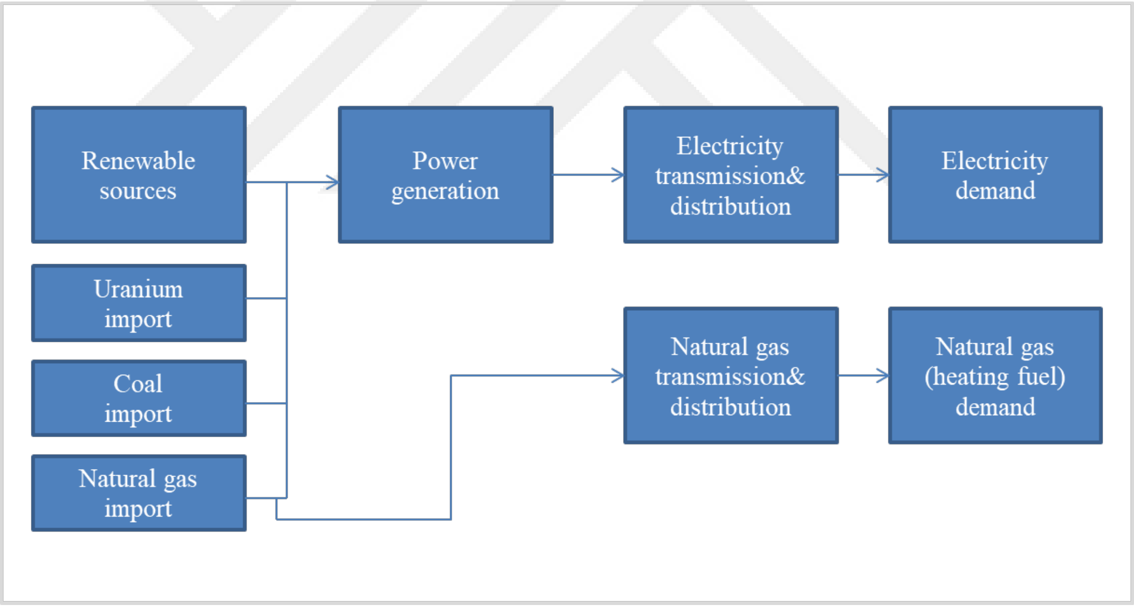

Figure 4.2 Simplified reference energy system of Turkey

4.3 Scenarios

Scenarios are used in energy system modelling to examine the impacts of changes and/or new measures on the energy system. New scenarios are usually compared to a reference, usually referred as BAU scenario. In this study, two scenarios have been created to help capture the effects of hydrogen blending in the energy system of Turkey.

Comparing BAU scenario with H2 scenario, economical feasibility of hydrogen blending into natural gas network for Turkey can be better evaluated. Each scenario has its own peculiarities. These are implemented by adjusting the input data for one parameter or more. In BAU scenario, none of the hydrogen related technologies are presented. It is created to make a comparison and to validate the built model. The H2 scenario is created with the base of hydrogen farm concept proposed by Dincer et al. (2021) and the roadmap to transition to hydrogen in the natural gas sector suggested by GAZBİR (2021). In the hydrogen farm concept, renewable energy sources (solar, wind, hydro, biomass and geothermal) are used to produce hydrogen. Figure 3.3 shows the development of suggested blending percentages over the course of modeling period by GAZBİR (2021).

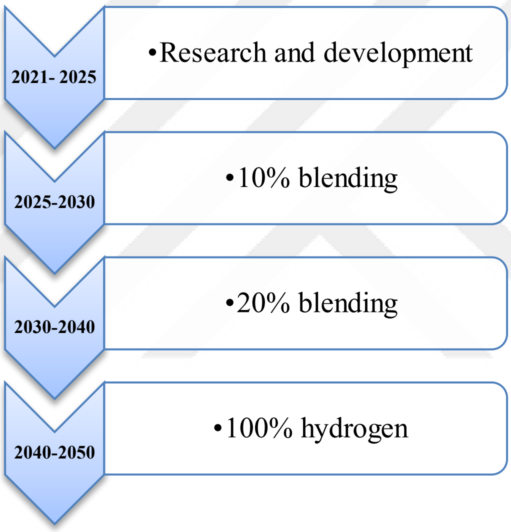

Figure 4.3 Roadmap to transition to hydrogen in the natural gas sector (GAZBİR, 2021)

Since the modeling period is decided to be 2020-2040, hydrogen blend starts in 2025 by 10% and in 2030 the blend rate is increased to 20%. What is meant by 20% blending is that the gas delivered to the end users is 20% hydrogen by volume. However hydrogen has around only a third of the calorific value of natural gas by volume. Therefore, only 6-7% of final energy demand can be met by hydrogen. Measuring in energy terms, the hydrogen to be delivered matches the natural gas displaced (Frontier Economics, 2020). The existing natural gas pipeline system consists of gathering, transmission, and distribution lines. Hydrogen blending is expected to occur in both transmission and distribution lines that connect commercial and residential end users (Mahajan et al., 2022). Although in real life, blended gas is supplied directly through the injection of hydrogen into natural gas pipelines, two separate demands for hydrogen and natural gas are defined in the model. This is essentially to control the blending percentages. By creating a demand for hydrogen, the model pushes hydrogen production.

The schematic representation of the model can be seen in Figure 3.4. In schematic representation lines represents energy carriers, fuels and demands. They are connected to blocks symbolizing technologies such as fuel extraction, conversion processes, and energy services. The whole system is illustrated from energy resources on the left to generation, transmission and distribution, and final energy demands on the right.

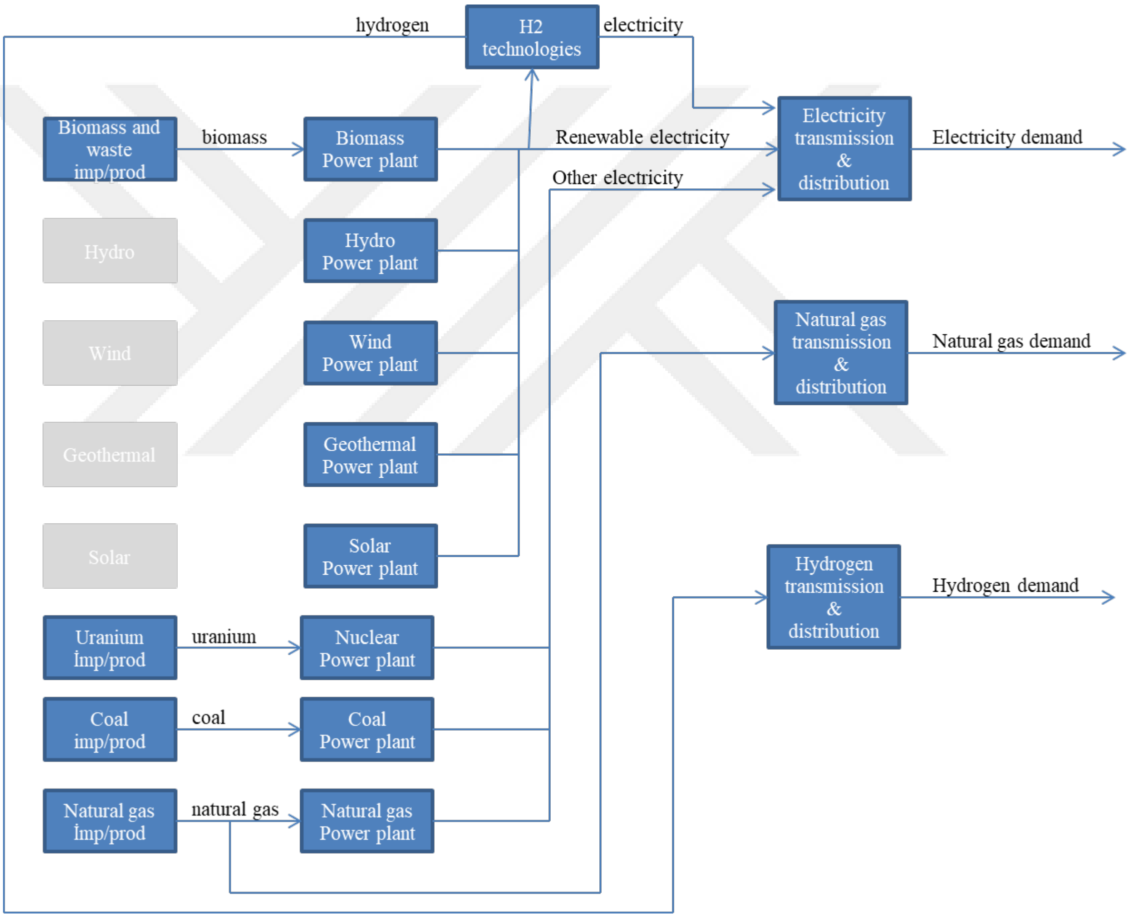

Figure 4.4 Schematic representation of the H2 scenario

Detailed representation of hydrogen technologies module is given in Figure 4.5. The hydrogen is produced via polymeric exchange membrane (PEM) electrolysis, stored in TANK and can be used for direct hydrogen demand or it can be converted back to electricity by fuel cell. In real life, it is not possible to separate renewable electricity from other electricity (i.e. fossil fuel or nuclear) in the grid. However, for modeling purposes, the input fuel of PEM electrolyzer is referred as renewable electricity. This is mainly for the purpose of taking into account total renewable energy potential capacity of Turkey. Another way would be using dedicated power plants for green hydrogen production which would not let the model to consider total renewable potential properly, meaning it is not possible to limit different technologies by the same parameter in OSeMOSYS.

