KADİR HAS UNIVERSITY
SCHOOL OF GRADUATE STUDIES
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# DECARBONIZATION PATHWAYS FOR TURKISH POWER SYSTEM USING THE LEAP MODEL

FATMA ECE ÖZER

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APPROVED BY:

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

Prof. Dr. Ahmet Deniz Yücekaya (Co-advisor) ......................
Kadir Has University

Assist. Prof. Dr. Emre Çelebi ......................
Yeditepe University

Prof. Dr. Volkan Ş. Ediger ......................
Kadir Has University

Prof. Dr. Gülgün Kayakutlu ......................
Istanbul Technical University

I certify that the above signatures belong to the faculty members named above.

......................
Prof. Dr. Mehmet Timur AYDEMİR
Dean of School of Graduate Studies
DATE OF APPROVAL: 13.08.2021

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# ABSTRACT

The negative impact of GHG released into the atmosphere on global warming cannot be ignored. Fossil-fueled power plants constitute a large part of Turkey's electricity production, as every country has a growing economy. Therefore, the electricity generation sector accounts for a significant portion of GHG emissions in Turkey. In addition to national bindings such as the Paris Agreement and the Kyoto Protocol, it is known that the Republic of Turkey aims to make not only electricity but also energy production greener in the coming years, in line with its own efforts. For this purpose, there are different modeling studies in the literature. This thesis aims to model Turkey's electricity generation sector in 2017, reveal the current situation, and then analyze how a greener and sustainable energy transformation will be possible with different scenarios and different main factors. In this direction, Turkey's electricity generation sector was modeled using the LEAP tool, then the decarbonization scenarios created within the openENTRANCE project were adapted to Turkey's data, and the numerical results of the scenarios were compared. As a result, it has been revealed that social awareness, adaptation to new technologies, and incentives of decision-makers are all critical factors in this regard.

**Keywords: energy modeling, net-zero pathways, OSeMOSYS, carbon emission reduction scenarios, LEAP, Turkish electricity market**

# LEAP MODELİ KULLANILARAK TÜRKİYE ELEKTRİK SİSTEMİ İÇİN DEKARBONİZASYON YOLLARI

## ÖZET

Atmosfere salınan GHG'in küresel ısınmaya olan olumsuz etkisi göz ardı edilemez. Fosil yakıtlı elektrik üretim santralleri, ekonomisi büyümekte olan her ülke gibi Türkiye'nin de elektrik üretiminin büyük bir kısmını oluşturmaktadır. Dolayısıyla, elektrik üretim sektörü Türkiye'deki GHG salınımının önemli bir kısmını meydana getirmektedir. Paris Anlaşması ve Kyoto Protocol'ü gibi ulusal bağlayıcıların yanı sıra Türkiye Cumhuriyeti Devleti'nin kendi yaptığı çalışmalar doğrultusunda önümüzdeki yıllarda sadece elektrik değil enerji üretimini de daha yeşil hale getirmeyi amaçladığı bilinmektedir. Bu amaçla literatürde yapılan farklı modelleme çalışmaları bulunmaktadır. Bu tezin amacıysa, Türkiye'nin 2017 yılındaki elektrik üretim sektörünü modelleyerek, güncel durumun gözler önüne serilmesi ve ardın-dan oluşturulan farklı senaryolar, farklı ana etkenlerle daha yeşil ve sürdürülebilir enerji dönüşümünün nasıl mümkün olacağını analiz etmektir. Bu doğrultuda, LEAP aracı kullanılarak Türkiye'nin elektrik üretim sektörü modellenmiş, ardından openENTRANCE projesi kapsamında oluşturulan dekarbonizasyon senaryoları Türkiye verilerine uyarlanmıştır ve senaryoların sayısal sonuçları karşılaştırılmıştır. Bunun sonucunda sosyal farkındalık, yeni teknolojilere adaptasyon ve karar-alıcıların teşviklerinin üçünün de bu doğrultuda önemli etkenler olduğu ortaya konmuştur.

**Anahtar Sözcükler: enerji modellemesi, net-sıfır senaryoları, OSeMOSYS, karbon emisyonu azaltma senaryoları, LEAP, Türkiye elektrik piyasası**

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To Ali and my family...

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# LIST OF SYMBOLS/ABBREVIATIONS

| | |
|---|---|
| CC | Combined Cycle |
| CCS | Carbon Capture and Storage |
| $CO_{2eq}$ | Carbon Dioxide Equivalent |
| DT | Directed Transition |
| GD | Gradual Development |
| GDP | Gross Domestic Product |
| GHG | Green House Gases |
| GWP | Global Warming Potential |
| KTOE | Kilotonnes of Oil Equivalent |
| LEAP | Long Range Energy Alternatives Planning |
| MENR | Ministry of Energy and Natural Resources |
| IEA | International Energy Agency |
| IGCC | Integrated Gasification Combined Cycle |
| IPP | Independent Power Producer |
| SC | Societal Commitment |
| TF | Techno-Friendly |

# 1. INTRODUCTION

As countries develop socially and economically, their energy consumption and energy demands increase in direct proportion to this development. As (Stern, 2003) stated, it can be said that the per capita energy consumption of developed countries is higher than in less developed countries. In the graph below, Bangladesh, Turkey, and China have been chosen to represent the underdeveloped, developing, and developed countries, respectively, to compare the annual GDP and energy consumption values. The fact that the final energy consumption values in Figure 1.1 and the GDP values in Figure 1.2 change directly supports the aforementioned assumption. (Chontanawat et al, 2008) For instance, in 1990, Turkey's energy consumption was 40392 KTOE, and this value increased to 102960 KTOE in 2018 and where it is also seen that the GDP values are also increasing in this period.

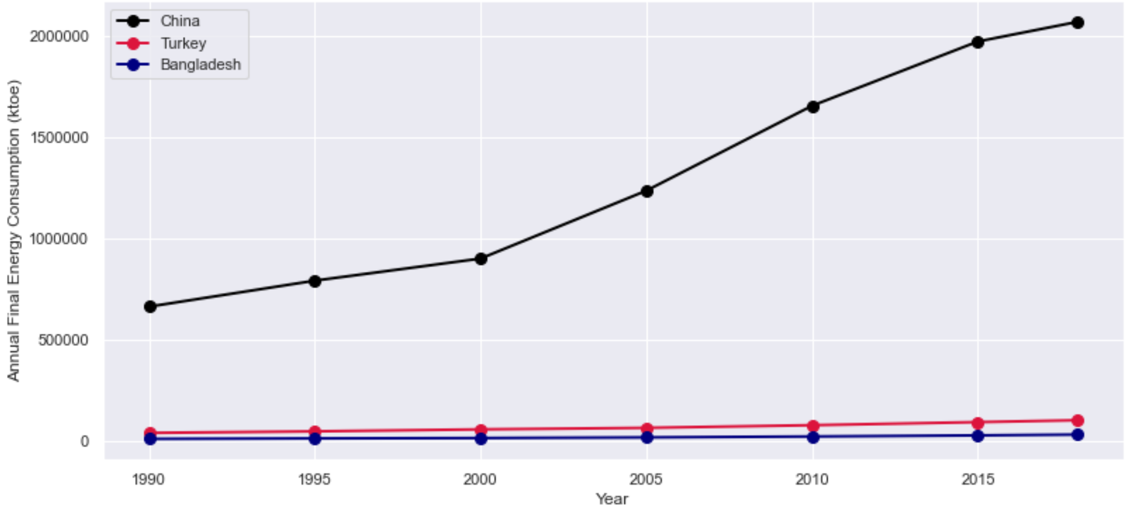


**Figure 1.1** Annual Energy Consumption by Country

Source: The International Energy Agency

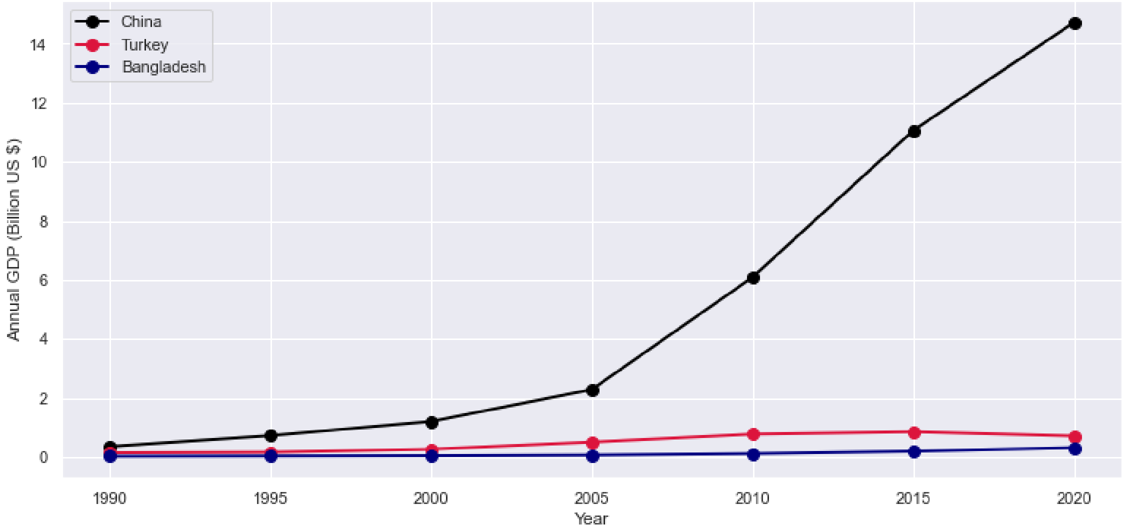


**Figure 1.2** Annual GDP by Country

Source: The World Bank Open Data

For years, countries have preferred relatively cost-effective and efficient resources to meet their increasing energy demands. For example, coal, oil, and natural gas have been among the most preferred energy resources for years. Figure 1.3 shows the energy production from different resources. As can be clearly seen from the graph, the demand for fossil fuels has increased gradually. However, since fossil fuels are greenhouse gas-emitting fuels, as their use increases, the CO2 emission levels of the countries have gradually become severe. As seen in Figure 1.4, CO2 emission values have gradually reached dangerous levels as countries prefer fossil fuels for energy production.

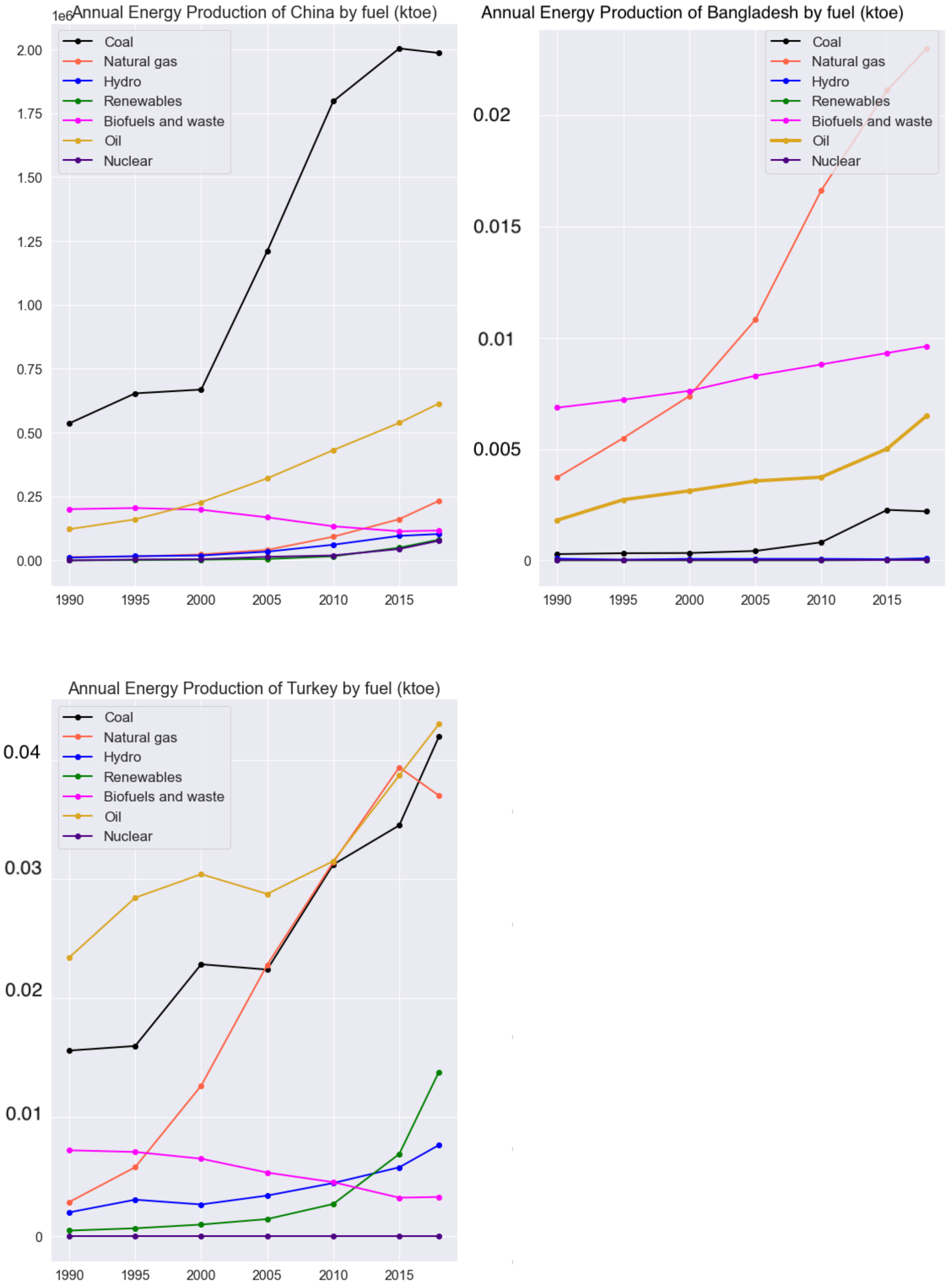


**Figure 1.3** Annual Energy Production by Source

Source: The International Energy Agency

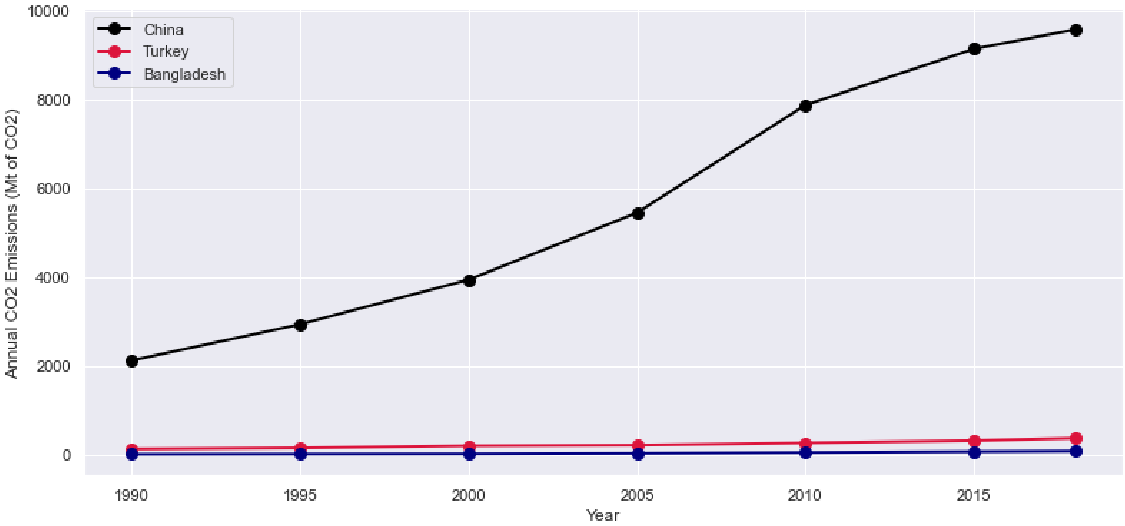


**Figure 1.4** Annual $CO_2$ Emissions

Source: The International Energy Agency

After the carbon emissions reached severe levels, countries decided to take measures to reduce their carbon emission values. Regional and global targets have been set to reduce carbon emissions in the world and especially in Europe. It is possible to say that Europe is a pioneer in this regard. The Kyoto Protocol and the Paris Agreement are among the important works that officialize these goals. Turkey has also started to follow various ways to reduce carbon emissions in energy production in order to adapt to the European Union's sustainable energy portfolio and decarbonization goal. Turkey's electricity demand has increased rapidly in recent years, and electricity generation to meet this demand has also increased proportionally. This growth in electricity generation has increased carbon emissions with the effect of the resources used. According to Energy Exchange Istanbul (EXIST)'s 2020 report, 36% of electricity generation is produced by fossil fuels at the end of December (EXIST, 2021). The increasing demand for electricity in parallel to speed up Turkey's economic development is an expected result. Accordingly, if the use of existing resources continues, an increase in carbon emissions is inevitable. It is accepted that the increase in demand, primarily arising from industrial growth, will continue despite the increase in energy efficiency. Some studies are being done to slow down or even stop this increase. The Kyoto Protocol and the Paris Agreement are among the important ones.