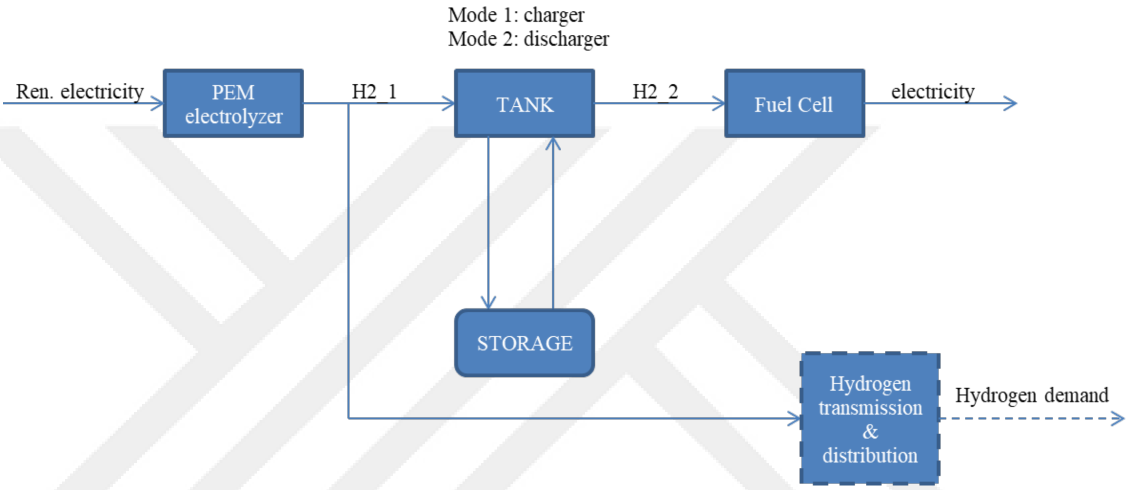

Figure 4.5 Hydrogen technologies module

5. DATA AND ASSUMPTIONS

This chapter aims to explain the different sets and parameters, as well as their respective data, which are used to build the OSeMOSYS model. Key assumptions for the model are listed below:

- The modeling period is 2020 to 2040, where 2020 is used as the base year.
- Monitory units used are; United States Dollar (USD) for currency, Petajoule (PJ) for energy, Giga Watt (GW) for capacity.

Following sections are classified according to indications in MoManI User Manuel (Almulla et al., 2017). All input data can be reached out at Github repository (Tetik, 2022).

5.1 Sets

Sets are used to define the structure of the model and they are constant across scenarios. A summary of the sets used for this model is given in Table 5.1.

Table 5.1 Summary of the sets in OSeMOSYS

Name of the set	*Input*	*Description*
Daily time bracket	1, 2	i.e. day and night
Day type	1	All week days are considered same
Emission	CO2	It is used to present the effects of hydrogen in decarbonisation efforts.
Fuel	bio, co, e, eren, ex, h2, 2h2, hx, ng, ngx, ur	All fuels, energy carriers (hydrogen, electricity etc.) and final demands are expressed as fuels.
Mode of operation	1,2	It is used to enable technologies to have different operation modes. Only TANK has 2 modes of operation; charger in mode 1, discharger in mode 2.
Region	TR	Turkey
Season	1, 2, 3	Intermediate (Autumn and Spring), Winter, Summer
Storage	STO	Hydrogen storage
Technology	BIOIMP, BIOPP, COIMP,	Importation& production of

	ELCTRLZR, ELTD, FC, GEOPP, H2TD, HYDROPP, IGCC, NGCC, NGIMP, NGTD , NUCPP, PV, RENELCONV, TANK, UR_IMP, WIND	fuels, power plants, heat generation plants (solar thermal and geothermal), electrolyzer, transmission and distribution are expressed as technologies.
Time slice	ID, IN, WD, WN, SD, SN	3 seasons (intermediate, winter, summer) & 2 time brackets for each day (day, night)
Year	2020-2040	2020 is the base year.

5.2 Parameters

Parameters can be defined as the functions of the elements within each set, which are used for defining technical and cost data for the model. Unlike sets, parameters may change within and between scenarios. This chapter will go through parameters, at the same time it will give an overview of the data used to build the model.

5.2.1 Costs

Since this is a cost optimization model, the cost parameters (capital, variable and fixed costs) are the main drivers of OSeMOSYS during the consideration of different technologies. The model will always choose the least cost option to meet the system demand. That's why, the right representation of the cost of each technology is highly important. The data is gathered from several sources which are given in more detail in Table 5.2.

Table 5.2 Summary of cost data sources

Cost parameter	***Source***
Power plants	Optimum electricity generation capacity of Turkey towards 2030 (SHURA, 2020)
Hydrogen technologies	Techno-economic study of Turkey's production and export potential for green hydrogen (SHURA, 2021b)

Projections towards 2050	Projected costs of generating electricity (IEA-NEA, 2020)
Fuel variable costs	EU28 fuel prices for 2015, 2030 and 2050 (Duic et al., 2017)

The transmission and distribution grid for electricity and heating fuels are included in the model but no costs are defined related to them. The reason behind this assumption is that they already exist, further the potential expansion of these grids is not considered in the model. The input data for all technology costs can be found in the Annex A.

5.2.2 Performance

The performance parameters are used to create links between different types of fuels and technologies that use them as input/output so that the reference energy system can be built.

Input Activity Ratio and *Output Activity Ratio* parameters are used to link system components. The ratio of these two parameters gives the efficiency of the related technology. *Output Activity Ratio* is usually assigned as 1, so that *Input Activity Ratio* can be easily assigned as 1 divided by efficiency (Table 4.3).

Table 5.3 Efficiency (Keller et al., 2019) and InputActivityRatio values for technologies

	Efficiency	***InputActivityRatio***
BIOPP	0.34	2.95
IGCC	0.33	3.03
NGCC	0.51	1.96
NUCPP	0.37	2.70
ELCTRLZR	0.72 (2020) – 0.8 (2040)	1.38 – 1.25

The exception to this assumption is transmission and distribution technologies, since there is an energy loss during these activities. Electricity transmission and distribution technology has 0.9528 as output activity ratio and natural gas/hydrogen transmission and distribution technologies have 0.92 as output activity ratio. Renewable power plants' efficiency values are considered under the capacity factor parameter since they have no input resource.

The *Capacity Factor* of the power plant is the total energy produced by the plant in a certain period divided by the energy it can produce at full capacity. The capacity factor may vary depending on the type of fuel used and the design of the plant. Capacity factor should not be confused with availability factor or efficiency. Capacity factors are calculated for the base year except for nuclear power plant, where necessary hourly generation data is gathered from EPİAŞ Transparency Platform (2022a), and total capacity data is gathered from EMRA (2021) electricity market report; as the example given in Table 5.4. The calculated results are compared to capacity factor intervals presented by TEİAŞ (2019), and found to be within the given range. Since there are not any operating nuclear power plants in Turkey, the global average capacity factor value gathered from World Nuclear Association (2022) is used.

Table 5.4 Example for capacity calculation

	Calculation for wind power plants
ID	$= \dfrac{7422679.22\ \text{MWh}}{{}^{365}/_{2}\, day \times \left(24 \times {}^{2}/_{3}\right) {}^{hour}/_{day} \times 8761.57 MW}$

For this model to be more accurate, it is chosen such that to use three seasons (intermediate, summer, winter—with intermediate combining the seasons of autumn and spring), one day type (meaning all week days are same), and two daily time brackets (day, night). The daily time bracket "day" is set to 16 h (2/3 of one day), while "night" is 8 h long (1/3). Since current model has a total of 6 time slices (ID, IN, WD, WN, SD, SN), each power plant type will have 6 capacity factor values (Table 5.5).

Table 5.5 Capacity factors for each time slice

	ID	***IN***	***WD***	***WN***	***SD***	***SN***
BIOPP	0.45	0.45	0.45	0.45	0.45	0.45
GEOPP	0.66	0.69	0.70	0.72	0.58	0.62

HYDROPP	0.32	0.27	0.27	0.19	0.32	0.26
IGCC	0.60	0.60	0.60	0.60	0.60	0.60
NGCC	0.30	0.30	0.30	0.30	0.30	0.30
NUCPP	0.80	0.80	0.80	0.80	0.80	0.80
PVUTIL	0.31	0.000011	0.16	0.000001	0.35	0.000020
WIND	0.29	0.36	0.37	0.37	0.33	0.34

Capacity factors of biomass, coal and natural gas have been kept constant between the time slices, due to getting nearly equal results from calculations for each time slice. For renewable energy sources such as solar, wind and hydro, the availability of the energy source is generally main reason for getting reduced capacity. The plant may be capable of producing electricity during the given time slice, but its "fuel" may not be available (e.g. there is no sunlight during night time).

Another performance parameter is *Capacity to Activity Unit.* It is used to recognize the amount of energy that each specific technology can generate by one unit of installed capacity. Since we have the capacity in GW and generation (activity) in PJ, the *Capacity to Activity Unit* for all generation technologies including PEM electrolyzer and fuel cell is 31.536. It is calculated by multiplying hours of the day by days in a year divided by 1000 and multiplying the result by 3.6 (to convert TWh to PJ).

Last performance parameter is Operational Lifetime. It represents the time that a technology is designed to remain operational. It is expressed in years and stays constant over the years for the model (Table 5.6). The lifetime data is gathered from same sources as related technologies' cost data.

Table 5.6 Lifetime of the technologies

Tech.	**BIO_PP**	**FC**	**GEO_PP**	**HYDRO_PP**	**IGCC**	**NGCC**	**NUC_PP**	**PEM**	**PV_UTIL**
Lifetime (years) / ***Lifetime***	20	8	30	40	30	20	50	15	20

(years)				

5.2.3 Capacity

The first capacity parameter is *Residual Capacity* which represents the available capacity from the period prior to the first modeling year. Starting with historical installed capacity values for the years 2020 and 2021 from TEİAŞ (2022) and MENR (2021), the residual capacity for each technology has been calculated. The starting residual capacity in the year 2021 is decreased through interpolation so that all residual capacity is zero at the end of the technology’s operational lifetime. This will drive the need for substitution of old capacity by reinvestment. This assumption might cause creation of an exceptionally fast changing energy system; since in real life, many technologies can be used long after their calculated economical lifetime. The specific data for the residual capacity can be viewed in Annex A.

All other capacity parameters serve as constraints that can be used to limit installation or to force installation of certain power plants. For this model, *Total Annual Max Capacity, Total Annual Max Capacity Investment* and *Total Annual Min Capacity* parameters have been used to simulate a realistic development of the Turkish energy system. For the nuclear power plant (NUC_PP), these parameters used to model Akkuyu Nuclear Power Plant, coming into effect in 2023 with a capacity of 4.8 GW. For other power plants, max capacity has served to include Turkey’s renewable power capacity potential limitations and max capacity investment has served to limit annual investment at a reasonable amount (Şahin et al., 2021),.

5.2.4 Demand

As it was stated before in costs section, the aim of the model is to meet the system demand by the least cost option. Thus, the demand drives the cost optimization model and its specification has an important place in OSeMOSYS. With the selected boundaries, there are three demands in the system; electricity, natural gas and hydrogen demand. The base year -2020- consumption data for electricity and natural gas which will serve as a basis for demand forecast is gathered from 2020 Energy Balance Table provided by MENR (2021). In recent years, various demand forecasts have been proposed to show the developments and changes of the demand in the coming years. These forecasts could be obtained from statistical evaluations or projections of former consumption trends.

Electricity demand projection is conducted according to Power Demand Projection Report of MENR. The report suggests three different scenarios (low, reference and high) and assigns different growth rates. The growth rates of reference scenario are chosen to work with (Table 5.7).

Table 5.7 Electricity demand growth rates (MENR, 2018)

Years	2020-2025	2025-2030	2030-2035	2035-2040
Growth rate	3.9%	3.6%	2.9%	3.1%

For the natural gas demand projection, the reference scenario of Turkey Energy Outlook (TEO) report by IECEC (2020) which applies a growth rate of %1.5/year is used (36% cumulative growth in 2040). TEO reference scenario reflects a growing natural gas sector that is supported by Turkey's developed infrastructure and growing economy facilitating the replacement of other fossil fuels by natural gas. Moreover, the report foresees natural gas to become concentrated in the residential, industrial, and commercial sectors as renewable energy sources are expected to increase their shares in power generation. As a result, different cumulative growth rates for each sector are given. By applying compound annual growth rate formula, yearly growth rates for each sector are calculated (Table 5.8).

Table 5.8 Natural gas demand yearly growth rates for sectors until 2040

Sector	Industrial	Residential	Commercial
Growth rate	2.1%	0.9%	1.6%

This study aims to find effects of hydrogen blending into natural gas network. This mixed gas is expected to be used as a fuel in the residential, industrial, and commercial sectors. In the model, natural gas demand corresponds to total of these sectors demand. Hydrogen demand is calculated with reference to blend percentages. The 10% hydrogen blend by volume equals to 3.35% by energy, meaning 3.35% of natural gas demand is replaced by hydrogen. Same applies to the 20% by volume (6.7% by energy).

Figure 5.1 shows the final energy demands as inputted in OSeMOSYS. Where EX is the final electricity demand, NGX is the final natural gas demand (total final demand of residential, industrial, and commercial sectors) and HX is hydrogen demand that matches the natural gas displaced by the blending process.

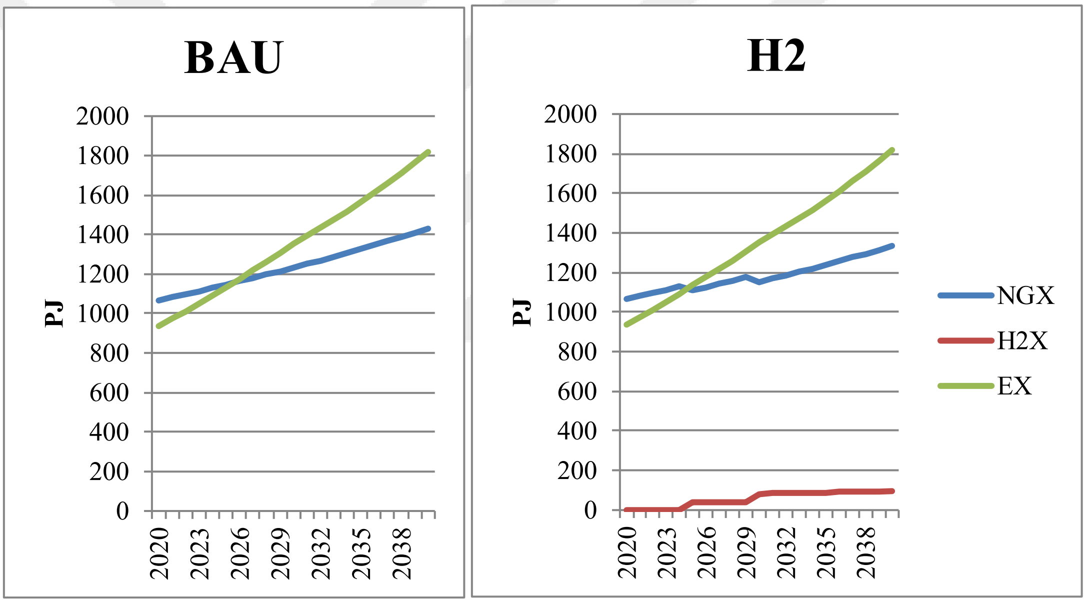

Figure 5.1 Demands in BAU and H2 scenarios

There are two different kinds of demands in OSeMOSYS. While entering demand data, a decision must be made so that demand can be entered either as *Accumulated Annual Demand* or as *Specified Annual Demand*. The difference is that accumulated annual demand can be met at any time during the year, as long as the total is satisfied. Demand for energy carriers (e.g. electricity, hydrogen) should rather be modeled as a specified annual demand, since in this case demand has to be supplied instantly when a demand occurs. It is linked to *Specified Demand Profile* to work with. For each time slice, the corresponding consumption amount is divided by total consumption over the year to find the profile of that time slice. The specified demand profile for electricity is calculated according to real time hourly power consumption data of 2020 retrieved from EPİAŞ Transparency Platform (2022b). For natural gas demand, monthly natural gas sector reports of EMRA (2022) are used to attain the consumption amounts of industrial, residential and commercial sectors in each month of 2020. While electricity has a more stable demand over the year, natural gas demand is considerably lower during summer than during winter. Hydrogen's profile is assumed to be same as natural gas, since it replaces natural gas. Table 5.9 presents specified demand profile data as inputted to OSeMOSYS.

Table 5.9 Specified demand profile of system demands

	ID	***IN***	***WD***	***WN***	***SD***	***SN***
EX	0.32	0.15	0.18	0.08	0.18	0.09
NGX	0.3	0.15	0.28	0.14	0.09	0.04
H2X	0.3	0.15	0.28	0.14	0.09	0.04

5.2.5 Emissions

First step is to decide which type of emissions will be included in the model. While other gases also contribute to the greenhouse effect, only carbon dioxide CO_2 emissions are included in this study because of its significance. In the model, the emissions are linked with import technologies. Emission levels are defined by *Emission Activity Ratio* parameter. It is calculated by dividing the produced CO_2 (million tons) by total supplied energy (PJ) for each fossil fuel. However, the country specific CO_2 emission factors are already given in the Turkish GHG Inventory report published by UNFCCC (2021). Therefore, emission activity ratio for natural gas and coal were calculated by making the necessary unit conversion (Table 5.10).

Table 5.10 Emission activity ratio calculation

Import technology	***CO_2 emission factor (ton/TJ)***	***Emission activity ratio (Mton/PJ)***

CO_IMP	96.89	0.09689
NG_IMP	53.67	0.05367

5.2.6 Division of the year

In OSeMOSYS, demands are distributed over units of time called time slices. The parameter that is used to define duration of each time slice is named *Year Split*. In order to build time slices, it is necessary to define several sets (season, day type, daily time bracket, and time slice) and parameters (Days in Day Type, Day Split and Year Split) in the model.

Days in Day Type refers to number of days for each day type, within one week. Since, only one day type is defined in the current model, this parameter is set to 7, meaning in one week there are 7 of the same day type. Day Split corresponds to length of one daily time bracket in one specific day as a fraction of the year. In this study, the daily time bracket "day" is set to 16 h (5:00- 20:00), while "night" is 8 h long (21:00- 4:00). The number of time slices should be decided in a way that it is large enough to account for all major variations in the model and should not be too large to minimize problem size, data processing and computational efforts. Having 1 day type, 2 daily time brackets and 3 seasons, the model has a total of 6 time slices (intermediate day, intermediate night, summer day, summer night, winter day, and winter night). *Year Split* parameter is used to express duration of a modelled time slice as a fraction of the year. The only requirement is that the sum of all the value entries for the parameter Year Split should be equal to 1 (Table 5.11). Year split values are calculated by dividing total length of a time slice with total hours in a year ($365 \times 24 = 8760$).

Table 5.11 Year split values for each time slice

Time slice	ID	IN	SD	SN	WD	WN
Each year	0.3333	0.1667	0.1667	0.0833	0.1667	0.0833

5.2.7 Storage

The correct representation of storage in energy systems modeling has gained significant importance due to the expansion of renewable electricity portfolios. The storage modeling methodology in OSeMOSYS is simple, allowing storing or discharging energy in each time slice as long as the storage level constraints are met. After defining a storage, next step is to introduce the sequence of the time slices, which is done by assigning each time slice to a season, a day type and a daily time brackets using the following parameters: *Conversionls*, *Conversionld* and *Conversionlh* respectively.

In OSeMOSYS, the storage is linked to one or more technologies for charging and discharging. To define charging technology, *Technology to Storage* parameter, and to define discharging technology, *Technology from Storage* parameter is used. In this case, both charger and discharger technology is TANK (Figure 5.2).