The first global agreement aiming to control greenhouse gas emissions is the Kyoto Protocol signed in 1997. In the Protocol, which also forms a basis for the Paris Agreement, the targets to be set by the developed countries emphasized. Paris Agreement was opened for signature at the Center of United Nations in the USA between the 22 April 2016 and 21 April 2017. (Kyoto Protocol Reference Manual On Accounting Of Emissions And Assigned Amount, 2008) With the Paris Agreement, which entered into force in November 2016, an important step is taken to fight against global climate change. (Paris Agreement, 2016) The agreement, signed by almost all countries globally, entered into force after being ratified by 55 countries responsible for 55% of the world's total emissions. Turkey's participation in the Paris Agreement is vital by being Turkey's first greenhouse gas emission reduction target. (Paris Agreement, 2016) The agreement's primary purpose was stated as "to keep the increase in global temperatures below 2 ° C and to make all efforts to limit this increase to 1.5 ° C" (UNFCCC, 2016). Turkey delivered the National Contribution Statement of Intent in September 2016 and has signed the deal in April of the same year. However, the deal has still to be approved by the Grand National Assembly of Turkey to become official. In the National Contribution Statement presented by the Republic of Turkey in the United Nations Framework Convention on Climate Change Secretariat (UNFCCC), a 21% reduction target is envisaged between 2020 and 2030 compared to the baseline scenario (UNFCCC, 2019).

In addition to these international agreements and goals, the Ministry of Energy and Natural Resources (MENR) are regularly working since 2009 to determine Turkey's five-year periods' energy targets. These studies are shared with the public every five years under the name of Strategic Plan. For example, in the Strategic Plan published in 2019, it is stated that it is aimed to increase the ratio of the installed capacity of electricity plants based on domestic and renewable energy sources to the total installed power from 59% to 65% until 2023. (Strategic Plan, 2019) The same report also includes targets such as implementing technological transformation practices in the electricity sector and continuing efforts to increase energy efficiency. In line with the aforementioned agreements, it is obvious that some planning should be done in order to comply with the decarbonization target. According to the International Energy Agency, in 1990, Turkey's $CO_2$ emission was 128 Mt $CO_2$. This value has increased to 369 Mt $CO_2$ with 161 Mt $CO_2$ from coal, 115 Mt $CO_2$ from oil, and 93 Mt $CO_2$ from natural gas in 2018. According to a study conducted by Özer et al. (2013), if not taken any action related to decarbonization targets in the energy sector, Turkey's total $CO_2$ emissions in 2030 are expected to exceed 425.147 Mt $CO_2$. Moreover, looking at the actual value in 2018, it can be anticipated that the $CO_2$ emission in 2030 will be much more than the projected value. In this context, considering Turkey's booming economy, energy import dependency and, growing demand for electricity, short-medium-long term electricity capacity plans should be made.

Turkey's future energy outlook should be created and analyzed with different scenarios by energy system modeling. With the scenarios and analysis results, the steps to be taken for decarbonization can be determined properly. Modeling energy systems is vital to generate different insights and analyses of a country's current and future energy supply and demand. Knowing a country's possible future energy outlook is necessary for making policies on energy security, energy efficiency, energy supply, and greenhouse gas (GHG) emission mitigation. Therefore, there are various common software tools used in the field of energy modeling. In this study, Low Emission Analysis Planning 2020 (LEAP 2020), developed by Stockholm Environment Institute (SEI) for energy policy analysis and climate change mitigation assessment and widely used by many researchers and institutions, is used. LEAP is an integrated, scenario-based energy modeling tool incipiently designed to track energy consumption, production, and resource extraction in every sector of an economy (Heaps et al., 2021).

## 1.1 Contribution of the Study

Based on the Turkish electricity sector situation in 2017, this thesis aims to reduce Turkey's carbon emission values in 2050 to zero with different scenarios. For this purpose, four scenarios (Directed Transition, Societal Commitment, Techno-Friendly, Gradual Development) created within the scope of the openENTRANCE project were adapted to Turkey, taking into account Turkey's energy and especially electricity outlook. openENTRANCE aims at developing and disseminating an open, transparent, and integrated modeling platform for evaluating low-carbon transition pathways in Europe. The EU has set an ambitious goal to decrease greenhouse gas emissions to the point of achieving climate neutrality by 2050 and prevent the adverse and unchangeable effects of climate change. This goal involves changing the energy system to a renewable and clean design and technological, behavioral, and organizational changes in the economy and society. To achieve these, the coordination of proper technologic solutions, policies, funding, and participants, with well-defined targets based on analyses, will be needed. (Storylines for Low Carbon Futures of the European Energy System, 2019) In this regard, they created different pathways. This thesis aims to analyze what actions can be taken to decarbonize Turkey's electricity sector and to analyze the results of different pathways for this purpose. What steps should be taken, and which technologies/fuels should be incentivized or which fuels should phase out to decarbonize Turkey's electricity sector? Four different scenarios, created within the scope of the openENTRANCE project, were adapted to the Turkish electricity system to answer these questions. Then the results were compared with the cost, capacity, electricity generation by fuel, and emission values. Hence, all modeling was done on the LEAP and then solved with Gurobi Optimizer. Detailed information about the programs used is given in Chapter 3.

The rest of the paper is organized as follows. In Section 1.2, the energy models in the literature were analyzed in two stages, as those in Turkey and those in similar countries. In Chapter 2, the changes and developments in Turkey's electricity sector from past to present, fuels used, and annual carbon emission values are discussed. In Chapter 3, the data collection process and the programs used in the project are mentioned in detail. In this chapter, the storylines, numerical values, and results of the scenarios created are detailed. Finally, the findings of this study are summarized and discussed in Chapter 4.

### 1.2 Literature Review

In the literature, there are several models and analyzes generated using LEAP. For instance, Kale and Pohekar (2014) have developed an electricity demand and supply analysis presented between 2012 and 2030 for India's Maharashtra state. The electricity demand analysis had done by using a statistical method and by generation four different scenarios. Holt's exponential smoothing method (ARIMA) was used to find growth rates as the first method. Rests of the scenarios were generated considering GDP and varying values of elasticity demand. Authors generated three different scenarios on the supply side for power generation: Business as Usual (BAU), Energy Conservation (EC), and Renewable Energy (REN). The scenarios compared the perspectives of demand projections, electricity generation, GHG emissions, and cost analysis. Also, sensitivity analysis has been done to study the effect of varying parameters on the scenarios' total cost. As expected, the REN has the least GHG emissions, and the BAU has the most. REN is the most expensive scenario, while the EC is economical. However, the sensitivity analysis states that with the increase in fuel and technology costs, there is a cost increase in all scenarios. The increase in REN cost is comparatively less than BAU and EC. Therefore, this study suggests applying the REN scenario pathway to meet Maharashtra's future electricity demand, considering both $CO_2$ emission goal and long-term costs of the fuels and technologies.

In another study, Ibrahim and Kirkil (2018), generated three different scenarios between 2010 and 2040: Business as Usual (BAU), Energy Conservation (EC), and Renewable Energy (REN) to find a solution to the power outages in Nigeria. Projections of the three scenarios are in terms of electricity demand and supply, GHG emissions and cost analysis. The scenario results compared with the total energy consumption, $CO_2$ emission and costs. According to the numerical results of the LEAP model, the REN scenario has the least GHG emission value by 2040 but has the most fixed and variable costs. Since the EC scenario has the least electricity demand and supply and costs by 2040, the authors propose that EC is the most realistic scenario to apply to solve the electricity supply problem of Nigeria.

Furthermore, Huang et al. (2011), provided an overview of energy supply and demand in Taiwan by applying a LEAP model of Taiwan's energy sector. To analyze the energy sector, they created five scenarios: Business as Usual (BAU), Government's Target (GOV), Financial Tsunami (FIN), Retirement (RET), and Combination of All Scenarios (ALL). In the GOV scenario, the government's energy conservation target (enhancing energy efficiency by over 2% annually through 2025) is applied. In the FIN scenario, the authors assumed that the recent "financial tsunami" would result in comprehensive effects on Taiwan's economic growth, and applied lowered economic growth assumptions in the medium and long term on energy use. In the RET scenario, it is assumed that the existing nuclear power plants of Taiwan are retired. Moreover, as the last one, the ALL scenario consisted of all of the previous cases. The Taiwan LEAP model is used to compare future energy demand and supply patterns and greenhouse gas emissions, for several alternative scenarios of energy policy and energy sector evolution. According to the LEAP model results, this article states that the retirement of existing nuclear power plants as scheduled (RET) harms the energy supply (increasing the need for coal and other fossil fuels) and increases emissions. The rest of the scenarios result in significantly reduced energy demand by 2030. Therefore, this study highlights that unless alternative energy sources can be developed to fill the gap, nuclear power is a must in Taiwan's energy agenda in coping with global warming.

After looking at the generated models created for different countries, we can now look at the LEAP models generated for Turkey. Ates (2015) focused on the energy efficiency, and emission reduction potential of the iron and steel industry in Turkey from 2010 to 2030. The author have created four different scenarios: Business as Usual (BAU), Slow-speed Energy Efficiency Improvement (SEI), Accelerating Energy Efficiency Improvement (AEI), and Cleaner Production and Technology (CPT) scenarios. After analyzing the scenario results, the study found that the energy intensity rate can be lowered by 13% in SEI, 38% in AEI, and 51% in CPT scenario. The study also highlights the fact that improvements in energy efficiency are highly linked to the governmental policies and actions along with the industries' endeavors. Given the high energy import bill, high energy intensity rates, challenges associated with the post-Kyoto agreement, intensifying pressure regarding global economic competition, and environmental regulations, Turkey has to propose a comprehensive energy efficiency action map that should include new regulations on energy efficiency activities.

In another study, Özer et al. (2013) created two different scenarios based on the composition and structure of electricity and fuel use to analyze the reduction of emissions in Turkey's electricity sector between 2006 and 2030 by using the LEAP model. Business as Usual (BAU) and Mitigation Scenarios represent a different development path possible in Turkey's electricity sector due to various policies. A common net demand projection for future power generation is assumed to be the same among the scenarios, and gross electricity production is established for each scenario. This study's results imply that electricity demand and associated $CO_2$ emission in Turkey will rise in both scenarios due to economic growth. Emissions under the BAU scenario will rise significantly, while the Mitigation Scenario increases slower. This study presents comparative results for decision-makers to develop national strategies for establishing a long-range policy for emissions mitigation in Turkey's electricity sector, which may then be discussed in climate change negotiations.

In another study, which is called Decarbonization of Turkish Public Electricity Sector: Adopting Sustainable Energy Portfolio, the author aimed to decarbonize the Turkish public electricity sector from 2011 until 2050 via LEAP by scenario analysis. (Şahin, 2014) In this regard, the author created four different scenarios. The first one is Reference Scenario (BAU), which states the current strategies in the public electricity sector. The second one is the No Privatization(NP) scenario, which maintains the installed electricity generation capacity of 2012, the base year of the study. Additionally, sustainable energy portfolios are offered in the Nuclear Energy (NE) and Renewable Energy (RE) scenarios. In conclusion, the RE scenario distinguishes itself by its low projected costs and its expanded energy portfolio.

Also, in 2019 (Massaga et al., 2019) published a study called A Comparative Study of Energy Models for Turkish Electricity Market Using LEAP. In this study, the authors considered three scenarios in the shift to renewable energy for Turkey; the Business As Usual (BAU), Energy Conservation (EC), and Renewable Energy (REN) scenarios. EC scenario holds energy-efficient appliances and requiring a carbon tax, whereas the REN scenario considers increasing the share of the renewable energy sources as much as possible in the power generation mix. These scenarios were assessed in terms of cost and environmental impact. The REN scenario is Turkey's optimal energy policy option in terms of cost and environmental impact.

There are also numerous studies in the literature which are modeled the Turkish electricity sector without LEAP. One of the most recent of these is Turkey Energy Outlook 2020, published in November 2020 by IICEC. (IICEC, 2020) This study aims to offer policies to increase the use of domestic energy resources, improve energy efficiency, create green energy infrastructure, develop a more ambitious energy market with cost-reflective energy pricing, and support all essential steps towards reaching a sustainable energy system in Turkey. In this regard, they created two different scenarios. One is the reference scenario representing the business as usual situation, and the other is the alternative scenario that considers additional policy initiatives that, while cost-effective, require more challenging policy barriers to be overcome to complete energy policy goals, including efficiency, competitiveness, and sustainability. As a result, in both scenarios, IICEC projects an increased share of renewables and nuclear in the power sector, more use of electricity, natural gas, and renewables in all energy end-use sectors, and increased efficiency in every aspect of energy production, transformation, and use. The Reference and Alternative Scenarios differ in how much and how fast these gains can be realized with the more robust energy policies assumed for the Alternative Scenario.

In 2017, (Sulukan et al., 2017) developed a model for Turkey based on the MARKAL energy system model and used it to analyze potential technological pathways Turkey could take between 2005 and 2020. According to the findings of their model, Turkey's reliance on imported fuels would be reduced if indigenous renewable energy resources were heavily preferred, but more importantly, the entire energy system should be refurbished in tandem with Turkey's national energy strategies. The analyses also advise that energy efficiency measures should be implemented across all energy technologies, all major demand sectors, and transmission and distribution operations and that Turkey should aim to improve cogeneration practices in order to reduce both demand and prices.

After reviewing many studies based on the modeling method, the claim should be remembered which is widely known in the fields of statistics and modeling, "All models are wrong." (Box, 1976). Thus, it cannot be said that aforsaid studies and their predictions are absolutely correct. In conclusion, as in previous studies, the aim of this study is to gain insights into Turkey's future energy outlook and give policy recommendations.

# 2. A GLANCE AT TURKISH POWER SECTOR

## 2.1 Milestones in Turkish Electricity Market

Electricity markets are evolving from a monopolistic system to a competitive one. The liberalization of electricity markets started after 1980 in many countries, and Turkey is one of these countries. Electricity markets are generally composed of production, transmission, and distribution levels. The vertically integrated utility has been observed in electricity markets until the 1980s since production in the electricity market is capital intensive and requires a specific scale size, and the product cannot be stored. Electrical energy is in the compulsory need class. The electricity industry, which has a vertically integrated structure before 1980, is being restructured in the post-1980 period with the privatization moves adopted by many countries. Turkey applying this privatization moves in the sector is one of the countries that want to gain a competitive structure for the electricity sector. With the implementation of the reform in electricity markets, it is aimed to increase economic efficiency by making the markets competitive. The privatization of state-owned services characterizes the reform process in the electricity markets through a corporation, the adoption of electricity reform laws, the separation of production, transmission, and distribution from the vertically integrated structure, the establishment of an independent regulator, the establishment of a competitive wholesale market and the liberalization of the retail market.

1960 period in Turkey, the production, transmission, distribution, and trading activities related to the electricity sector, will be brought under the control of public authorities as a whole. In line with this goal in 1970, TBMM introduced a new market, Law No. 1312, to establish electricity production, distribution, and transmission in Turkey, the Turkish Electricity Institution (TEK) was established. TEK maintains all activities in the electricity market under its supervision. Therefore, this organization has established a vertically integrated structure of the electricity market in Turkey. With Law No. 2705, the first change in Turkey's vertically integrated electricity market structure occurred in 1982. Thanks to this law, the authority to set up a power plant in Turkey is also given to the private sector after government organizations. The first step about the transition from a vertically integrated structure to a competitive structure in the electricity market in Turkey began with this amendment carried out in the production process. Liberalization of the electricity market in Turkey has continued with the Law No. 3096 issued in 1984. TEK was divided into two in 1994. Turkey Electricity Generation Transmission Company which is responsible for transmission in the electricity market (TEAŞ), and Turkey Electricity Distribution Company (TEDAŞ) which is responsible for the distribution of electricity in Turkey, were founded. With the decision taken in 2001, TEAŞ was divided into three independent sections. These include Turkey Electricity Transmission Inc. (TEIAŞ), Turkey Electricity Generation Inc. (EÜAŞ), and Turkey Electricity Trading and Contracting Inc. (TETAŞ). In Figure 2.1 you can see the transformation from a vertically integrated structure to a competitive model.

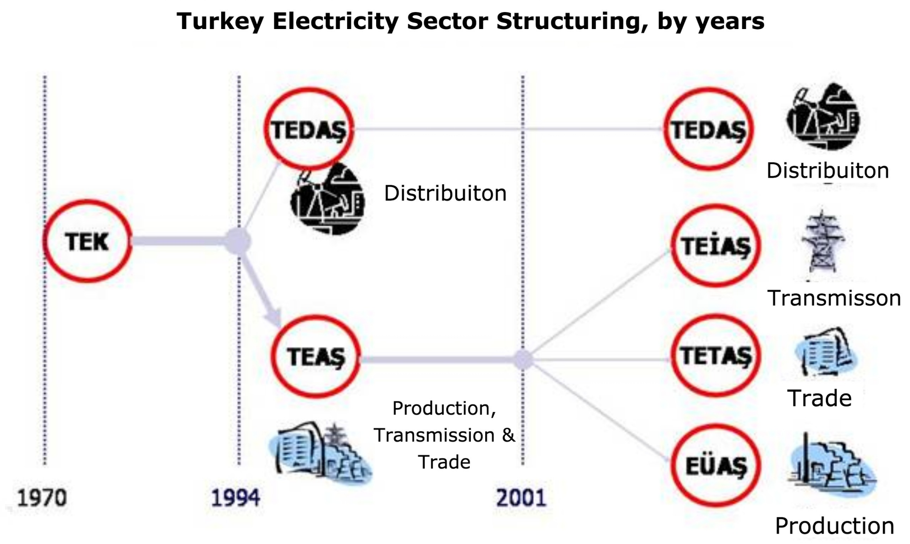
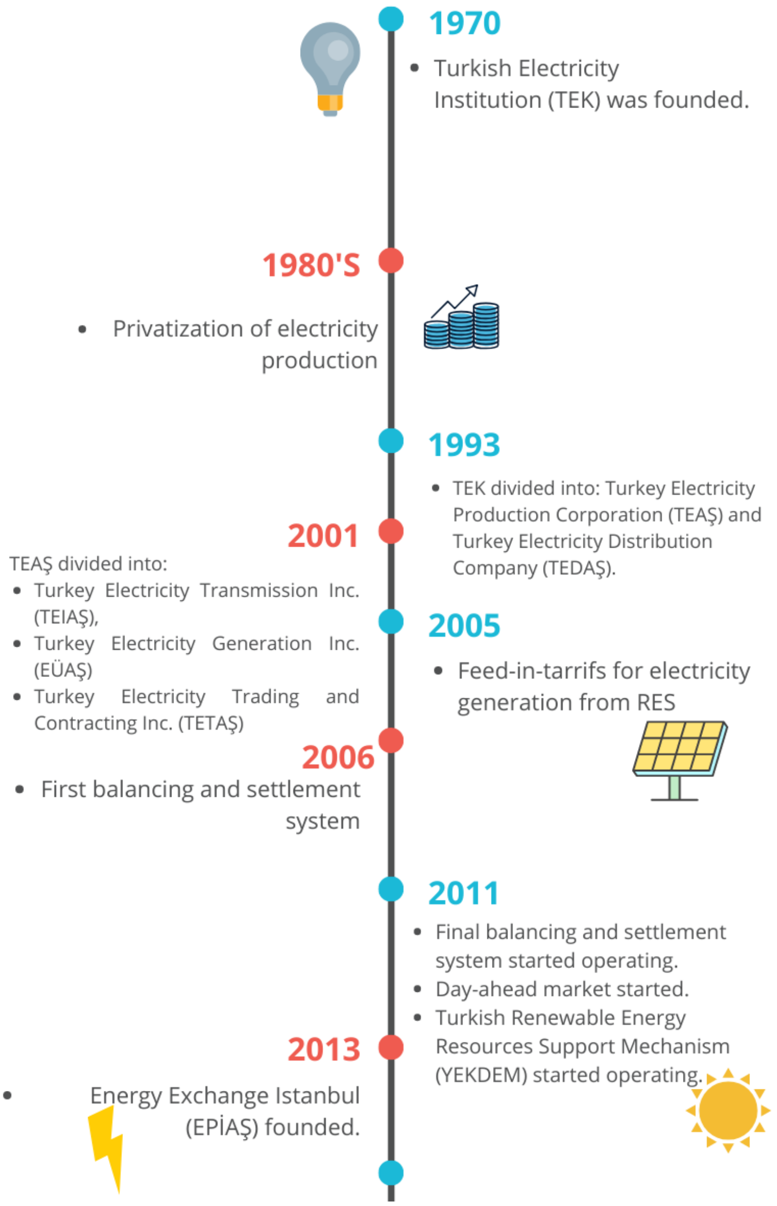

Turkey Electricity Sector Structuring, by years

**Figure 2.1** Turkey Power Sector Structuring

The Energy Markets Regulatory Authority (EMRA) was established to regulate the energy market with Law No. 4628. In 2005 TBMM passed a bill for renewable energy (Law No.5346) offering a fixed feed-in tariff (FIT) for renewable energy generation. The promotion legislation envisaged FIT for a total of 10 years of operation with upper and lower limits. Both caps corresponded respectively to 5.0 and 5.5 cents per kWh. FIT has been set at the same rate as the EMRA calculated Turkish average wholesale price. Since 2001, there have been some notable improvements in the market. Law No. 6446 provides for tandem progress in liberalization and privatization. Therefore, while the market continues to liberalize, production and distribution facilities owned by the state are being privatized. The government anticipates completing the privatization of the generation plants owned by the state by the end of 2014. As of August 2006, the balancing and settlement process began operating. Since then, market mechanisms have created electricity prices for the first time in Turkey's history. The impacts of this application have shown that due to increased demand and unusual climate conditions, there is a trend for prices to increase. Since December 1 2011, the final settlement and balancing system have been in operation. The new system is based on the market day-ahead and hourly settlement, with the demand side also taking part. Two system marginal prices are determined and recorded according to the new system: one is for the day-ahead market, and the other is for setting in real-time. Moreover, the operation of the RES support mechanism (YEKDEM) began on December 1, 2011. In Figure 2.2, milestones of the Turkish Electricity Market can be seen.



- Turkish Electricity Institution (TEK) was founded.

- Privatization of electricity production

- TEK divided into: Turkey Electricity Production Corporation (TEAŞ) and Turkey Electricity Distribution Company (TEDAŞ).

TEAŞ divided into:
- Turkey Electricity Transmission Inc. (TEIAŞ),
- Turkey Electricity Generation Inc. (EÜAŞ)
- Turkey Electricity Trading and Contracting Inc. (TETAŞ)

- Feed-in-tarrifs for electricity generation from RES

- First balancing and settlement system

- Final balancing and settlement system started operating.
- Day-ahead market started.
- Turkish Renewable Energy Resources Support Mechanism (YEKDEM) started operating.

- Energy Exchange Istanbul (EPİAŞ) founded.

**Figure 2.2** Milestones of Turkish Power Sector

### 2.1.1 The Current Situation in Turkish Electricity Market

Considering the main developments, we can divide the Turkish electricity market into three stages by using the study of PwC titled Overview of Turkish Electricity Market. (PwC,2020) The 1920s-1960s is The Early Market Stage, which includes state-funded and privately backed activities established to expand electricity generation throughout the country. In this stage, the lack of long-term planning and regulations has come to the fore. The second stage is the Structuring Stage, which covers the 1960s-2000s. During this period, long-term planning and significant capacity increases in power plants were made. In addition to these, the beginning of the liberalization of the market is also in this stage. Finally, Growth Stage, which dates back to the 2000s, can be regarded as having started with the Turkish Electricity Market Law enactment. Following this, the electricity market has become more coordinated with establishing the Energy Market Regulatory Authority (EMRA). After privatizations, the market began to be dominated by independent power producers (IPPs).(PwC,2020)

Considering the aforementioned developments in the Turkish electricity market, if we take a look at the electricity demand and supply in 2017, base year of this study;

According to the data obtained from the Ministry of Energy and Natural Resources (MENR), the total electricity demand of Turkey in 2017 is 21257 KTOE. The allocation of demand by sectors is shown in Figure 2.3. Subsequently, 72.8% of the total electricity demand comes from the industry and commercial sectors. Most of the remaining demand consists of residential demand. In 2017, electricity demand in the transportation sector was limited to only 111 KTOE. However, it is foreseen that the demand for electric energy in the transportation sector will increase in the future due to initiatives such as Turkey's plans to produce its own electric car in 2023 and the use of electric public transportation vehicles. Nevertheless, it is anticipated that the transportation sector's share in electricity demand will not increase significantly, especially for medium-targeted studies. (PwC,2020)

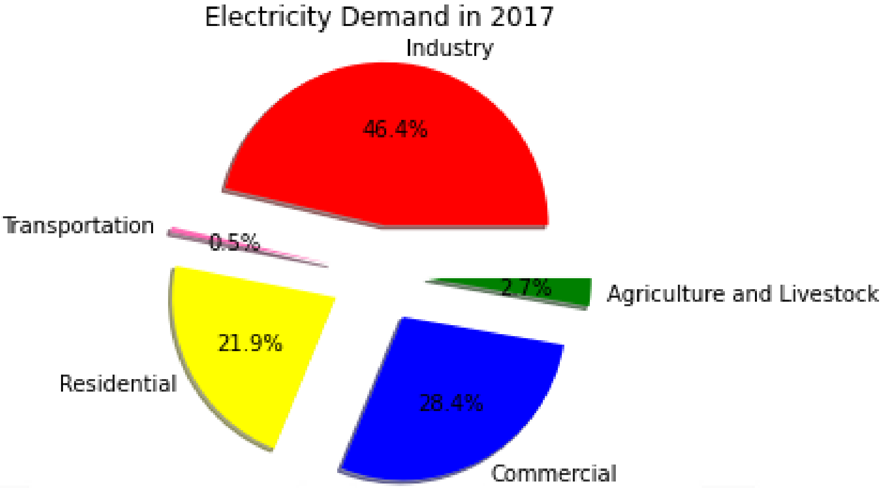


**Figure 2.3** Electricity Demand of Turkey by Sector, 2017

Source: EXIST

In 2017, 2898.5578 Million MWh of electricity was produced to meet the electricity demand of 21257 KTOE. As seen in Figure 2.4 prepared from EXIST data, 37.67% of electricity production in 2017 was produced from natural gas. Following this, Hydro with a share of 20.05%, Imported Coal with a share of 17.56%, and Lignite with a share of 13.79% was the most used fuel in electricity generation. On the contrary, the share of renewable resources in total production remained at 28.6%. According to the National Renewable Energy Action Plan published by EMRA, it is intended to increase the share of renewable energy sources in electricity generation to 38.8% in 2023 by increasing the number of power plants using renewable energy sources and expanding the capacity of existing ones. (MENR, 2019)

Figure 2.5 supports this claim as it can be certainly noticed that the electricity sector is dominating the annual $CO_2$ emission of Turkey. While look at the annual $CO_2$ emissions from 1990 to 2015, it is recognized that the electricity sector quickly left behind the industry and transportation sectors that were close to it in the first years. Furthermore, as shown in Figure 2.5, it can easily be said that this increase in $CO_2$ emissions is due to the use of coal and gas in electricity and heat generation.

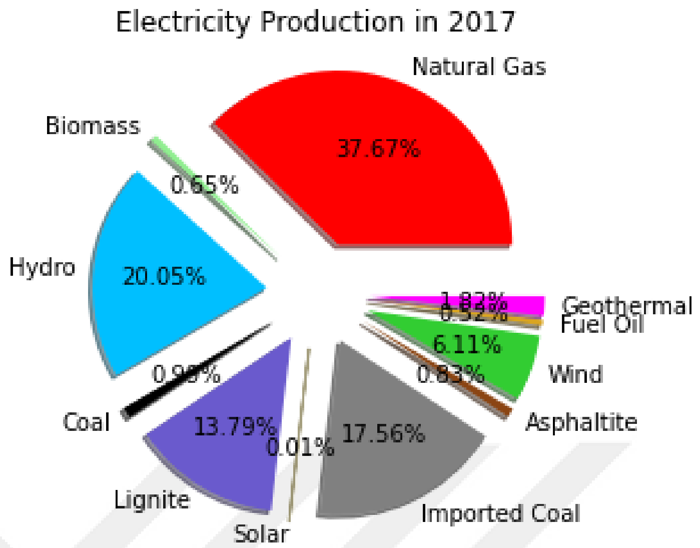
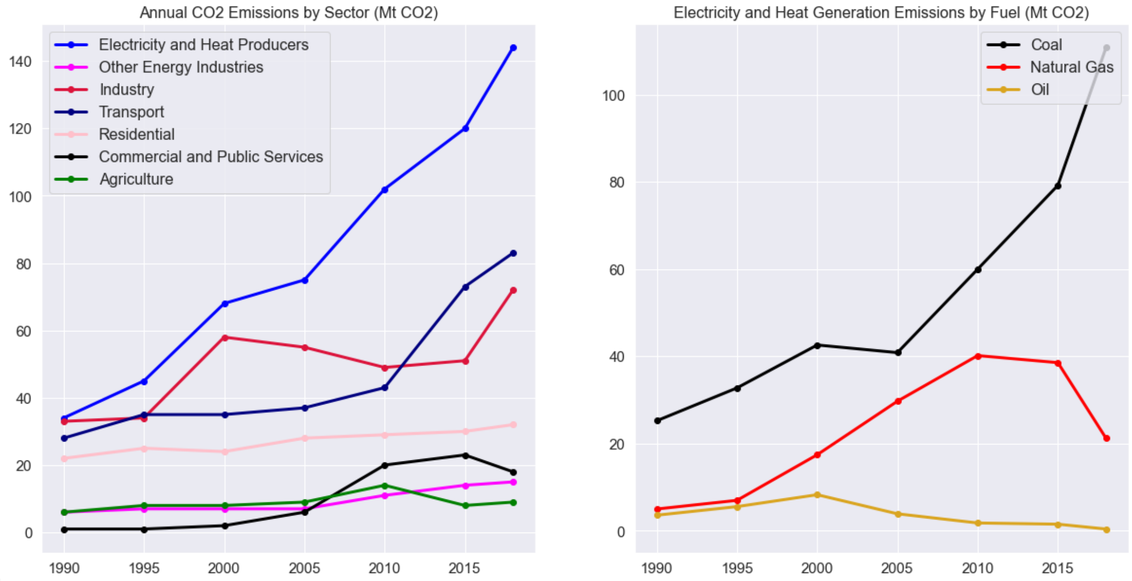


**Figure 2.4** Electricity Generation of Turkey by Fuel, 2017

Source: EXIST

As can be seen from the past data, Turkey's dependence on fossil fuels in electricity production cannot be ignored. However, if no solution is brought to this situation, the annual carbon emission will inevitably increase. An immediate action must be taken to solve this problem and achieve the European Union's net-zero greenhouse gas emission target for 2050 and keep the global temperature increase to below 1.5°C.


Annual CO2 Emissions by Sector (Mt CO2)

Electricity and Heat Generation Emissions by Fuel (Mt CO2)

**Figure 2.5** Annual CO2 Emissions of Turkey by Sector (Mt CO2)

Source: International Energy Agency

# 3. METHODOLOGY

## 3.1 Data Collection

Since there is currently no open-source database containing comprehensive data on power plants in Turkey, this project focused on the data collection process in its early stages. Firstly, a database containing the names and installed capacity data of all power plants operating in 2017 in Turkey was created. Later, comprehensive data of each power plant, such as located city, construction year, company, fuel type, technology, and lifetime, were added. In this way, it is aimed to prepare a dataset containing a large part of the publicly available technical information about power plants in Turkey. For this reason, approximately 2 months of the project was allocated to the data collection phase.

During the data collection process, websites of the authorized companies of all power plants and open-source power plant databases were used. Then, values such as the retirement year of each power plant, the electricity production potentials of the regions, and the exogenous capacities of the technologies were calculated with the data collected. The dataset is taken as the basis for calculating and checking the accuracy of the data to be entered into the model. The distribution of power plants in Turkey by cities is presented in Figure 3.1. Moreover, the installed capacities of Natural Gas, Solar, Wind, Lignite, and Hydro Power Plants by cities are also displayed in Figure A.3, Figure A.4, Figure A.5, FigureA.2, and Figure A.1 in Appendix A, respectively.

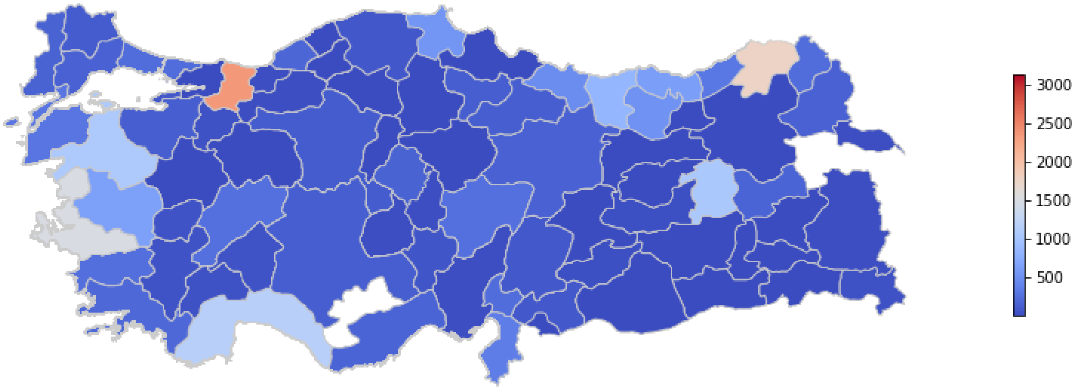


**Figure 3.1** Installed Capacity of Power Plants in Turkey, 2017 by City (MW)

## 3.2 Introduction to LEAP

In this study, a scenario-based energy-environment modeling tool called Long-range Energy Alternative Planning System (LEAP) has used to generate different energy consumption and CO2 emission scenarios for the power sector of Turkey. LEAP is an energy modeling platform for integrated environmental effect and greenhouse gas mitigation analysis developed by the Stockholm Environment Institute (SEI). Scenarios of LEAP are based on comprehensive accounting of how energy is consumed, converted, and produced in the corresponding region or economy under a range of alternative assumptions on population, economic development, technology, and price. LEAP as a database provides a comprehensive system for maintaining energy information. Also, it enables to make projections of energy demand and supply over a long-term horizon as a forecasting tool. Additionally, as a policy analysis tool, it simulates and assesses the economic and environmental effects of alternative energy programs, investments, and actions (LEAP User Guide, 2005).