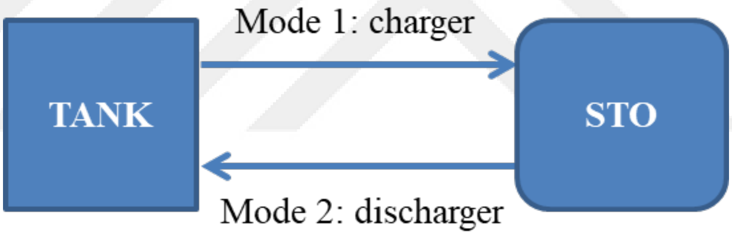

Figure 5.2 The links between storage (STO) and its charging/discharging technology (TANK)

Other important parameters to have a functioning storage are *Storage Max Charge Rate* and *Discharge Rate* which should be set to very high value (e.g. 999999). Finally, *Operational Life Storage* parameter should be set to a value higher than 0.

6. RESULTS AND DISCUSSION

After completing the data entry into MoManI, the executable file is downloaded from the webpage and it is run on the computer with GNU Linear Programming Kit (GLPK) solver. GLPK is an open-source linear solver. The results are automatically uploaded to MoManI webpage for screening the results. This section summarizes some of the key results of both scenarios, beginning with model validation.

As it was mentioned before, the main difference between scenarios is that H2 scenario has also hydrogen demand, in addition to electricity and natural gas demands. The total final demand rests same between two scenarios (Figure 6.1). Detailed explanation of projections to 2040 is given in Data and Assumptions section.

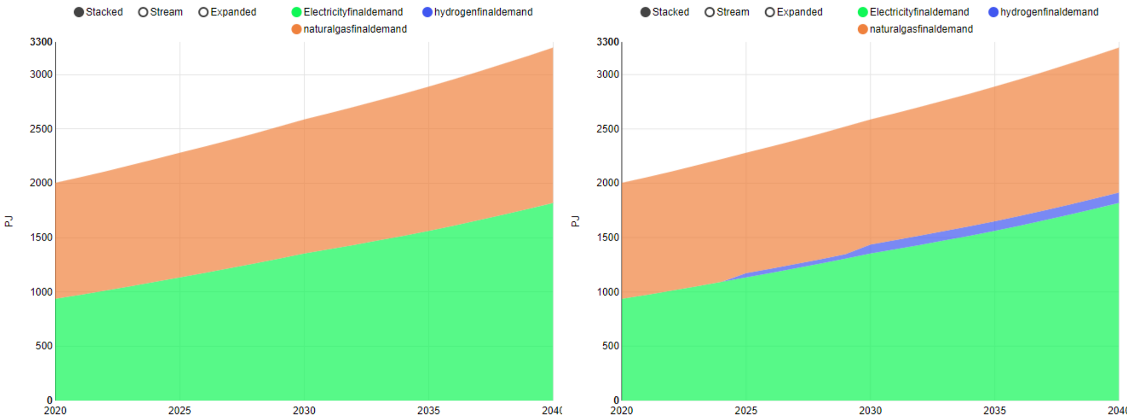

Figure 6.1 Demand charts for BAU (left) and H2 (right) scenarios

6.1 Model Validation

Before going into the scenario results display and discussion, it is important to validate the model. Model validation is conducted to confirm the outputs of the generated model are acceptable with respect to the existing real data. In order to provide the necessary validation, an analysis has been carried out between the model's power generation results and national statistical accountings for the base year 2020. Figure 6.2 shows shares of each power generation technology in total generation.

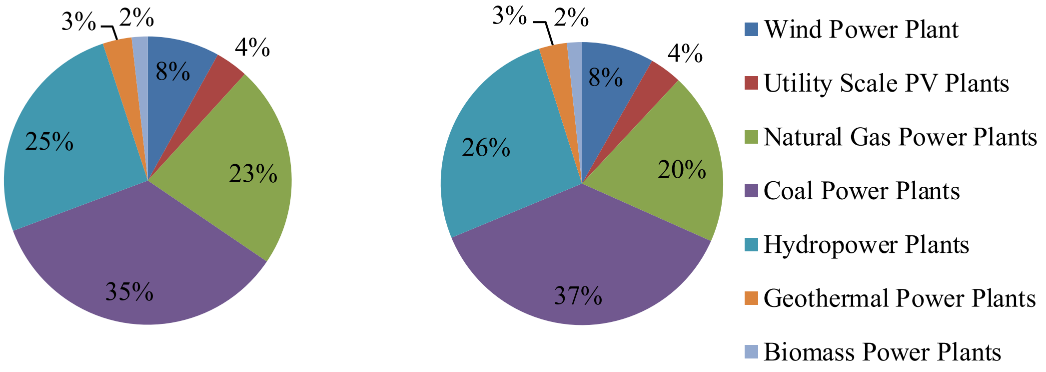

Figure 6.2 Actual power generation data from EMRA (2021) (left) and model's power generation technology shares (right) in 2020

On the right, model results and on the left, real power generation; it can be seen that the generated results are very close to real data. However, since the model does not include end use technologies, only energy loss takes place during transmission and distribution. This situation causes a decrease in the gap between generation and consumption. Moreover, having low capacity factor and high costs makes the natural gas power plants the least favorable option. As a result, hydro and coal power plants generate more electricity, and natural gas power plants generate less electricity than reality. In addition, other technologies that are used for power generation have been excluded from the real data. Although, they have a small share that corresponds to less than 1% of total power generation, the distribution of their power generation amounts to included power plants in the model affect the percentage shares.

6.2 Annual Production by Technology

In OSeMOSYS, all technologies have one or more output. As a result, all technologies including transmission and distribution have production results. However, in this part, electricity and hydrogen production are analyzed, respectively. Importation of fuels are also discussed in this part, since importation of fuels is also defined as technologies.

In BAU scenario, power is only generated to supply electricity demand. On the other hand, there is a need for extra generation in H2 scenario to power PEM electrolyzer. This extra power is generated by renewable power plants in order to produce green hydrogen. The change driven by hydrogen blending can be clearly seen in years 2025 and 2029. In 2025, hydrogen technologies are introduced and 10% blending begins. The situation in 2029 differs, as during that year power generation increases to prepare for higher percentage blending by storing hydrogen. Additionally, the storage option serves to increase the electricity that is supplied by renewable energy sources such as solar, wind and hydro. In 2040, the power generation difference between the two scenarios is about 200 PJ (Figure 6.3).

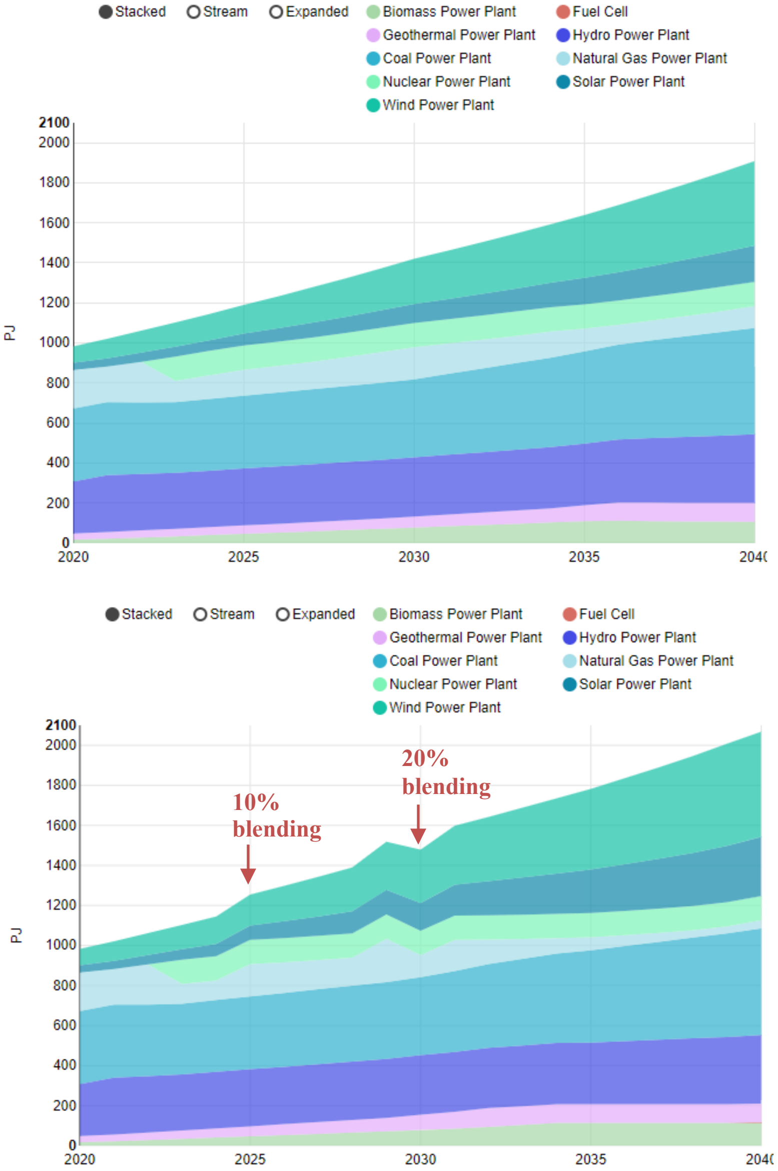

Figure 6.3 Annual power generation by technology in BAU (top) and H2 (bottom)

To visualize the hydrogen production, PEM electrolyzer's annual production is given in Figure 6.4. Hydrogen production begins in 2025, and smaller amounts are produced until 2029, since only 10% of hydrogen is blended into natural gas. In 2029, hydrogen production increases to supply for the next year's augmented hydrogen demand. Between the years 2030-2040, the amount of produced hydrogen grows by 18%, reaching 125 PJ in 2050.