LEAP procedure in this study consists of four major steps as follows: Electricity production via different technologies, energy demand, CO2 emissions, and emission mitigation potential. The methodology of this study is based on a bottom-up approach for the electricity generation simulation, including production capability with capacity factors of different fuelled power plants, the energy intensity of the power plants, and the emission intensity of the fuels. The structure of the LEAP model used in this study is presented in Figure 3.2. This model consists of a reference scenario and 4 different emission reduction scenarios. These scenarios are, Directed Transition, Societal Commitment, Techno-Friendly and Gradual Development. Emission reduction scenarios are the scenarios created to achieve the global warming temperature ceiling benchmark by the openENTRANCE project. Open Energy Transition Analyses for a low-Carbon Economy abbreviated as openENTRANCE project is funded by European Union's Horizon 2020 research and innovation programme. Creating an elaborative country-based database for electricity plants, combining detailed bottom-up and top-down modeling approaches, and creating various decarbonization and optimization scenarios using country-based socioeconomic data are the scopes of openENTRANCE. (Auer, 2020) Detailed information about the decarbonization pathways are provided in the Section 3.4.

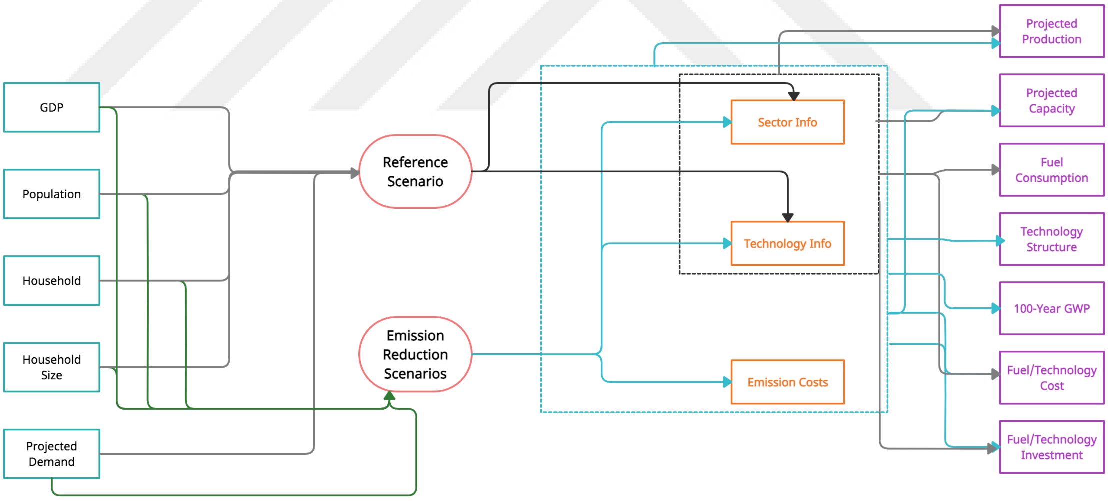


**Figure 3.2** Structure of LEAP Model

## 3.3 LEAP Model of Turkey

In this study, a national model with the base year 2017 and end year 2050 was created. In the model, Turkey's electricity production and consumption are discussed in terms of demand, transformation resources, costs, and energy effects. In order to better observe seasonal effects in demand and production, the model is divided into

48 different time-slice. Thus, the details considered in the model and all time-slices can be seen in Table 3.1, Appendix B.

**Table 3.1** Time-Slice Details for the Base Year

| **Seasons** | **Months** | **DAY** | **NIGHT** | **2017** |
|---|---|---|---|---|
| Winter | Dec-Feb | 08.00-18.00 | 19.00-07.00 | |
| Spring | Mar-May | 07.00-19.00 | 20.00-06.00 | |
| Summer | June-Aug | 05.00-20.00 | 21.00-04.00 | |
| Autumn | Sep-Nov | 06.00-19.00 | 20.00-05.00 | |
| **Total Annual Electricity Production(MW)** | | | **289.855.258,25** | |

There are hierarchically outlined branches in The Long-Range Energy Alternatives Planning tree. While creating Turkey's LEAP model, five different branches: Key Assumptions, Effects, Demand, Transformation, and Resources considered. After the Data Collection step, the collected data was analyzed by following the structures of these branches, and the necessary calculations and transformations were made and entered into the model. Current Accounts of Turkey's LEAP model finalized with the completion of the data entry step. Hence, the appearance of the electricity sector in Turkey in 2017 has been modeled on the LEAP. The variables and their calculations under the main branches are explained in detail in the following subsections.

### 3.3.1 Key Assumptions

*Key Assumptions* is the branch in which independent variables are created and edited to "drive" calculations in Demand, Conversion, and Resource analysis of the model. Key Assumptions are not calculated directly in LEAP but are used as intermediate variables referenced in modeling calculations. In this project, GDP, Population, Household, Household size, Demand Projections, Own Use and Transmission & Distribution Losses, and Growth Rates values are entered under the *Key Assumptions*. According to data from the World Bank Open Data, in 2017, Turkey's GDP value 858.080 Billion US Dollars, and its Population has been entered as 81.101 Million people. According to data from the report (Statistics on Family, 2017), Turkey's average household size for 2017 was entered as 3.4 (TSI, 2017). The household value is calculated as 23,853 million people by proportioning the aforementioned population and household size data in Equation 3.1. Electricity demand and Own Use and Losses data were taken from a projection provided by Turkey's Ministry of Energy and Natural Resources, including forecasts between 1990-2050. In Figure 3.3 information about the Own Use and Transmission & Distribution Losses used in model provided.

$$Households = Population[MillionPeople]/Householdsize[people]. \tag{3.1}$$

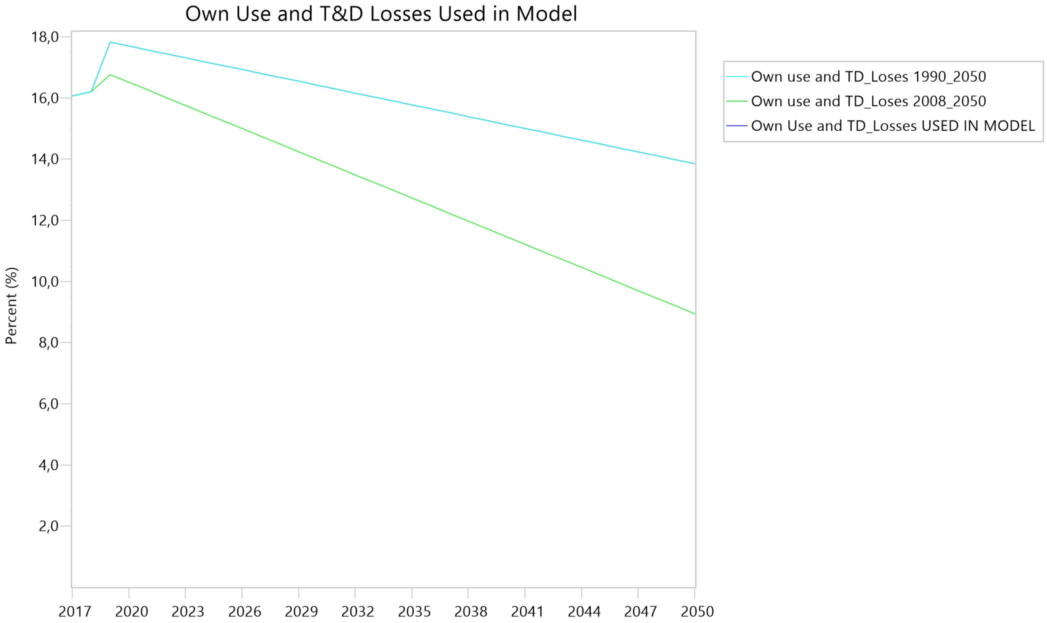


**Figure 3.3** Own Use and TD Losses

### 3.3.2 Effects

*Effects* is the branch in which external cost values for several pollutants can be created as well as limitations that serve to restrain emissions in scenarios using LEAP's lowest-cost optimization calculations. Environmental effects of fuels classified by technologies for electricity generation are entered into the model as Tier 1 (by fuel) or, if available, Tier 2 (by both fuel and technology) based on the default values of LEAP.

### 3.3.3 Demand

Demand is the branch under which the disaggregated structure of energy demand analysis is modeled. In this project, annual electricity demand projections made by the Ministry of Energy and Natural Resources from 2020 to 2050 at five-year intervals according to three different scenarios are based. These scenarios are low demand, reference scenario, and high demand scenarios, respectively. Hence, the demands forecasted by the ministry were interpolated until 2050, and a demand projection was made for each year between 2017-2050. In addition, projections made for the reference scenario are used in this model. Demand projections of three scenarios are presented in the Figure 3.4 below. In addition, detailed information is provided in Tables C.11 and C.12, Appendix C.

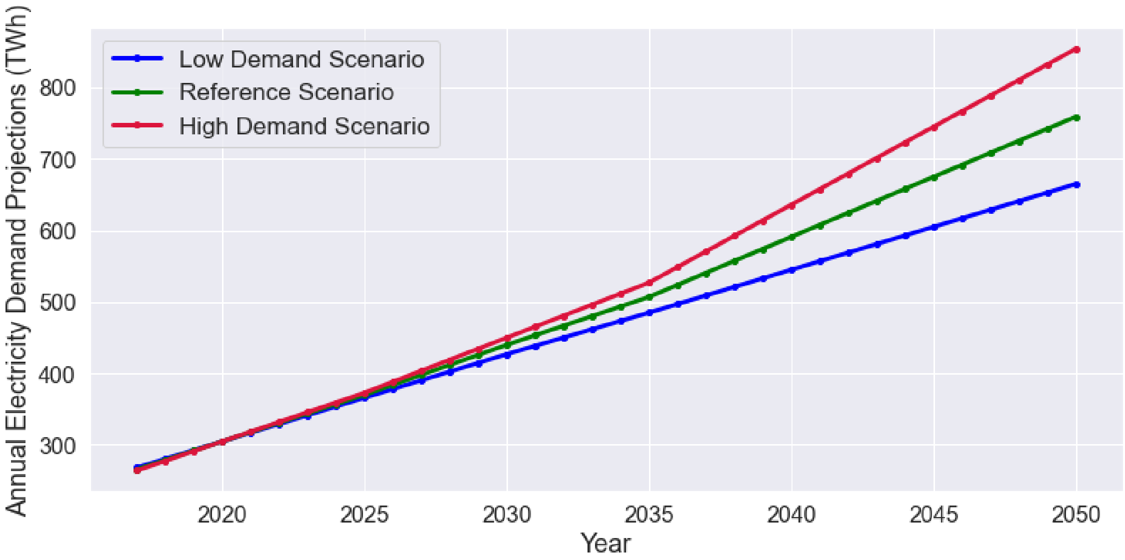


**Figure 3.4** Demand Projections

### 3.3.4 Transformation

*Transformation* analyses simulate the conversion and transportation of energy forms from the point of extraction of primary resources and imported fuels to the point of final fuel consumption. Transformation data are defined at two primary levels of detail. The **module**-level, a transformation branch representing an energy industry or sector, such as electricity generation, oil refining, district heating, or electricity transmission and distribution, represents energy industries or sectors such as electricity generation, refining, and district heating. Under each module, separate processes such as specific power plants or oil refineries and the output fuels produced by the module are described. For each **process** which is a transformation branch that describes a unique technology or group of technologies within a module such as a distinct electric plant or oil refinery, technical data such as input fuels, capacities, efficiency values, capacity factors, capital and operating and maintenance costs and emission factors are defined for each process.

In this project, the transformation branch consists of two main sections, Own Use Loss and Electricity Generation. In the Own Use Loss section, Own Use and Transformation and Distribution Losses values which are described in the previous subsection, are used. There are four parameters as System Load Shape, Module Costs, Planning Reserve Margin, and Peak Load Ratio in the main part of the Electricity Generation section. Module Costs and Peak Load ratio are left as default values within these parameters. For the System Load Shape, the hourly electricity production data in 2017 were arranged according to the time-slices of the model, which was explained in the aforesaid section. In this regard, the total electricity generation in each time-slices was calculated and entered in LEAP. Energy Load Shape of the LEAP model can be seen in the Figure 3.5.

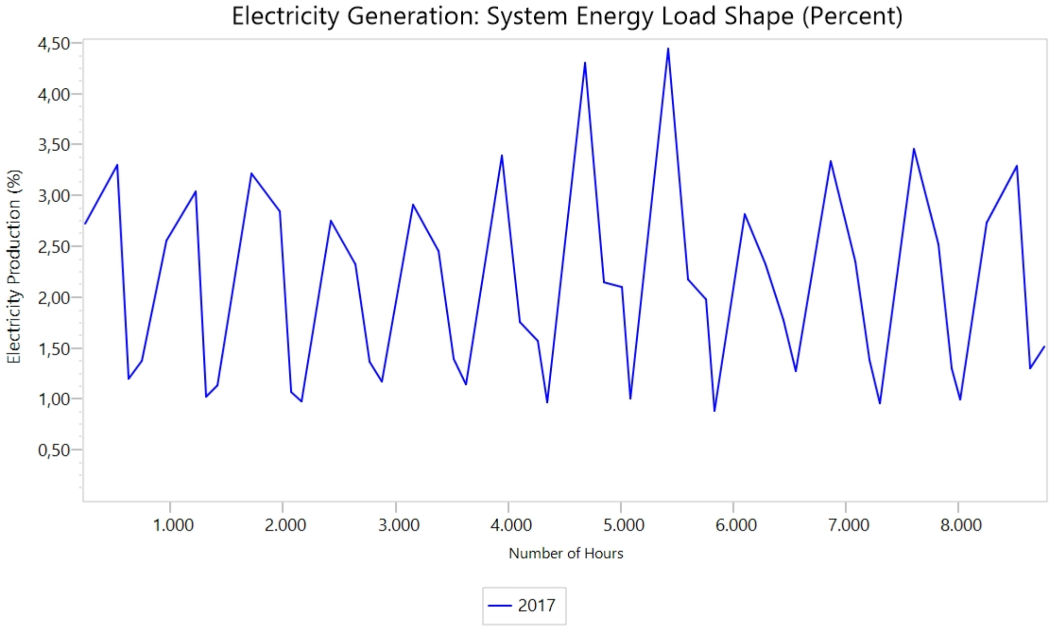


**Figure 3.5** Energy Load Shape 2017

The planning reserve margin is used by LEAP to determine when additional endogenous capacity will be added automatically. LEAP will add sufficient additional capacity to keep the planning reserve margin at or above the specified value. Turkey's reserve margin is stated to be around 34% (IEA, 2016). Therefore, for this model, the planning reserve margin is applied as 34%. LEAP calculates planning reserve margin as follows in Equation 3.2 and Equation 3.3 for all processes in the module. Moreover, peak load is estimated based on electricity requirements and module load factor. The Electricity Generation part has two subsections, Output Fuels and Processes. The output fuel in electricity production has been entered as only electricity. In the Output Fuels section, features such as the price of the electricity generated, import and export targets can be specified.

$$\text{Planning Reserve Margin}(\%) = 100\times(\text{Module Capacity} - \text{Peak Load})\div \text{Peak Load}, \tag{3.2}$$

$$\text{Module Capacity} = \sum (\text{Capacity} \times \text{Capacity Value}). \tag{3.3}$$

In this study, 15 different fuels were added to the model considering the electricity generation in Turkey. These fuels are asphaltite, biomass, coal, fuel oil, geothermal, hydro, imported coal, lignite, natural gas, nuclear, ocean, solar, waste, wind, and wood. Technologies defined in Processes Section are given in detail. Please see Appendix B.1, B.2, B.3, and B.4. The technologies used in this model and their economic and technical data have been prepared by considering the JRC-EU-TIMES model. (Radu et. al., 2014) In accordance with the JRC-EU-TIMES model, a total of 82 different processes are defined in the model, together with 15 different fuels and the technologies of these fuels. The Capital Cost, Fixed Cost and Variable OM Cost values of each process were entered by taking into account the JRC-EU-TIMES model. Detailed information about the specific investment costs and fixed operating maintenance costs are provided in Tables C.3, C.4, C.5, C.6, in Appendix C.