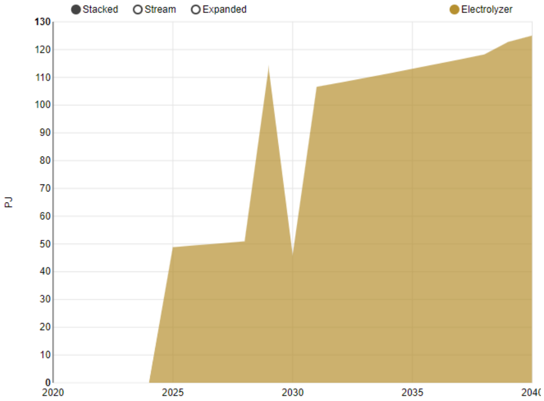

Figure 6.4 Hydrogen production in H2 scenario

Although fuel cell is included in the model as a component of hydrogen technologies, it only generates electricity in the years 2030 and 2040 (Figure 6.5). The most of the produced hydrogen is transmitted to hydrogen grid. Fuel cell is not considered as a viable option by the model during other years. This outcome is caused by the costs related to fuel cell and forced hydrogen demand in the model.

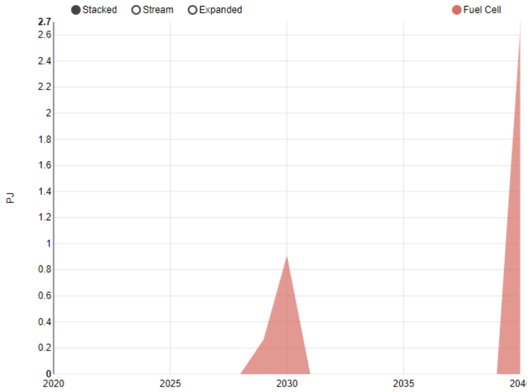

Figure 6.5 Power generation by fuel cell in H2 scenario

This study suggests hydrogen for Turkey as both a mid-term solution for decarbonization and an option to reduce energy dependency. To analyze, the effect of hydrogen blending into natural gas on energy dependency, a closer look into fuel import amounts is given in Figure 6.6. While similar results are observed for biomass, coal and uranium between two scenarios, natural gas shows the major change. Over the course of the modeling period, 2098 PJ of decrease is observed in cumulative natural gas import between the two scenarios. This amount is equal to almost twice the total natural gas demand of Turkey in 2020 (MENR, 2021). Based on this result, it can be concluded that, hydrogen blending decreases the energy dependency of Turkey, replacing natural gas import by domestically produced green hydrogen.

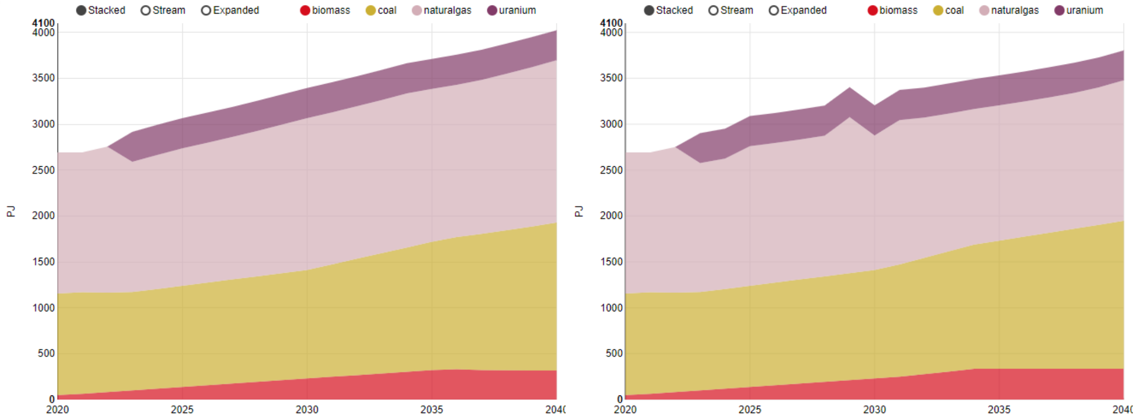

Figure 6.6 Fuel import and production in BAU (left) and H2 (right)

6.3 Storage Levels

In the model, hydrogen storage is included after 2025 to solve the intermittency problem of renewable energy sources. Renewable energy power plants have different capacity factor values over the course of one year depending on the availability of related source. In the current study, a year is split into 6 time slices by assigning 3 seasons (intermediate, summer and winter) and 2 daily time brackets (day and night). Excess electricity that is produced during one time slice can be stored, and used when there is more need in the following time slices. The changes in the level of hydrogen storage can be seen in Figure 6.7. Hydrogen storage begins to function in 2025 with lower results, as capacity of renewable power plants is low. At the beginning of 2030, highest level of storage is observed, which is to provide necessary amount of electricity during that year. The increase in blend rate of hydrogen causes an increase in power generation. During the next years, expansion of renewable power plants capacity results in higher storage levels.

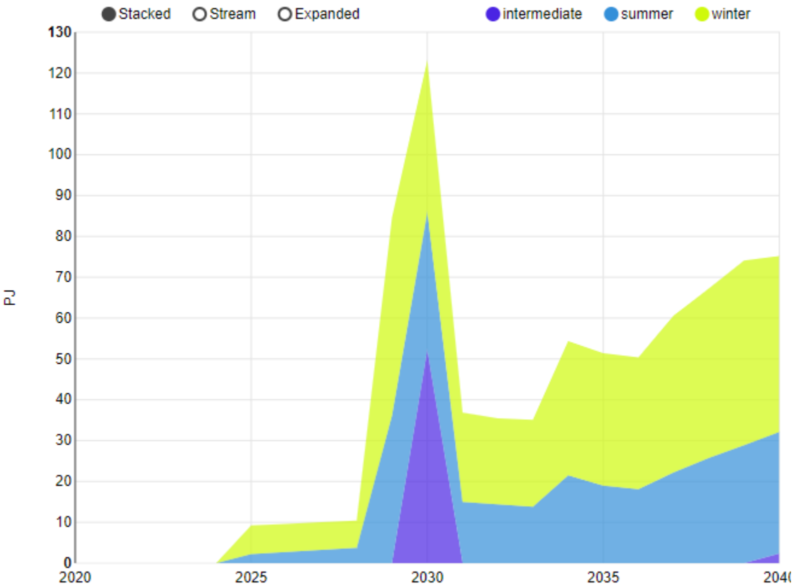

Figure 6.7 Storage levels at the beginning of each season in H2 scenario

6.4 Annual Emissions

CO_2 emissions is the most important result of this study, since it responds to the question of to what extent can hydrogen help decarbonizing Turkey’s energy system. The model takes into account only a specific portion of the Turkey’s energy system, which includes electricity system to produce green hydrogen and natural gas system for industrial, residential and commercial en uses. That’s why the results purely show the emission reduction generated by displacement of natural gas by hydrogen as heating fuel (Figure 6.8).

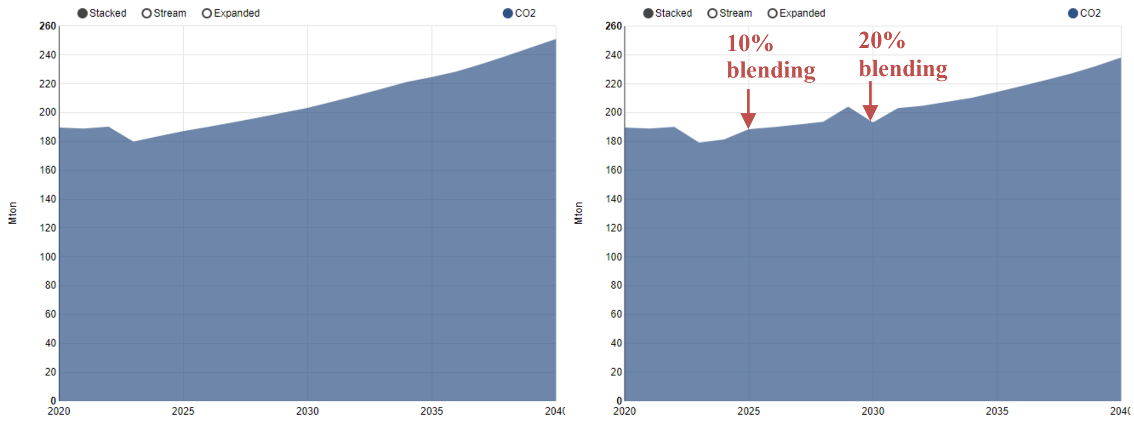

Figure 6.8 Annual emissions in BAU (left) and H2 (right) scenarios

Both scenarios yield the same results until 2025, as hydrogen was not added to energy mix until that year. In 2023, emissions decrease by 10 million tonnes as Turkey's first nuclear power plant starts generating electricity. With the start of hydrogen blending in 2025, emissions increase by 5 million tonnes, since renewable power generation capacity is not enough to supply for both final electricity demand and hydrogen production. However during the following years till 2029, emission levels stay lower than BAU scenario. Prior to increase of blending rate in 2030, the model generates more electricity and stores it during 2029 to use during the next year. Afterwards, emission levels keep getting lower results than BAU scenario. In the final year of the modeling period, BAU scenario has over 250 million tonnes of CO_2 emission, while H2 scenario has less than 240 million tonnes of CO_2 emission. The cumulative emission reduction between two scenarios is 112 million tonnes of CO_2 corresponding to more than half of the emission in the first modeling year. Although it is not enough to prevent carbon emissions from expanding, a cumulative emission reduction of 112 million tonnes of CO_2 corresponding to more than half of the emission in the first modeling year is obtained between two scenarios.

It should be noted that hydrogen blending could only serve as a mid-term solution to reach zero-carbon goal by 2053. Further emission reduction can be provided with hydrogen after 2040, if the hydrogen dedicated transmission and distribution grid would be ready by 2040 and natural gas is fully replaced by hydrogen. Moreover, developments in hydrogen technologies (i.e. electrolyzer, storage, fuel cell) such as cost reduction or efficiency increase, carbon pricing and government incentives on hydrogen investments could help cutting emissions. Hydrogen can be also used as a fuel that can help decarbonization in transportation sector, which hasn't been included in this study.

6.5 Capital Investments

Economic results of this study are analyzed by capital investments in each scenario (Figure 6.9). The capital investment of the base year 2020 and the following year 2021 is low, since all of the system components already exist which is established by residual capacity parameter. The highest investment is needed in 2023 caused by the nuclear power plant implementation. In real life, these costs are not assigned to one year, rather takes place over the years. Although the effects of nuclear power plant to Turkish energy system is not the subject of this study, based on the model results comparing emission reduction and total investment costs in 2023, nuclear power plant can be evaluated as a high cost solution for decarbonization efforts. Furthermore, it does not offer a solution to Turkey's energy dependency as Turkey relies on Russia in the construction and operation of the power plant (Telli, 2016), or energy security by making cyber security a significant concern, in addition to physical security (Bıçakcı and Evren, 2022).

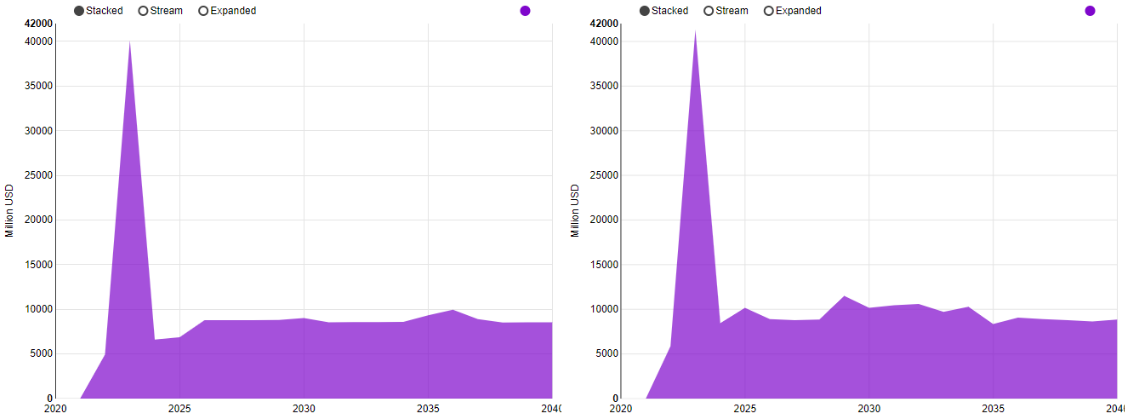

Figure 6.9 Capital investments in BAU (left) and H2 (right) scenarios

In H2 scenario, following the year 2025, where hydrogen demand starts to occur, capital investment costs start to differentiate from the BAU scenario. Green hydrogen production requires PEM electrolyzer and storage capacity and extra renewable power plant capacity, but expected cost reductions in these technologies prevent a big gap between the results of two scenarios. Additionally, a cost reduction is obtained in consequence of less natural gas import in H2 scenario. Table 6.1 presents total costs of each scenario, resulting in a need of nearly 17 million USD of more investment for H2 scenario. With the current boundaries of the model, the sensibility of the given capital investment costs is hard to evaluate. Therefore, these numbers should be seen as a way of making comparison between the two scenarios and not an indication of future energy system cost of Turkey.

Table 6.1 Total investment cost of each scenario and their difference

Scenario	***BAU***	***H2***	***Difference***
Total model period cost (Million USD)	190765.8	207612.5	16846.7

In the case where natural gas is fully replaced by hydrogen, additional costs should be included since natural gas pipelines can’t be used for over 20% blend of hydrogen. This can be added to model by defining capital cost to hydrogen transmission and distribution grid starting from the related year. Furthermore, other green hydrogen production methods such as alkaline electrolyzer, biomass gasification can be investigated if they offer a least cost option. It should be noted that if a carbon tax comes into effect in the future, H2 scenario would gain cost advantage by causing less emissions (Amil and Yılmazoğlu, 2022).

7. CONCLUSION

The objective of this study has been identifying hydrogen's role in Turkish energy system through display of the several effects of hydrogen blending into natural gas network. To achieve this objective, the OSeMOSYS tool was adapted to simulate future energy system of Turkey.

To join the efforts of building a hydrogen economy in Turkey, a comprehensive review on hydrogen and Turkish energy system is conducted. Hydrogen is under significant consideration by many countries as one of the means to tackle climate change (Velazquez Abad and Dodds, 2020). It has a wide range of end-uses, one being blending into natural gas (Figure 2.1). The review discussed the trends in Turkish energy system, underlining its renewable energy potential and energy dependency. Gas decarbonization has a significant importance for countries like Turkey where fuel poverty and energy vulnerability has been influencing energy policy for decades (Sandri et al., 2021). By adopting a similar approach as other countries that have already published their hydrogen roadmap, Turkey can benefit from hydrogen to reduce emissions and energy vulnerability, at the same time.

A further review was undertaken to explore energy system modeling tools, the various methodologies employed in scenario analysis and literature that applied the OSeMOSYS tool. The review on energy planning models further provided a justification for the selection of the OSeMOSYS tool, which has shorter learning curve, active community and no costs such as a license. This review also provided data and provided guidance to this study. The review on scenario methodologies provided the basis for developing the scenario framework for this study, thus two scenarios were built to make comparison of hydrogen's effects. The BAU scenario is built to simulate a realistic development of the Turkish energy system based on existing data, planned investments and projections towards 2040. In the H2 scenario, hydrogen technologies (i.e. electrolyzer, storage and fuel cell) and the demand for hydrogen is added, by replacing a certain amount of natural gas demand. The model finds the least cost option to meet inputted demands. The emission reduction has been calculated from the output of OSeMOSYS, after the cost optimization model has been run successfully for both scenarios.

The results of the study show that there is a potential for hydrogen; with accumulated emission reduction of 112 million tones of CO_2 in the H2 scenario between years 2020 and 2040 compared to BAU scenario. This reduction is almost equivalent of more than half the emission in the year first modeling year. While the H2 scenario causes less CO_2 emissions during the modeling period, it also causes an increase of nearly 17 million USD in the accumulated capital investments. This increase occurs as a result of hydrogen production process, which is in need of extra investments both hydrogen technologies and renewable power plant. However, it must be noted that the amount of imported natural gas decreases, resulting a decrease both in capital investments spent and energy import dependency of Turkey.

Being a modeling study, many limitations have been identified throughout the development period of the model. Since energy systems have a complex structure, determination of several boundaries are needed for simplification. The boundaries of the model are chosen on the basis of a trade-off between the resolution in the model and the computational time, as well as depending on the data availability. The modelling period begins in 2020, in which year the Covid pandemic has affected energy consumption. Another beginning year might cause a change in the results. Furthermore, inclusion of earlier years prior to first modelling year can help preventing edge effect. Electricity sector is included in the model, so that green hydrogen can be produced via electrolysis. However, power plants with the same input and output were modeled in OSeMOSYS as a single technology disregarding geographical characteristics and other specific plant characteristics. The location of power plant, especially for the ones using intermittent renewable sources such as solar and wind, has high importance for capturing fluctuations of generation. Similarly, to model importation and/or extraction of fossil fuels, biomass and uranium, one technology is defined for each that is only characterized by the price of the related fuel that is not taking into account fuel specific changes over the course of a year. Water use of electrolyzers could be included in the model, which will highly depend on the location of the facility. The model could therefore be improved with disaggregation of the technologies making used of their actual operating characteristics.

Among the various end uses of hydrogen, blending into natural gas network is chosen, which is considered as a mid-term solution in energy transition. Similar approach is adopted by choosing PEM electrolyzer for production. Other hydrogen production methods can be examined and compared in future work. Transportation sector could be seen as a possible extension to this study, since hydrogen can be used as a fuel in this sector with the introduction of fuel cell electric vehicles into Turkish energy system.

Despite OSeMOSYS mostly focusing on the techno-economical part, the energy system of Turkey is affected by all of the following components: social, economic and technical. All of these components have influence on the development of the energy system. However, social aspect is not considered in this study. This was not only due to lack of reliable data, but also on the scope of this study, which focuses on to what extent can hydrogen help decarbonizing Turkish energy system. Further research on the social aspect can also be recommended as future work.

In the light of the results of this study and recent hydrogen related developments that have taken place in Turkey and the world, hydrogen’s relevance to the future energy system of Turkey can be seen easily. Similar to other countries, an experiment project is already conducted in Turkey where green hydrogen produced by electrolysis is blended into natural gas for heating purpose. Turkey can benefit from the results of local and global projects for the preparation of a hydrogen deployment roadmap. Eventually, environmental benefits can be obtained by a decrease in related emissions. Furthermore, the potential of reducing energy import dependency offers a great advantage in favor of hydrogen related research and development projects and thus future investments.

BIBLIOGRAPHY

Acaroğlu, H., & Güllü, M. (2022). Climate change caused by renewable and non-renewable energy consumption and economic growth: A time series ARDL analysis for Turkey. *Renewable Energy*, *193*, 434-447.

Almulla, J., Broad, O., Shivakumar, F., Gardumi, A., Ramos, E., Avgerinopoulos, M., & Howells, G. (2017), *Model Management Infrastructure (MoManI) Training Manual.* KTH Royal Institute of Technology. Stockholm, Sweden. Available: http://www.osemosys.org/uploads/1/8/5/0/18504136/momani_training_manual-_rev170612.pdf.

Amil, C., & Yılmazoğlu, M. Z. (2022). The importance of hydrogen for energy diversity of Turkey's energy production: 2030 projection. *International Journal of Hydrogen Energy*, *47*(45), 19935-19946.

Amin, M., Shah, H. H., Fareed, A. G., Khan, W. U., Chung, E., Zia, A., ... & Lee, C. (2022). Hydrogen production through renewable and non-renewable energy processes and their impact on climate change. *International Journal of Hydrogen Energy*.

Apak, S., Atay, E., & Tuncer, G. (2017). Renewable hydrogen energy and energy efficiency in Turkey in the 21st century. *International journal of hydrogen energy*, *42*(4), 2446-2452.

Balta-Ozkan, N., & Baldwin, E. (2013). Spatial development of hydrogen economy in a low-carbon UK energy system. *International Journal of Hydrogen Energy*, *38*(3), 1209-1224.

Bard, J., Gerhardt, N., Selzam, P., Beil, M., Wiemer, M., & Buddensiek, M. (2022). The Limitations of Hydrogen Blending in the European Gas Grid.