According to market needs, dispatchable generation refers to power sources that can be sent on-demand at the request of power grid operators. Dispatchable generators can adjust their power output to an order. According to this definition, asphaltite, biomass, natural gas, fuel oil, hydro, imported coal, geothermal, coal, lignite, and concentrated solar power technologies are entered as dispatchable in the dispatchable section and wind, ocean, wood, waste, and solar technologies as non-dispatchable. Lifetime and Process Efficiency values of each technology are entered by taking into account the JRC-EU-TIMES model. (Radu et. al., 2014) The lifetime data used in this study are given in Appendix C. Please see Tables C.13 and C.14.

While calculating the changes in exogenous capacity for each technology over the years, the installed power data collected for 2017, the construction years of the power plants, and the lifetime data taken from the JRC-EU-TIMES model were taken into consideration. (Radu et. al., 2014) Consequently, the estimated retirement years were found by adding lifetime values to the construction year of the power plants. Then, considering the total installed power for each technology in 2017 and the retirement years of the power plants using these technologies, the exogenous capacity until 2050 was calculated for each process.

For the Maximum Availability section, generally, the availability factors determined by the JRC-EU-TIMES model for each technology are considered. (Radu et. al., 2014) However, for all wind, solar, and hydro technologies, a different calculation has been made, as the availability factors of these technologies are mainly seasonal. For this calculation, first of all, how much electricity was produced separately from these three fuels in 2017 was found. For these data, hourly electricity generation data for 2017 were taken. Next, 8760 lines of hourly production data for wind, solar and hydro are parsed. This hourly data is divided into 48 different time-slices such as day-night, weekdays-weekend, and month following the time slice of the model. Hence, total electricity generation in 48 different time-slice was calculated for these three fuels in 2017. Then, the number of hours in the calculated time slice is multiplied by the total installed power value of that year. Finally, these two calculated values are divided into each other, and the capacity factor values for these three fuels are calculated separately according to time-slices. Installed power and hourly production data are taken from the EPİAS Transparency platform.

### 3.3.5 Resources

Under *resources*, a data structure can be created that indicates the production of indigenous resources and the import and export of secondary fuels. Resources in the model are divided into two groups as primary and secondary due to LEAP's structure. The primary resources in this study are ocean, wood, hydro, wind, nuclear, coal, biomass, asphaltite, natural gas, lignite, solar and geothermal. Secondary resources are gasoline, fuel oil, heat, and electricity.

## 3.4 Scenario Development

This project, on the basis of Turkey's energy outlook in 2017 up to 2050, aimed to reduce carbon emissions. In this direction, scenarios were created over different contexts, and the closeness of the results to the desired goal was analyzed. In order to decarbonize Turkey's electricity sector, five different scenarios have been established. These are Reference Scenario (REF), Directed Transition (DT), Societal Commitment (SC), Techno Friendly (TF), and Gradual Development (GD) scenarios, respectively. The REF scenario is modeled to model Turkey's electricity sector's current situation and be able to see the exchange value of carbon emissions up to 2050 in case new policies are not adopted. The other four scenarios are based on the scenarios created to decarbonize the pan-European Energy System within the openENTRANCE project's scope. The ambition of the openENTRANCE project is to develop, use and disseminate an open, transparent and integrated modeling platform for assessing low-carbon transition pathways of the European energy and transport system. (Quantitative Scenarios for Low Carbon Futures of the pan-European Energy System, 2020) Accordingly, within the scope of this thesis, Turkey's electricity sector was modeled on the basis of 2017 and then aimed to be decarbonized using scenarios created within the openENTRANCE project. Further, each scenario was compared considering the total capacity, electricity generation by fuel, total cost, and emission values. In this context, it was discussed which scenario could be successful in decarbonizing Turkey's electricity sector. The formation of each scenario is explained in detail in the next subsections. An overview of the main cornerstones, drivers, and features of each story is given in Figure 3.6.

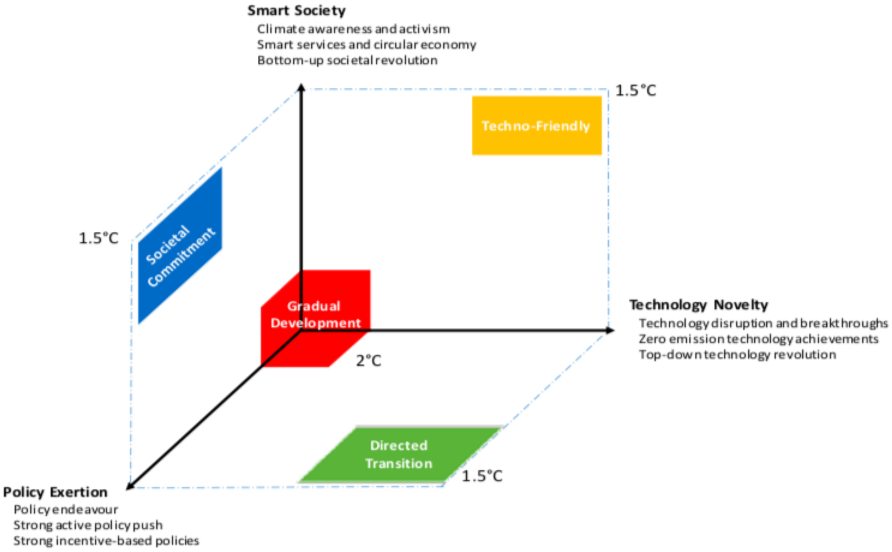


**Figure 3.6** openENTRANCE Storyline Typology

Source: openENTRANCE Deliverable NO. 3.1

The versions of the programs used while creating and solving the model is given in Table 3.2. In addition, the numerical values of the main changes performed in the scenarios are provided in detail in Appendix 3.4.

**Table 3.2** Versions of Programs Used in This Study

| Program/Solver | Version |
|---|---|
| LEAP | 2020.1.0.33 |
| NEMO | 1.6.0 |
| Gurobi | 9.1.2 |
| GLPK | 4.65 |
| CPLEX | 20.1 |

### 3.4.1 Reference Scenario

The basis of the model was created according to the LEAP user manual. After, it was validated for debugging and for checking the accuracy of the data sources. The Reference Scenario represents the energy pathway that is intended if current energy policies, supply and demand trends in Turkey persist. This primarily includes economic growth and energy transformation. Current trends in the Turkish economy and the power sector continue in the REF Scenario.

**3.4.1.1 Numerical Results** Let us look at the results of the Reference Scenario in Figure 3.7. If Turkey does not make any changes in its electricity generation policy for the coming years, 32.4% of the electricity production of 1208.75 Million Megajoules is provided from Hydro, and 10.84% is provided from Natural Gas . Coal and Lignite together make up 36.09% of electricity generation in 2020. When we look from 2020 to 2050, the apparent increase in Coal stands out. In fact, 38.28% of the electricity generation in 2050 is produced by Coal and Lignite. On the other hand, the increase in the share of renewable energy resources in electricity generation is not enough to phase-out the fossil fuels.

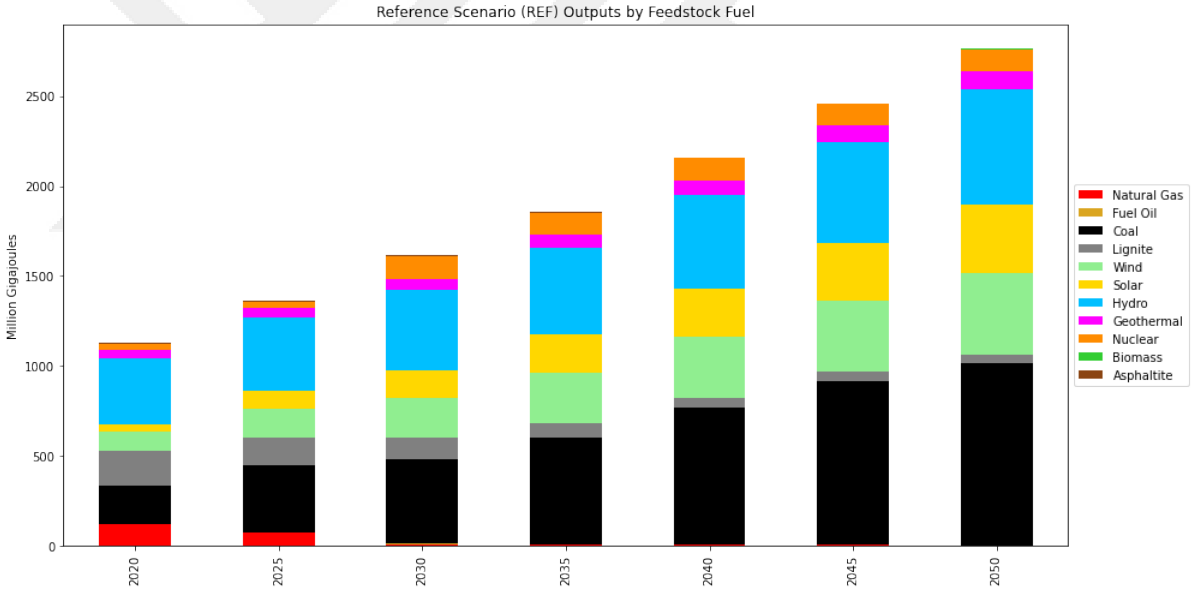


**Figure 3.7** Reference Scenario (REF) Outputs by Feedstock Fuel

The figure 3.8 shows the change in the total values of the exogenous and endogenous capacities over the years. While the total capacity of the power plants was 89.79 Thousand Megawatts in 2020, this value increased to 219.8 Thousand Megawatts in 2050. The capacity of Natural Gas power plants, which had a total capacity of 21.10 Thousand Megawatts in 2020, almost reduced by one-fifth in 2050 and reached 5.6 Thousand Megawatts. So much so that 3% of the total power plant capacity in 2050 is Natural Gas and 24.75% is Hydro. In parallel, although the capacities of fossil fuel power plants such as lignite and natural gas decrease, the total capacity of Solar, Wind, and Geothermal power plants constitute 67.8% in 2050.

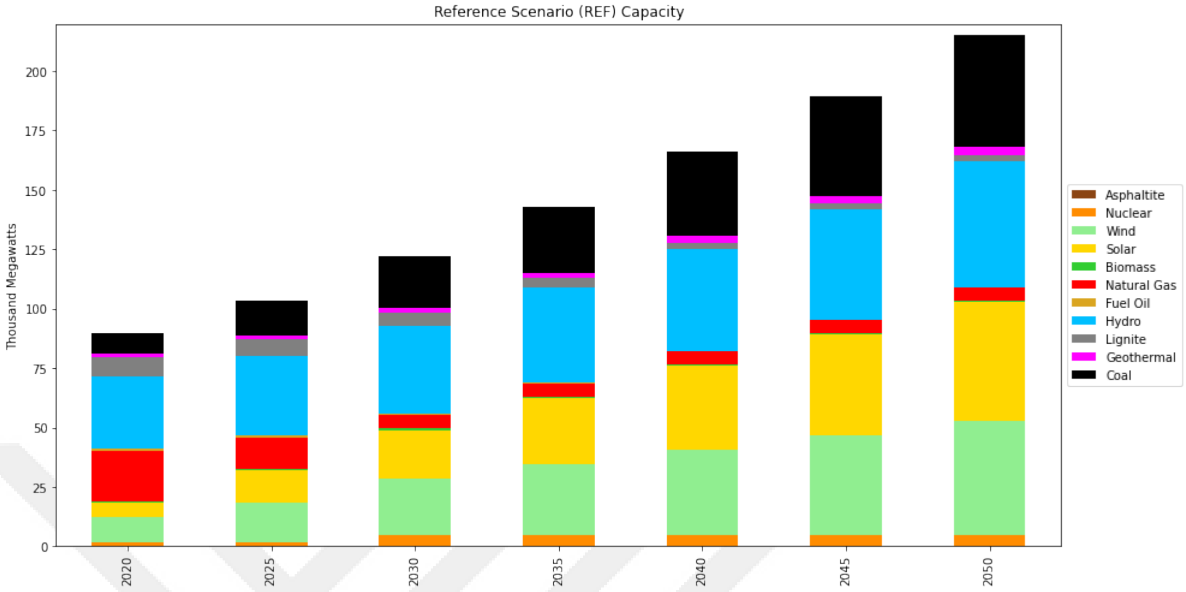


**Figure 3.8** Reference Scenario (REF) Capacity

Accordingly, as shown in Figure 3.9, Turkey's 100-Year GWP value in 2020 was 118.65 Million Metric Tonnes $CO_2$ Equivalent, while this value almost tripled in 2050 and reached 309.83 Metric Tonnes $CO_2$ Equivalent. Although the use of Lignite and Natural Gas for electricity generation has gradually decreased over the years, Turkey's 100-Year GWP continues to increase over the years as these fossil fuels are replaced by Coal, which is also another fossil fuel instead of renewable resources. As the Reference Scenario results reveal, Turkey has to take severe actions regarding electricity generation to comply with the Paris Agreement and achieve its 2050 carbon emission targets. In the following sections, different scenarios and their results that have been created to achieve the emission targets are explained.

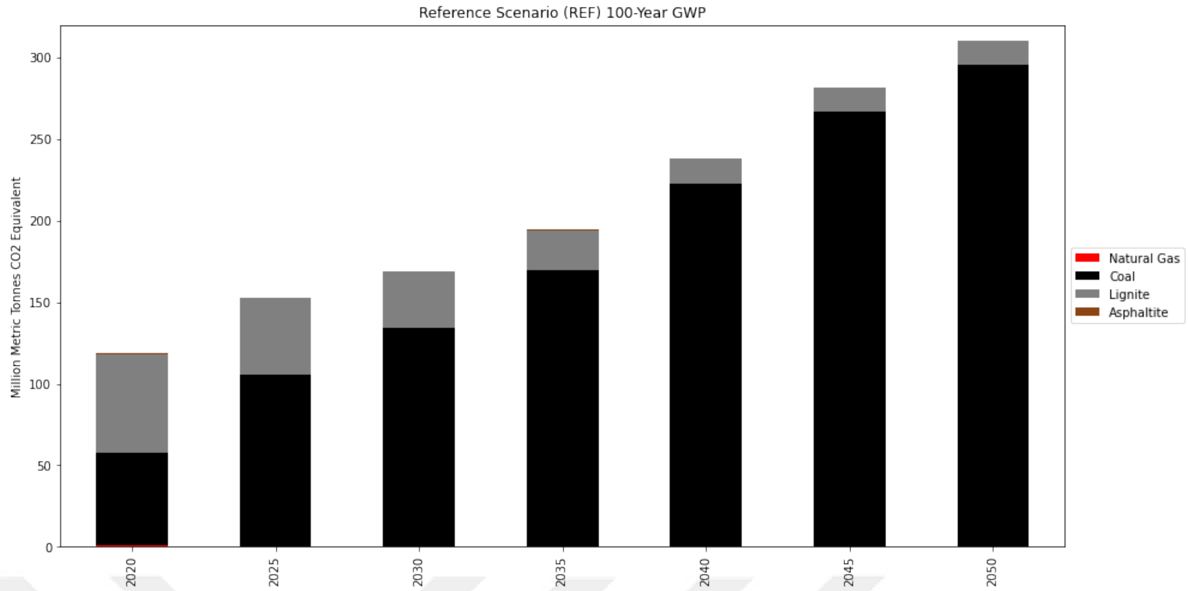


**Figure 3.9** Reference Scenario (REF) 100-Year GWP

**3.4.1.2 Validation of the Reference Scenario** In this section, the results of the reference scenario created within the scope of this thesis are compared with the reference scenario in the Turkey Energy Outlook 2020 report prepared by IICEC.The Sabancı University Istanbul International Center for Energy  Climate (IICEC) is an independent Center at Sabancı University that produces energy policy research and uses its convening power at the energy crossroad of the world. In this regard, they published the Turkey Energy Outlook (TOE), which is built on a detailed bottom-up accounting of the Turkish energy economy. (Turkey Energy Outlook IICEC, 2020)

Table 3.3 shows the electricity demand and electricity generation values in 2030 and 2040 for both projects. According to the table, it is seen that the demand values of IICEC are lower than the demand values projected for this thesis. On the other hand, it is commonly anticipated to both projects that demand will follow an increasing trend from 2030 to 2040. Further, for the electricity generation side, it has been seen that the electricity generation values of IICEC are also less than the calculated values in this thesis, due to the low demand. In addition, the ratio of fuels other than natural gas in total electricity generation is similar in the both projects. The difference in natural gas values can be attributed to the different operating and maintaining cost values.

**Table 3.3** Validation of the Reference Scenario Results

| | **Reference Scenario of IICEC** | | **Reference Scenario of This Thesis** | |
|---|---|---|---|---|
| | **2030** | **2040** | **2030** | **2040** |
| **Net Electricity Demand (TWh)** | 364 | 494 | 440 | 591 |
| **Gross Electricity Generation (TWh)** | 424 | 571 | 448.3 | 599.1 |
| Natural Gas | 59 | 76 | 12.8 | 8.9 |
| Coal | 161 | 166 | 130.8 | 212.2 |
| Nuclear | 18 | 63 | 34.4 | 34.4 |
| Renewables | 186 | 266 | 245 | 334.7 |

In Figures 3.10 and 3.11 electricity generation percentages from fuels for both scenarios are given. According to the respective figures, it is shown that according to the results of both projects, there is no significant difference between the percentages of Turkey's electricity generation mix in 2040. However, it is noteworthy also in this graph that the natural gas value differs. In addition, it can be said that Hydro's share in electricity generation is modeled differently for the two projects. In fact, according to the results of IICEC, the share of hydro in electricity production in 2040 is 12%, while it is 24% according to the results of the reference scenario of this thesis.