Berk, I., & Ediger, V. Ş. (2018). A historical assessment of Turkey's natural gas import vulnerability. *Energy*, *145*, 540-547.

Bıçakcı, A. S., & Evren, A. G. (2022). Thinking multiculturality in the age of hybrid threats: Converging cyber and physical security in Akkuyu nuclear power plant. *Nuclear Engineering and Technology*.

BP (2020). BP statistical review of world energy. *BP Plc, London, United Kingdom*, 14-16.

Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., & Hartley, P. (2018). National hydrogen roadmap. *Australia: CSIRO*.

Diab, J., Fulcheri, L., Hessel, V., Rohani, V., & Frenklach, M. (2022). Why turquoise hydrogen will Be a game changer for the energy transition. *International Journal of Hydrogen Energy*, *47*(61), 25831-25848.

Dincer, I., Javani, N., & Karayel, K. G. (2021). Hydrogen farm concept: an application for Turkey. *International Journal of Energy Research*, *45*(13), 18309-17.

Drela, K. (2021). Harnessing solar energy and green hydrogen–the energy transition. *Procedia Computer Science*, *192*, 4942-4951.

Duic, N., Štefanic, N., Lulic, Z., Krajacic, G., Puksec, T., & Novosel, T. (2017). EU28 Fuel Prices for 2015, 2030 and 2050. *Heat Roadmap Europe*, *2050*.

Ediger, V. Ş., & Berk, I. (2011). Crude oil import policy of Turkey: Historical analysis of determinants and implications since 1968. *Energy Policy*, *39*(4), 2132-2142.

EMRA (2021). *Electricity Market Sector Report 2020*. Republic Of Turkey Energy Market Regulatory Authority. Ankara.

EMRA (2022). *Natural Gas Market Monthly (January- December) Sector Reports.* [online] Available at: https://www.epdk.gov.tr/Detay/Icerik/3-0-95-1007/dogal-gazaylik-sektor-raporu

Elberry, A. M., Thakur, J., & Veysey, J. (2021). Seasonal hydrogen storage for sustainable renewable energy integration in the electricity sector: A case study of Finland. *Journal of Energy Storage*, *44*, 103474.

EPİAŞ Transparency Platform (2022a). *Real Time Generation.* [online] Available at: https://seffaflik.epias.com.tr/transparency/uretim/gerceklesen-uretim/gercek-zamanli-uretim.xhtml

EPİAŞ Transparency Platform (2022b). *Real Time Consumption.* [online] Available at: https://seffaflik.epias.com.tr/transparency/tuketim/gerceklesen-tuketim/gercek-zamanli-tuketim.xhtml

Espegren, K., Damman, S., Pisciella, P., Graabak, I., & Tomasgard, A. (2021). The role of hydrogen in the transition from a petroleum economy to a low-carbon society. *international journal of hydrogen energy*, *46*(45), 23125-23138.

Evrendilek, F., & Ertekin, C. (2003). Assessing the potential of renewable energy sources in Turkey. *Renewable energy*, *28*(15), 2303-2315.

Fonseca, R. H., & Gardumi, F. (2022). Assessing the impact of applying individual discount rates in power system expansion of Ecuador using OSeMOSYS. *International Journal of Sustainable Energy Planning and Management*, *33*, 35-52.

Frontier Economics (2020). Indicative analysis of blending hydrogen in gas networks. Available: https://www.industry.gov.au/sites/default/files/2021-09/hydrogen-blending-final.pdf

GAZBİR (2021). *Roadmap to transition to hydrogen in the natural gas sector*.

GAZBİR (2022). *Renewable Gas Production Project Final Report*.

Gielen, D., Taibi, E., & Miranda, R. (2019). Hydrogen: A renewable energy perspective. *Abu Dhabi: International Renewable Energy Agency*.

Global Energy Monitor (2021). Pipeline Bubble 2021: Tracking Global Oil and Gas Pipelines. *Published February*.

Güler, M. G., Geçici, E., & Erdoğan, A. (2021). Design of a future hydrogen supply chain: A multi period model for Turkey. *International Journal of Hydrogen Energy*, *46*(30), 16279-16298.

Heynes, G. (2022, February 18). Turkey to establish its 'first' green hydrogen production plant. H2 View. https://www.h2-view.com/story/turkey-to-establish-its-first-green-hydrogen-production-plant/

Hjeij, D., Biçer, Y., & Koç, M. (2021). Hydrogen strategy as an energy transition and economic transformation avenue for natural gas exporting countries: Qatar as a case study. *International Journal of Hydrogen Energy*.

Howarth, R. W., & Jacobson, M. Z. (2021). How green is blue hydrogen?. *Energy Science & Engineering*, *9*(10), 1676-1687.

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., ... & Roehrl, A. (2011). OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development. *Energy Policy*, *39*(10), 5850-5870.

IEA (2019). *The Future of Hydrogen*. International Energy Agency, Paris.

IEA (2021). *Turkey 2021*. International Energy Agency, Paris. Available: https://www.iea.org/reports/turkey-2021

IEA (2021b). *Hydrogen*, IEA, Paris. Available: https://www.iea.org/reports/hydrogen

IEA-NEA (2020) *Projected Costs of Generating Electricity*. OECD Publishing, Paris.

IICEC (2020). *Turkey Energy Outlook 2020*. Sabancı University.

IPCC (2022). *Summary for Policymakers. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press. In Press.

IRENA (2020), *Green Hydrogen: A guide to policy making*, International Renewable Energy Agency, Abu Dhabi.

Jarosch, C., Jahnke, P., Giehl, J., & Himmel, J. (2022). Modelling Decentralized Hydrogen Systems: Lessons Learned and Challenges from German Regions. *Energies*, *15*(4), 1322.

Kar, S. K., Harichandan, S., & Roy, B. (2022). Bibliometric analysis of the research on hydrogen economy: An analysis of current findings and roadmap ahead. *International Journal of Hydrogen Energy*.

Karayel, G. K., Javani, N., & Dincer, I. (2022). Hydropower energy for green hydrogen production in Turkey. *International Journal of Hydrogen Energy*.

Keller, V., Lyseng, B., Wade, C., Scholtysik, S., Fowler, M., Donald, J., Robertson, B., Wild, P., & Rowe, A. (2019). Electricity system and emission impact of direct and indirect electrification of heavy-duty transportation. *Energy*, *172*, 740-751.

Kırtay, E. (2010). Current status and future prospects of renewable energy use in Turkey. *Energy exploration & exploitation*, *28*(5), 411-431.

Löffler, K., Hainsch, K., Burandt, T., Oei, P. Y., Kemfert, C., & Von Hirschhausen, C. (2017). Designing a model for the global energy system—GENeSYS-MOD: an application of the open-source energy modeling system (OSeMOSYS). *Energies*, *10*(10), 1468.

Mahajan, D., Tan, K., Venkatesh, T., Kileti, P., & Clayton, C. R. (2022). Hydrogen Blending in Gas Pipeline Networks—A Review. *Energies*, *15*(10), 3582.

MENR (2018). *Turkey Electricity Demand Projection Report.* Available: https://enerji.gov.tr/eigm-raporlari

MENR (2021). *2020 National Energy Balance Table.* Available: https://enerji.gov.tr/eigm-raporlari

Miao, B., Giordano, L., & Chan, S. H. (2021). Long-distance renewable hydrogen transmission via cables and pipelines. *International journal of hydrogen energy*, *46*(36), 18699-18718.

Ministry of Energy, Government of Chile, 2020. C*hile National Green Hydrogen Strategy*. Santiago, Chile

Motalebi, S., Barnes, T., Kaspar, S., Niet, T., & Wright, A. S. (2021). Hydrogen to Provide Flexibility in The Canadian Energy System. . Energy Modelling Initiative.

Mutluel, F., & Sulukan, E. (2017). Reference energy system development for Turkish residential sector. In *Towards 100% Renewable Energy* (pp. 179-186). Springer, Cham.

Novo, R., Minuto, F. D., Bracco, G., Mattiazzo, G., Borchiellini, R., & Lanzini, A. (2022). Supporting Decarbonization Strategies of Local Energy Systems by De-Risking Investments in Renewables: A Case Study on Pantelleria Island. *Energies*, *15*(3), 1103.

Ozturk, M., & Dincer, I. (2021). Development of a combined flash and binary geothermal system integrated with hydrogen production for blending into natural gas in daily applications. *Energy Conversion and Management*, *227*, 113501.

Ozturk, M., & Dincer, I. (2022). Utilization of waste heat from cement plant to generate hydrogen and blend it with natural gas. *International Journal of Hydrogen Energy*.

Paris Agreement to the United Nations Framework Convention on Climate Change. (2015). T.I.A.S. No. 16-1104

Pingkuo, L., & Xue, H. (2022). Comparative analysis on similarities and differences of hydrogen energy development in the World's top 4 largest economies: A novel framework. *International Journal of Hydrogen Energy*, *47*(16), 9485-9503.

Razi, F., & Dincer, I. (2022). Renewable energy development and hydrogen economy in MENA region: A review. *Renewable and Sustainable Energy Reviews*, *168*, 112763.

REN21 (2021). *Renewables 2021 Global Status Report*. Paris: REN21 Secretariat. ISBN 978-3-948393-03-8

Republic of Turkey. (2015). *Intended Nationally Determined Contribution.* https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Turkey%20First/The_INDC_of _TURKEY_v.15.19.30.pdf

Russo, M. A., Carvalho, D., Martins, N., & Monteiro, A. (2022). Forecasting the inevitable: A review on the impacts of climate change on renewable energy resources. *Sustainable Energy Technologies and Assessments*, *52*, 102283.

Sandri, O., Holdsworth, S., Hayes, J., Willand, N., & Moore, T. (2021). Hydrogen for all? Household energy vulnerability and the transition to hydrogen in Australia. *Energy Research & Social Science*, *79*, 102179.