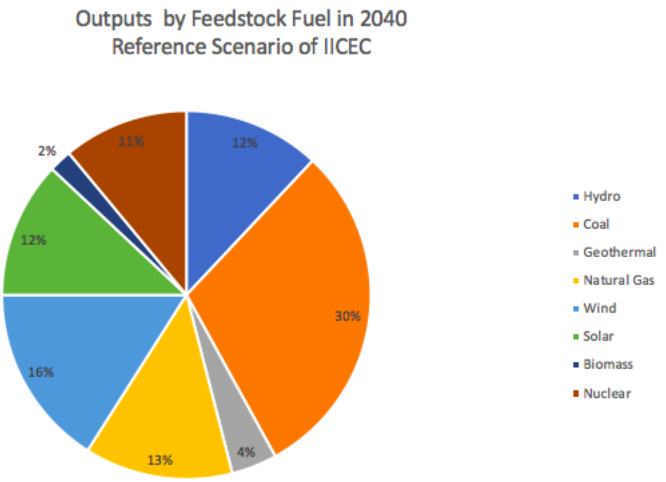


**Figure 3.10** Outputs by Feedstock Fuel in 2040, IICEC

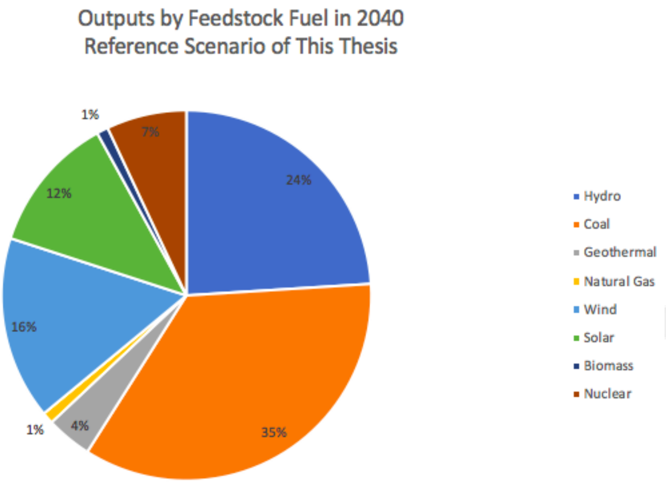


**Figure 3.11** Outputs by Feedstock Fuel in 2040, This Thesis

Finally, in Figures 3.12 and 3.13, the installed capacity values of both scenarios are compared. According to these graphs, it is remarkable that the differences in the percentages of natural gas and hydro in the electricity generation mix have decreased. It is possible to say that the installed capacity values of these two projects for 2040 are related.

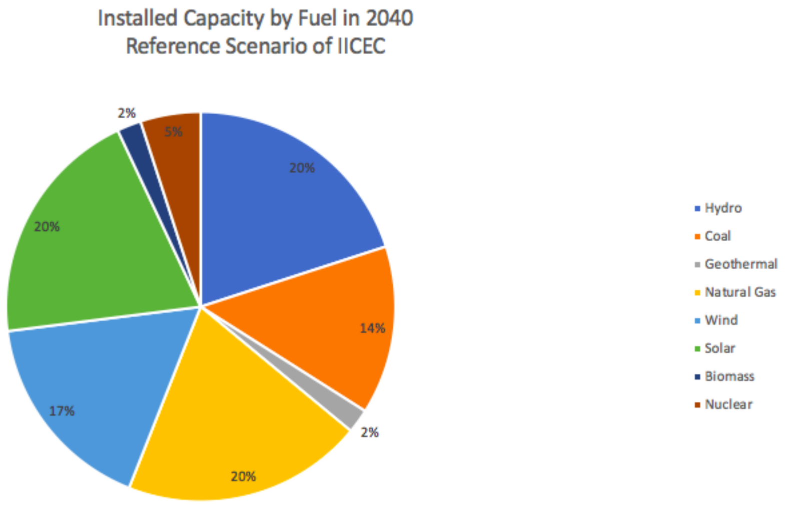


**Figure 3.12** Installed Capacity by Fuel in 2040, IICEC

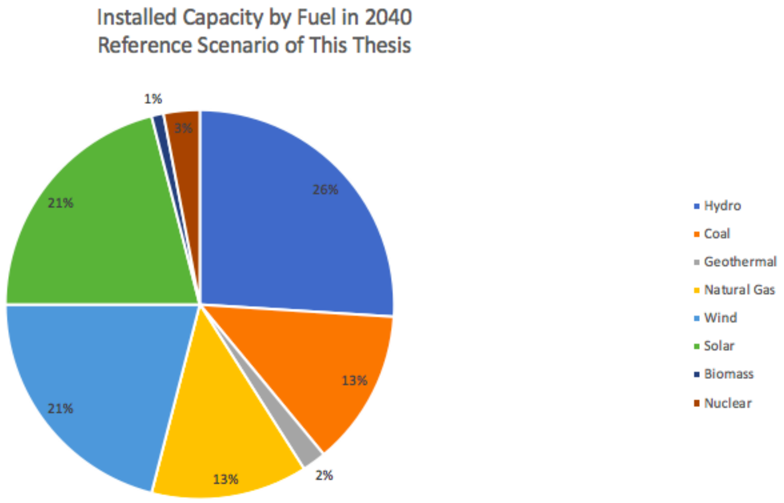


**Figure 3.13** Installed Capacity by Fuel in 2040, This Thesis

### 3.4.2 Directed Transition

This scenario is based on the callous attitude of the public and the lack of social undertaking. As a result, it is assumed that an effective and continuous incentive-based policy should be adopted in order to use new technologies in energy production. In the competitive environment of the global marketplace, the industry provides low-carbon technology portfolios in the absence of significant active societal contributions. Along with the lack of social participation and technological breakthrough, the energy system's decarbonization by 2040 is facilitated mainly by political action and technology-specific support.

In order to further develop the energy system, the greenhouse gas reduction target is implemented by the end of 2050. Besides, it was assumed that demand for all sectors would decrease due to policy incentives to reduce demand. In the industry sector, it aims to increase the electrification of the sector, thanks to the heavy subsidies applied to reduce technology costs. Accordingly, it is predicted that wind and solar power will become the leading source for primary energy supply. Additionally, technologies that are not currently available are not considered by the model.

**3.4.2.1 Numerical Results** As can be seen in Figure 3.14, Solar and Wind, whose share in electricity production in 2020 is 6.02% and 11.20%, respectively, constitutes 21.78% and 18.83% of electricity production in 2050. In addition, Turkey achieves to provide 100% of its electricity generation in 2050 from renewable energy sources. According to the results of this scenario, Fuel Oil in 2040, Lignite and Asphaltite in 2045, Coal will be phase-out in 2050. On the other hand, Hydro appears to be the most used fuel for electricity generation.

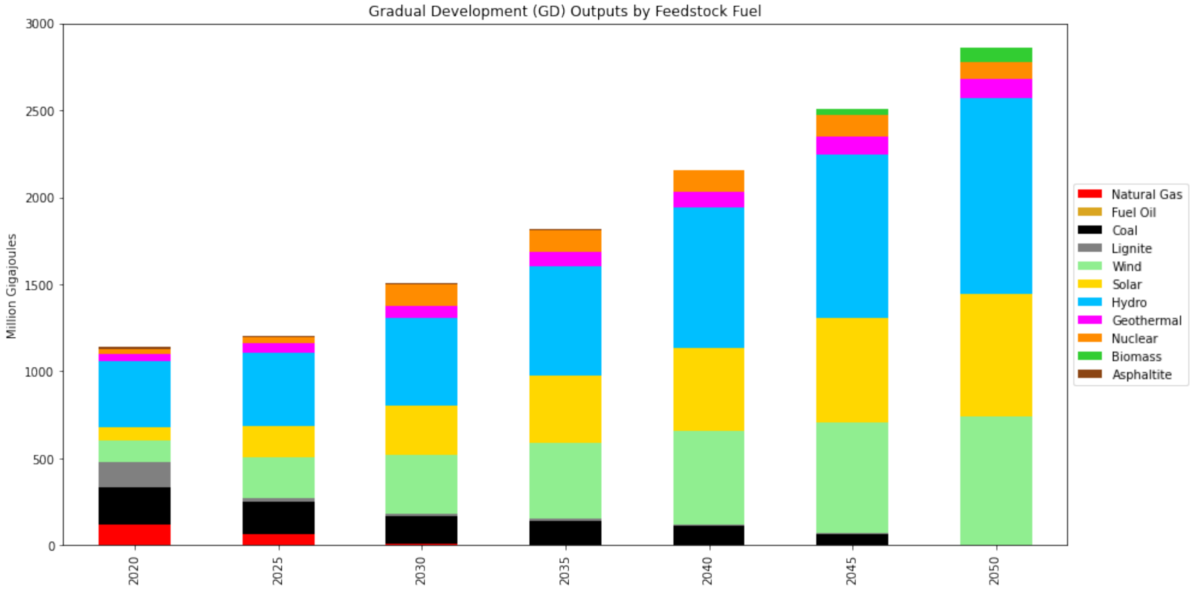


**Figure 3.14** Directed Transition (DT) Outputs by Feedstock Fuel

As shown in Figure 3.15, the total capacity of renewable energy sources increased from 56.08% in 2020 to 90.5% in 2050. In the Reference Scenario, this value is 30.1%

in 2050. According to this, the capacities of fossil fuels such as Fuel Oil, Natural Gas, and Lignite are gradually decreasing or being completely zeroed and leaving their place to renewable energy resources. Furthermore, the major increase in the capacities of solar, wind, and hydro is also striking. Since the capacities of fossil fuels are replaced by the increase in the capacities of renewable energy sources, it can be said that this scenario will provide the targeted emission reduction.

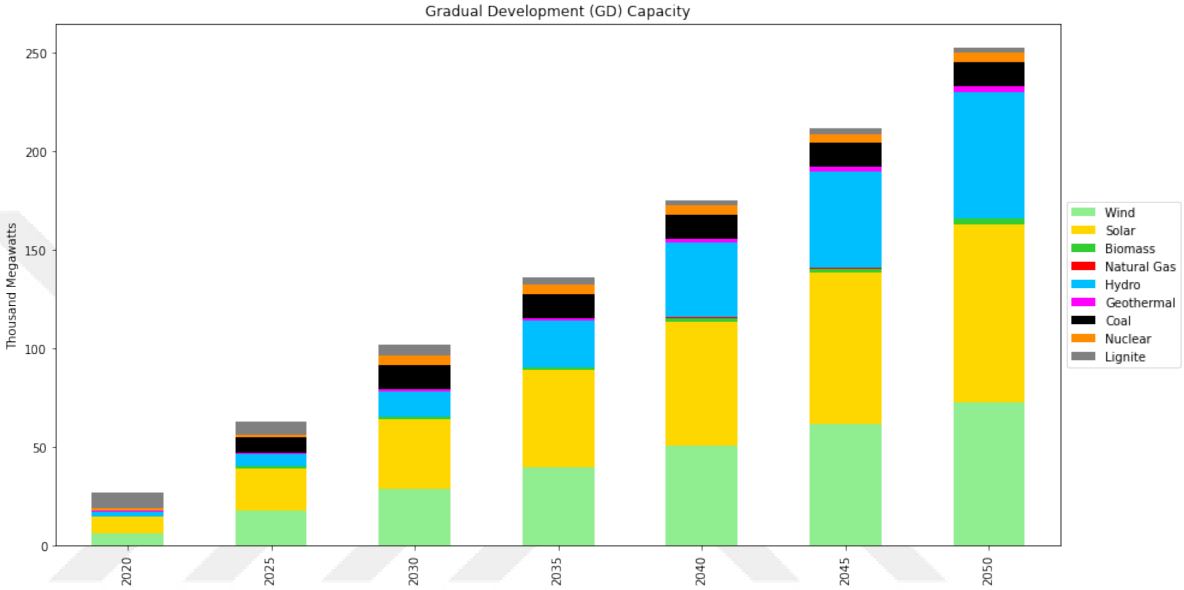


**Figure 3.15** Directed Transition (DT) Capacity

Figure 3.16 shows the change of the Directed Transition Scenario's 100-Year GWP value over the years. The 100-Year GWP value, which was 117,493 Million Metric Tonnes $CO_2$ Equivalent in 2020, decreased to 33 Million Metric Tonnes $CO_2$ Equivalent in 2045 with the phase-out of Natural Gas and was zeroed in 2050. In this scenario, it was seen that with the incentives of policy-makers, Turkey's annual carbon emission could be decreased to zero in 2050 in a controlled manner.

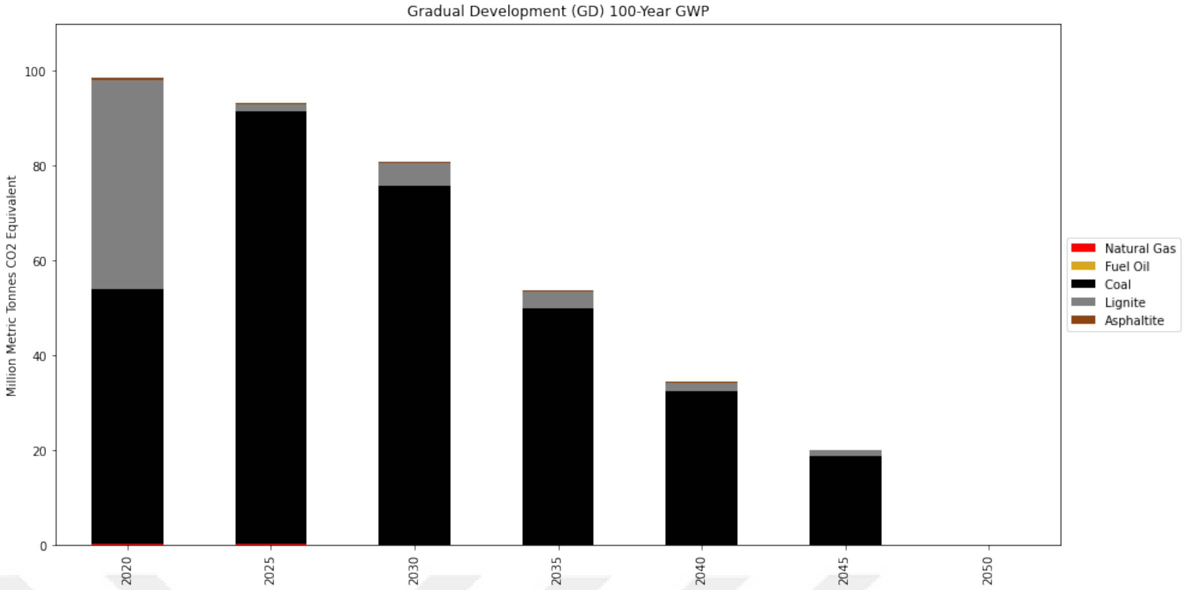


**Figure 3.16** Directed Transition (DT) 100-Year GWP

### 3.4.3 Societal Commitment

In the Societal Commitment scenario, a sustainable and environmentally conscious lifestyle and the presence of a circular economy are envisaged that has been adopted by society is accepted. Thus, it is assumed that there will be a significant decrease in energy demand in energy and transportation services. These goals and developments, especially in the energy and transportation sectors, have created the need for personalized policymaking due to the lack of new technologies. With this scenario, which focuses on sustainability and behavioral changes, the overall energy demand in the created energy model is changed to reflect these aspects.

With the formation of public awareness, it is predicted that the general energy demand will decrease consistently in all sectors. Renewable technologies often see higher potentials and market interaction than they do, as public support and policy focus on removing regulatory barriers. Therefore, society is expected to be willing to invest in the sustainable transformation of the energy system. Besides, the use of renewable resources can be encouraged with actions such as penalty sanctions on conventional technologies. Regarding the technology environment, no adverse emission technology is allowed in this scenario. Also, it is not allowed to build new nuclear power plants or to increase the capacity of existing nuclear power plants. Currently dominant fossil fuels such as hard coal and lignite are expected to be phased out by half of the planned time interval.

**3.4.3.1 Numerical Results** According to the results of the Societal Commitment scenario, Turkey's electricity generation mix over the years is shown in Figure 3.17. In 2020, 33.9% of electricity production was made up of Hydro, and 49% of fossil fuels, including Natural Gas, Coal, Lignite, Nuclear, and Asphaltite. When we look at the change over the years, we can see that Natural Gas, Lignite, and Coal will be phase-out in 2040. Contrarily, Solar and Wind's share in electricity generation increased from 6.02% and 11.58% to 20.86% and 53.05%, respectively. Besides, Hydro also continues to maintain its level in electricity generation.

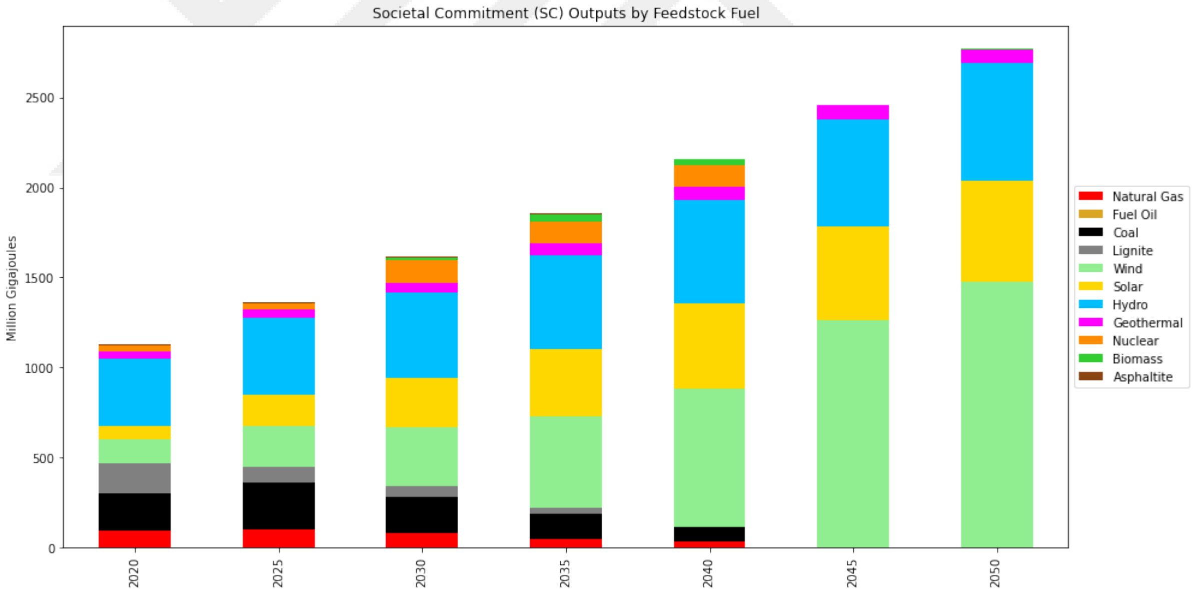


**Figure 3.17** Societal Commitment (SC) Outputs by Feedstock Fuel

In addition, as shown in Figure 3.18, fossil fuels, which constitute 45.88% of the total capacity in 2020, have been replaced by renewable energy sources over the years. For this reason, 94% of the total capacity in 2050 consisted of renewable energy sources. Fuel Oil and Lignite's zeroized capacity in 2040, Asphaltite in 2045 strengthens this conclusion. Furthermore, the increase in the installed capacity of solar and wind is clearly seen in 3.18. Hydro also continues to maintain its capacity.

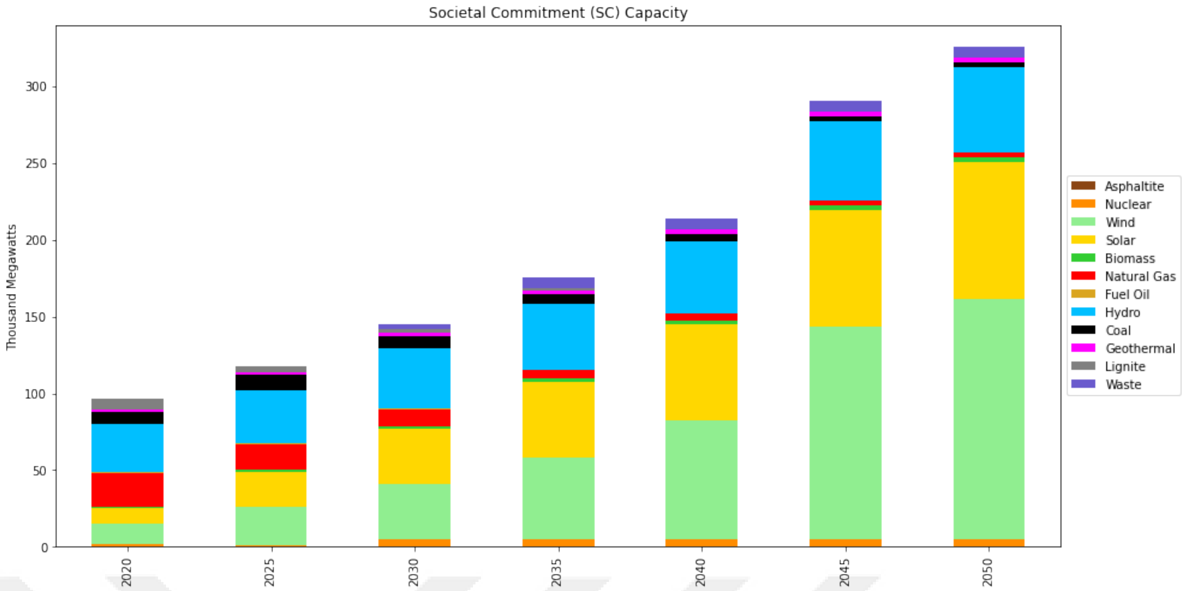


**Figure 3.18** Societal Commitment (SC) Capacity

Consequently, over the years, fossil fuels have been replaced by renewable energy sources in both electricity generation and installed capacity, and Turkey has succeeded in reducing carbon emissions in electricity generation to zero in 2045. As seen in Figure 3.19, the 100-Year GWP value, which was 108.22 Million Metric Tonnes $CO_2$ Equivalent in 2020, decreased rapidly from 2020 to 6.5 Million Metric Tonnes $CO_2$ Equivalent in 2040 and finally zeroized in 2045. It has been seen that it is achievable to reach this result a little faster by utilizing new technologies and informing the public about natural resources and adopting a sustainable lifestyle.

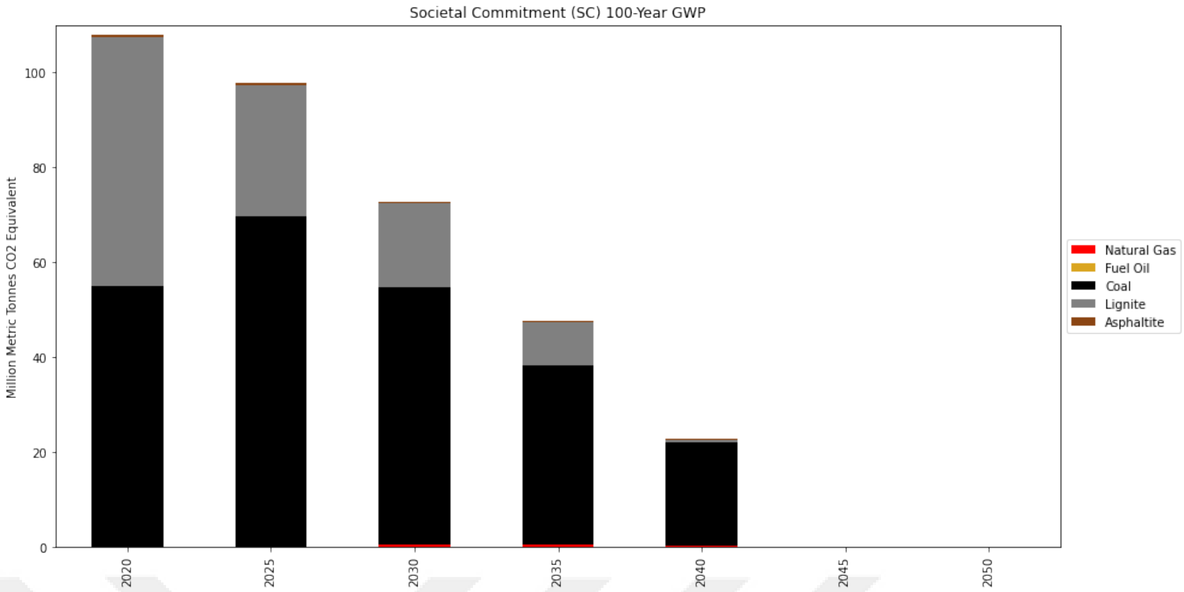


**Figure 3.19** Societal Commitment (SC) 100-Year GWP

### 3.4.4 Techno Friendly

As the name suggests, this scenario focuses on breakthroughs in new technologies (including $H_2$ and CCS) that are widely available to meet energy and transportation service needs. Besides, it is assumed that society will adopt these technologies by adopting a positive attitude towards large-scale infrastructure projects that mitigates the climate problem. Due to the availability of adequate low-carbon technology, reductions in energy demand and active demand-side involvement of consumers are less substantial but still necessary. Optimistic values are applied for the cost and efficiency development of these new technologies. Higher technological learnings can be seen for technologies currently in a less mature state of development and demonstrate a breakthrough potential. Also, new capacities can be built at a higher implementation rate within two periods as infrastructure investments, and capacity extensions are facilitated through the scenario. Accordingly, primary energy consumption is expected to decrease by approximately 50% until 2050. Also, it is anticipated that there will be significant reductions in oil and natural gas use until 2040.

**3.4.4.1 Numerical Results** When we look at the numerical results of the Techno-Friendly scenario, the change in Turkey's electricity generation mix over the years is presented in Figure 3.20. Accordingly, 33.13% of electricity generation in 2020 is provided by Hydro, and this value reaches 50.19% in 2050. In addition, while the share of Natural Gas in electricity generation was 12.76% in 2020, it is seen that Natural Gas is in phase-out by 2040. Similarly, Lignite became phase-out in 2035 and Coal in 2050. As fossil fuels gradually leave their place to green resources, all of the electricity production was provided by renewable energy resources in 2050 as desired. Thus, in 2050, Turkey's energy mix in electricity generation consists of solar, wind, hydro, and geothermal.

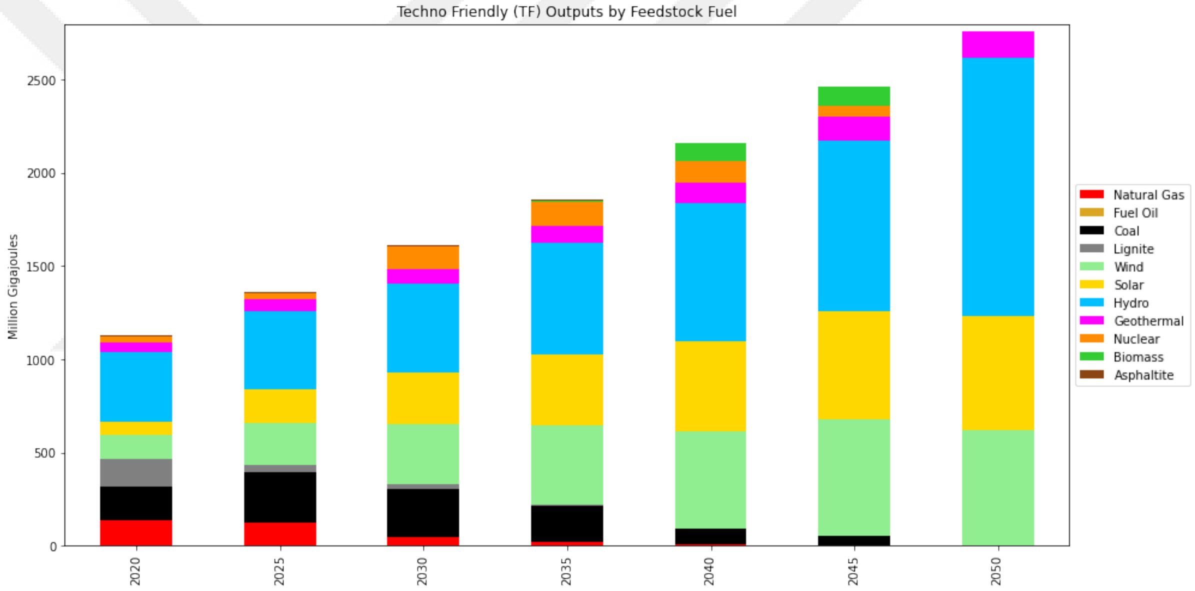


**Figure 3.20** Techno Friendly (TF) Outputs by Feedstock Fuel

The change of capacities over the years in the Techno-Friendly scenario is shown in Figure 3.21. The significant increase in Solar, Wind, and Hydro capacities can be easily seen from the Figure 3.21. Contrarily, it is also seen that fossil fuels such as lignite, and asphaltite are gradually disappearing from the chart, and natural gas and coal remains to exist even if their percentage value significantly decreases.

Subsequently, as presented in Figure 3.22 the 100-Year GWP value of Turkey , which was 93 Million Metric Tonnes $CO_2$ Equivalent in 2020, decreased to 15.54 Million Metric Tonnes $CO_2$ Equivalent in 2045 and then zeroized in 2050. By adapting

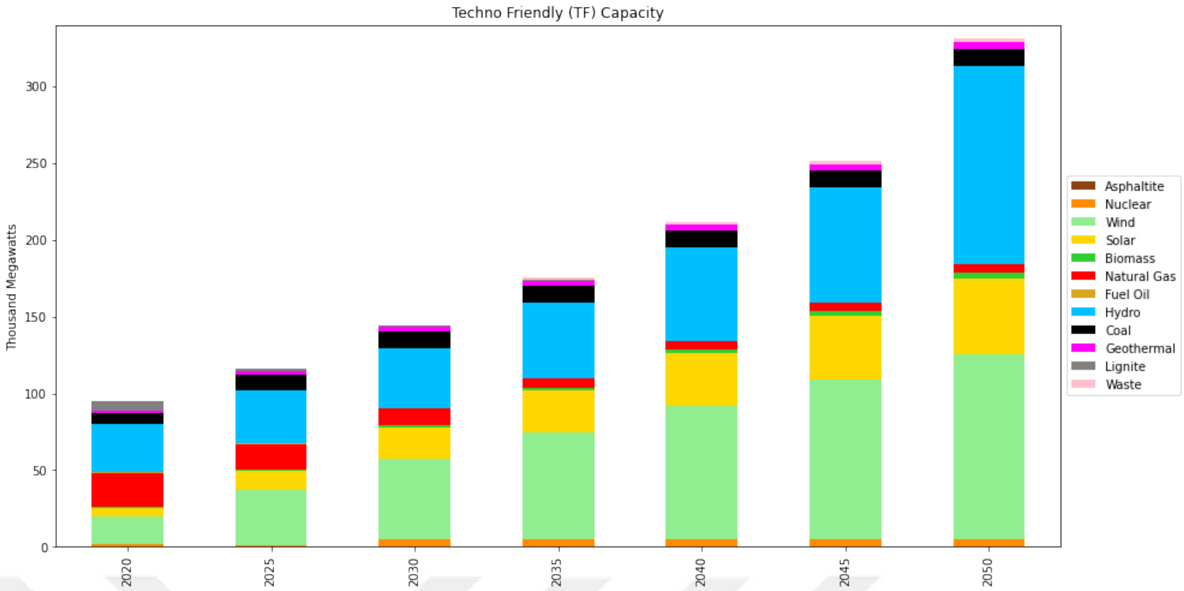


**Figure 3.21** Techno Friendly (TF) Capacity

to novel technologies and using and encouraging renewable energy resources, it has been seen that carbon emissions in electricity production can be reduced to zero in 2050.

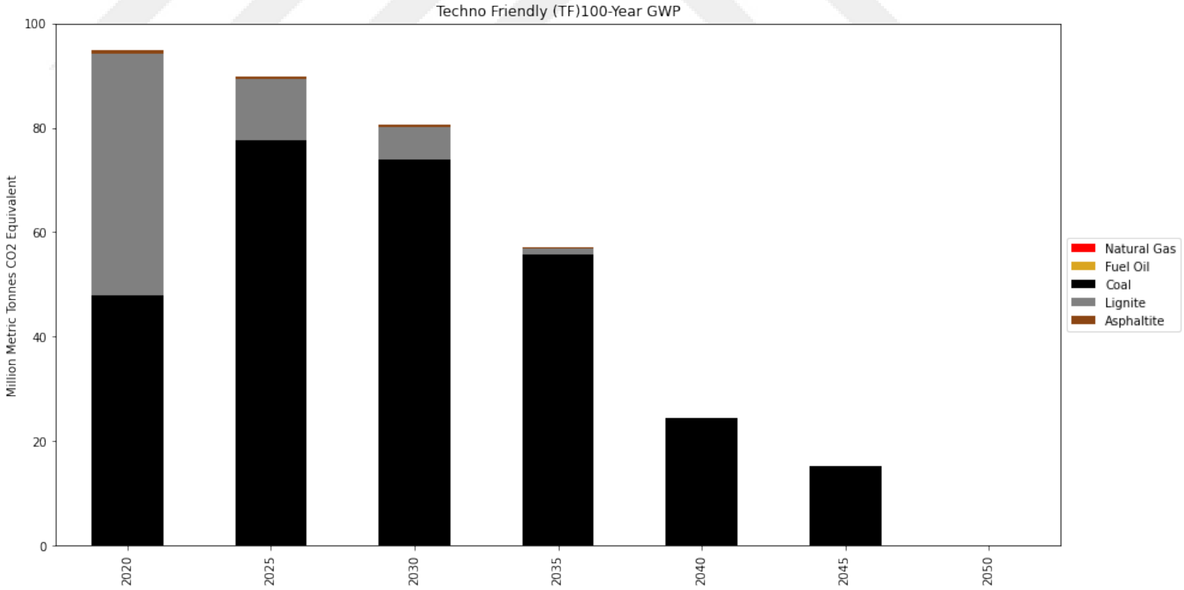


**Figure 3.22** Techno Friendly (TF) 100-Year GWP

### 3.4.5 Gradual Development

This scenario contains ”a little of each” components of the aforementioned openENTRANCE scenarios. The Gradual Development scenario has created the challenging energy transition with equal parts of social, industrial/technological, and policy action. Several of these three interrelated dimensions take responsibility and provide significant contributions to achieve the climate mitigation target. Compared to the other three scenarios, features and traits from Techno Friendly, Societal Commitment, and Directed Transition are included collectively in this path rather than focusing on a particular aspect.