SHURA Energy Transition Center (2021a). *Priority Areas for a National Hydrogen Strategy for Turkey*. Istanbul.

SHURA Energy Transition Center (2021b). *Techno-economic Study of Turkey's Production and Export Potential for Green Hydrogen*. Istanbul.

Sorgulu, F., & Dincer, I. (2022). Analysis and techno-economic assessment of renewable hydrogen production and blending into natural gas for better sustainability. *International Journal of Hydrogen Energy*.

Stern, J. (2019). Narratives for Natural Gas in a Decarbonising European Energy Market. *Oxford Institute for Energy Studies.*

Şahin, Ü., Tör, O., Kat, B., Teimourzadeh, S., Demirkol, K., Künar, A., Voyvoda, E., & Yeldan, E. (2021). *Decarbonization Pathway for Turkey: Net Zero in 2050.* IPM. [online] Available at: https://ipc.sabanciuniv.edu/Content/Images/CKeditorImages/20220220-22020792.pdf

Tabkhi, F., Azzaro-Pantel, C., Pibouleau, L., & Domenech, S. (2008). A mathematical framework for modelling and evaluating natural gas pipeline networks under hydrogen injection. *International journal of hydrogen energy*, *33*(21), 6222-6231.

Taibi, E., Miranda, R., Vanhoudt, W., Winkel, T., Lanoix, J. C., & Barth, F. (2018). Hydrogen from renewable power: Technology outlook for the energy transition. *Abu Dhabi: International Renewable Energy Agency*.

TEİAŞ (2022). *Türkiye Elektrik Enerjisi 5 Yıllık Üretim Kapasite Projeksiyonu (Turkey Power Generation 5-Year Capacity Projection).* [online] Available at: https://www.teias.gov.tr/turkiye-elektrik-uretim-iletim-istatistikleri

TEİAŞ (2022). *Kurulu Güç Raporu (Installed Power Report).* [online] Available at: https://www.teias.gov.tr/tr-TR/kurulu-guc-raporlari

Telli, A. (2016). Akkuyu nuclear power plant from the perspective of energy security: A solution or a deadlock?. *Caucasus Int*, *6*, 151-166.

Tetik, H. (2022). Turkey Hydrogen Osemosys Data. Github. [online] Available at: tetikh/Turkey-hydrogen-osemosys-data (github.com)

Timmons, D., Dhunny, A. Z., Elahee, K., Havumaki, B., Howells, M., Khoodaruth, A., Lema-Driscoll, A.K.; Lollchund, M.R., Ramgolam, Y.K. & Surroop, D. (2019). Cost minimization for fully renewable electricity systems: A Mauritius case study. *Energy Policy*, *133*, 110895.

TSKB (2021). *Hidrojen Enerjisi Bilgilendirme Notu (Hydrogen Energy Information Document)*. Istanbul.

United Nations Framework Convention on Climate Change (UNFCCC) (2018). *UN Climate Change Annual Report.* [online] Available at: https://unfccc.int/resource/annualreport/media/UN-Climate-AR17.pdf [Accessed 10 Aug. 2022].

United Nations Framework Convention on Climate Change (UNFCCC) (2018). *Turkish GHG Inventory 1990-2019.* [online] Available at: https://unfccc.int/documents/271544

Vargas-Ferrer, P., Álvarez-Miranda, E., Tenreiro, C., & Jalil-Vega, F. (2022). Assessing flexibility for integrating renewable energies into carbon neutral multi-regional systems: The case of the Chilean power system. *Energy for Sustainable Development*, *70*, 442-455.

Velazquez Abad, A., Dodds, P. E. (2020). *Green hydrogen characterization initiatives: Definitions, standards, guarantees of origin, and challenges*. Energy Policy 2020;138: 111300.

White, L. V., Fazeli, R., Cheng, W., Aisbett, E., Beck, F. J., Baldwin, K. G., Howarth, P & O'Neill, L. (2021). Towards emissions certification systems for international trade in hydrogen: The policy challenge of defining boundaries for emissions accounting. *Energy*, *215*, 119139.

World Bank (2019), *World Development Indicators*. World Bank. Washington, DC. [online] Available at: https://databank.worldbank.org/data/download/GDP.pdf

World Nuclear Association (2022). *World Nuclear Performance Report 2022 Edition*. [online] Available at: https://world-nuclear.org/our-association/publications/global-trends-reports/world-nuclear-performance-report.aspx

Zhou, D., Yan, S., Huang, D., Shao, T., Xiao, W., Hao, J., Wang, C., & Yu, T. (2022). Modeling and simulation of the hydrogen blended gas-electricity integrated energy system and influence analysis of hydrogen blending modes. *Energy*, *239*, 121629.

APPENDIX A: DATA INPUTS

A.1 Capital Cost (MUSD/GW)

	BIOPP	GEOPP	HYDROPP	IGCC	NGCC	NUCPP	ELCTRLZR	PV	WIND
2020	2500	3750	2000	1100	750	7500	1400	650	900
2021	2500	3713	1980	1100	750	7426	1360	607	891
2022	2500	3676	1961	1100	750	7352	1320	568	882
2023	2500	3640	1941	1100	750	7279	1280	531	874
2024	2500	3604	1922	1100	750	7207	1240	496	865
2025	2392	3568	1903	1100	750	7136	1200	463	856
2026	2392	3533	1884	1100	750	7065	1160	433	848
2027	2392	3498	1865	1100	750	6995	1120	405	839
2028	2392	3463	1847	1100	750	6926	1080	378	831
2029	2392	3429	1829	1100	750	6858	1040	354	823
2030	2288	3395	1811	1100	750	6790	1000	340	815
2031	2288	3361	1793	1100	750	6722	960	329	807
2032	2288	3328	1775	1100	750	6656	920	317	799
2033	2288	3295	1757	1100	750	6590	880	307	791
2034	2288	3262	1740	1100	750	6525	840	296	783
2035	2288	3230	1723	1100	750	6460	800	286	747
2036	2288	3198	1706	1100	750	6396	760	277	732
2037	2288	3166	1689	1100	750	6333	720	267	718
2038	2288	3135	1672	1100	750	6270	680	258	704
2039	2288	3104	1655	1100	750	6208	640	249	690
2040	2210	3073	1639	1100	750	6147	600	241	677

A.2 Fixed Cost (MUSD/GW)

	BIOPP	GEOPP	HYDROPP	IGCC	NGCC	NUCPP	PV	WIND
All years	90	40	10	30	20	90	15	15

A.3 Variable Cost (MUSD/PJ)

	BIOPP	GEOPP	HYDROPP	IGCC	NGCC	NUCPP	PV	WIND
All years	3.60	36.00	0.36	14.40	3.60	18	15.48	1.80

A.4 Fuel Importation and Production Variable Cost (MUSD/PJ)

	BIOIMP	COIMP	NGIMP
2020-2029	74.86	42.68	154.89
2030-2044	74.86	53,05	174.69
2045-2050	74.86	63.64	234.48

A.5 Residual Capacity (PJ)

	BIOPP	GEOPP	HYDROPP	IGCC	NGCC	PV	WIND
2020	1.182	1.515	28.544	20.284	25.669	6.105	7.762
2021	1.514	1.624	31.327	20.323	25.700	6.964	9.361
2022	1.455	1.573	30.588	19.613	24.366	6.621	8.935
2023	1.396	1.523	29.850	18.904	23.033	6.279	8.509
2024	1.337	1.472	29.111	18.194	21.699	5.936	8.084
2025	1.278	1.422	28.373	17.485	20.366	5.593	7.658
2026	1.219	1.371	27.634	16.775	19.033	5.250	7.233
2027	1.160	1.321	26.895	16.066	17.699	4.908	6.807
2028	1.100	1.270	26.157	15.356	16.366	4.565	6.381
2029	1.041	1.220	25.418	14.647	15.032	4.222	5.956
2030	0.982	1.169	24.680	13.937	13.699	3.879	5.530
2031	0.923	1.119	23.941	13.228	12.365	3.537	5.105
2032	0.864	1.069	23.203	12.519	11.032	3.194	4.679
2033	0.805	1.018	22.464	11.809	9.699	2.851	4.254
2034	0.746	0.968	21.725	11.100	8.365	2.509	3.828
2035	0.687	0.917	20.987	10.390	7.032	2.166	3.402
2036	0.628	0.867	20.248	9.681	5.698	1.823	2.977
2037	0.569	0.816	19.510	8.971	4.365	1.480	2.551
2038	0.509	0.766	18.771	8.262	3.031	1.138	2.126
2039	0.450	0.715	18.032	7.552	1.698	0.795	1.700
2040	0.391	0.665	17.294	6.843	0.364	0.452	1.274

APPENDIX B: Technology Specification

Technology	*Description*
BIOIMP	Biomass and waste import and production
BIOPP	Biomass Power Plants
COIMP	Coal import and production
ELTD	Electricity transmission &distribution
GEOPP	Geothermal Power Plants
H2TD	Hydrogen gas transmission & distribution
HYDROPP	Hydropower plants
IGCC	Coal-Integrated gasification combined cycle (Coal power plants)
NGIMP	Natural gas import and production
NGTD	Natural gas transmission & distribution
NGCC	Natural Gas power plants
NUCPP	Nuclear Power Plants
ELCTRLZR	PEM electrolyzer
PV	Utility scale photovoltaic plants (solar power plants)
RENELCONV	Renewable electricity to electricity (this technology used as a dummy technology, so that hydrogen can be produced only by renewable sources)
TANK	Technology linked to hydrogen storage (STO)
URIMP	Uranium import and production
WIND	Wind power plants

CURRICULUM VITAE

Personal Information

Name and surname: Hepnur Tetik

Academic Background

Master’s Degree Education: Energy and Sustainable Development, Kadir Has University, Istanbul, Turkey, 2020-2022

Bachelor’s Degree Education: Industrial Engineering, Galatasaray University, Istanbul, Turkey, 2014-2019

Foreign Languages: English, French

Work Experience

Mobile Solutions Specialist, Samsung Electronics Turkey, August 2019-September 2020