Since this pathway completes decarbonization by 2050, the transformation of the energy system is not as severe as in the other three scenarios, and measures are more balanced. Costs and efficiencies of all technologies are changed slightly to reflect the scenario characteristics, similar to the Techno-Friendly scenario. Nevertheless, the values are less promising, and improvements happen at a slower rate. Also, novel and not already demonstrated technologies are not integrated. Like Societal Commitment, this scenario is also designated by reductions in energy demand of all different sorts. Primary energy demand sees a similar development compared to the Techno Friendly pathway and sees a reduction of nearly 50% in 2050 compared to 2020. Oil and natural gas play a significant role even until 2040 but are phased out to achieve the carbon neutrality targets in 2050. Hard coal and lignite are phased out until 2040. The lesser carbon price compared to the other scenarios result in significantly higher emissions in 2040.

**3.4.5.1 Numerical Results** When we look at the numerical results of the Gradual Development scenario, which is the last scenario in this study, it is represented in Figure 3.23 that fossil fuels provided 48.44 % of the electricity generation in 2020. Nevertheless, over the years, with the phase-out of Natural Gas and Lignite in 2035 and the share of coal gradually decreasing, fossil fuels have been replaced by renewable energy sources. Thus, in 2050, 100% of electricity production was provided by renewable energy sources. It is also seen that especially the shares of hydro, wind, and solar in total production have increased significantly over the years. And this increase supports the realization of the net-zero target in electricity generation.

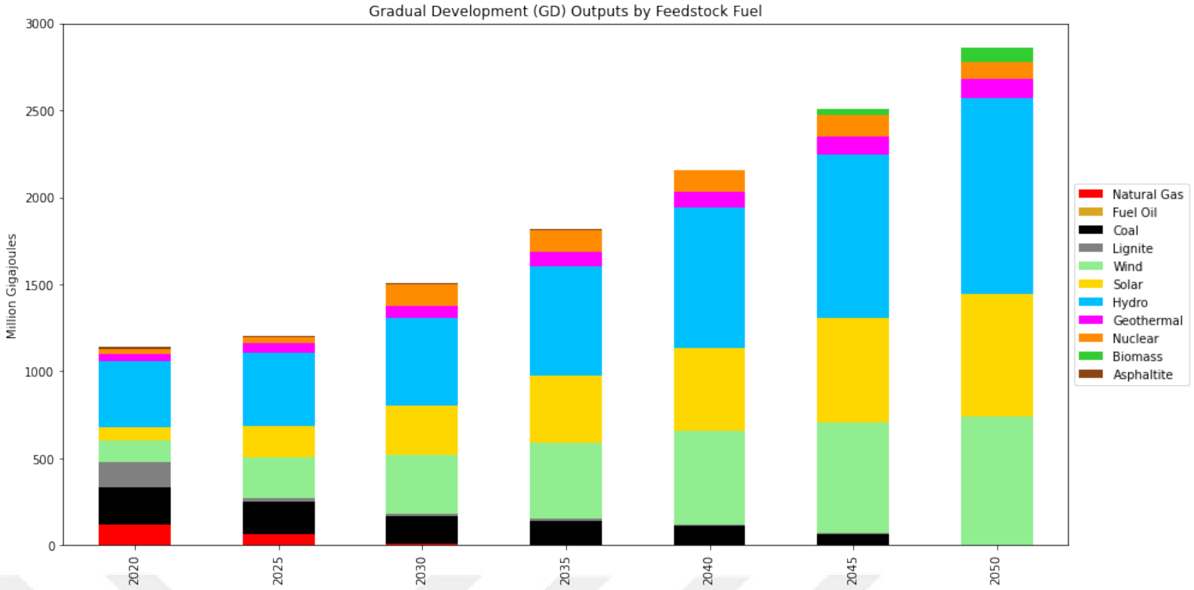


**Figure 3.23** Gradual Development (GD) Outputs by Feedstock Fuel

When we look at the change of capacities over the years in Figure 3.24, the increase in solar, wind, and hydro draw attention. However, the installed capacities of fossil fuels such as natural gas and lignite have decreased significantly.

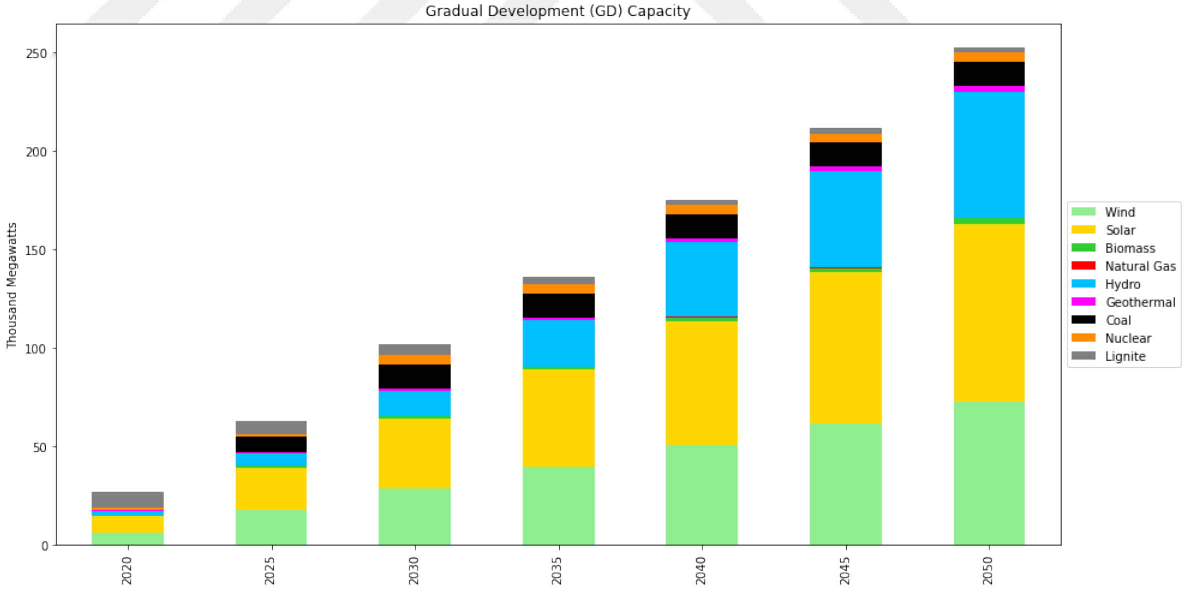


**Figure 3.24** Gradual Development (GD) Capacity

Consequently, the 100-Year GWP value, which was 98.84 Million Metric Tonnes $CO_2$ Equivalent in 2020, has been declining rapidly since 2020 and has been zeroed in 2050. It is possible to say that also this scenario fulfills Turkey's decarbonization target in electricity generation.

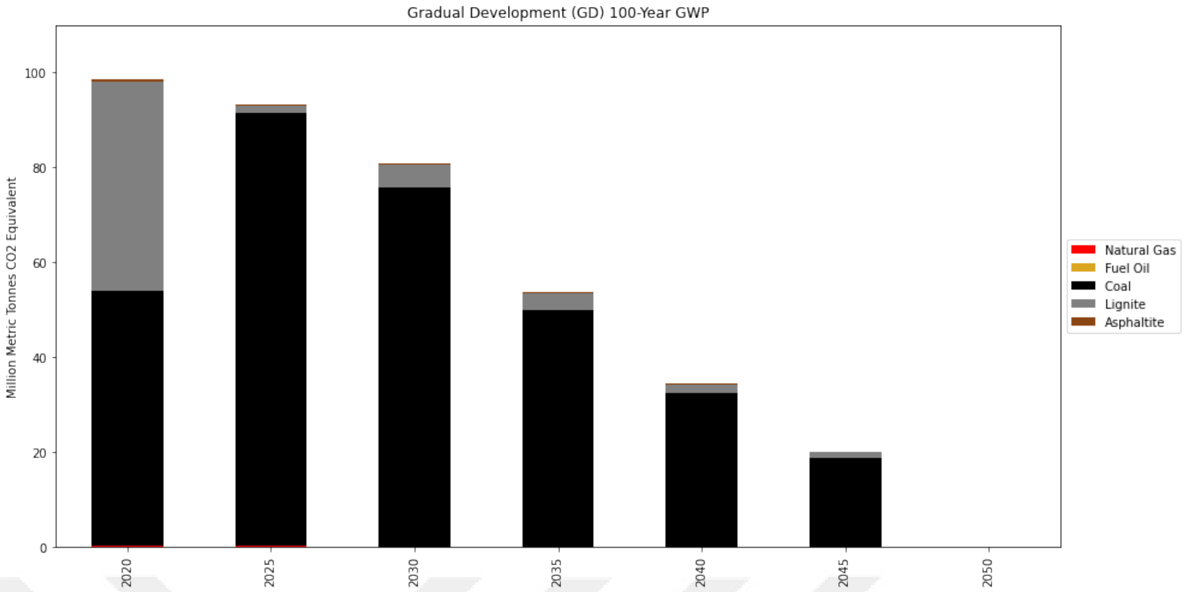


**Figure 3.25** Gradual Development (GD) 100-Year GWP

### 3.4.6 Comparison of the Scenarios

In this section, the electricity generation mixes and total capacities of the scenarios in 2050 are compared. Additionally, total costs of the scenarios over the years are represented. Figure 3.26 shows the electricity generation mixes by the end of 2050 for all four scenarios. Accordingly, it is seen that total electricity production in Societal Commitment and Techno-Friendly scenarios decreased slightly compared to the other two scenarios. The reason for this is the corresponding decrease in electricity demand with the increase of social awareness and the increase in the efficiency of power plants by encouraging the use of novel technologies in electricity generation. In all scenarios, it is seen that in the final year of the modeling, all of the electricity generation was supplied from renewable energy sources as desired; only the percentages of the sources changed based on the scenario.

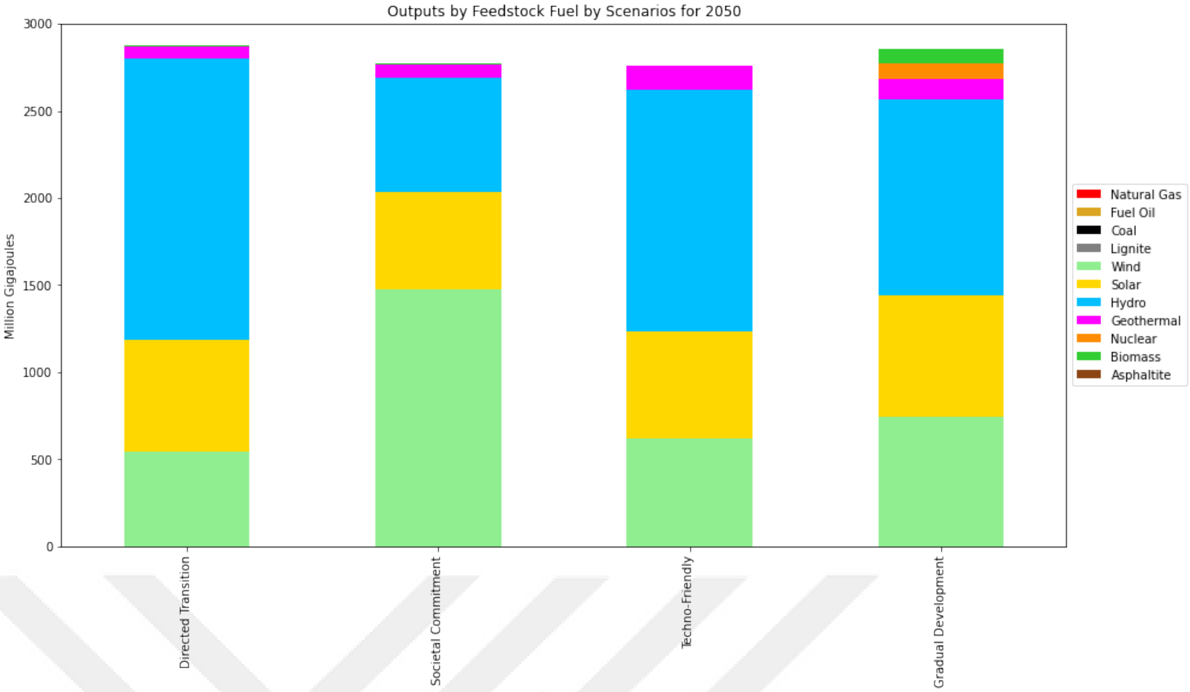


**Figure 3.26** Outputs by Feedstock by All Scenarios

Further, the installed capacities of all scenarios at the end of 2050 are given in Figure 3.27. Accordingly, it has been observed that the installed capacities of Societal Commitment and Techno-Friendly scenarios, which have lower electricity demands and generation compared to the other two scenarios, are also lower than Directed Transition and Gradual Development Scenarios. In these scenarios, which are more pushing than the other two scenarios, the installed capacity ratios of fossil fuels at the end of 2050 are 4.5% for the Societal Commitment and 7.9% for the Tecno-Friendly scenario. While the installed capacity rate of fossil fuels for 2050 is 18.03% in the Directed Transition scenario, this ratio is the highest with 19.05% in the Gradual Development Scenario.

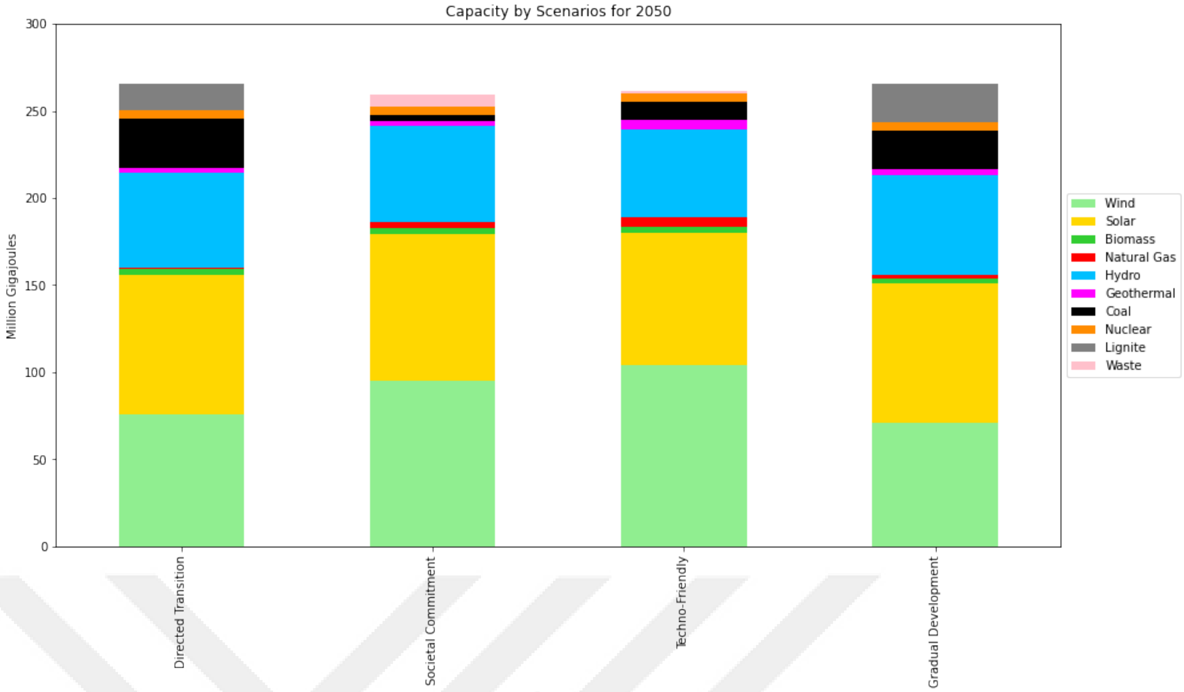


**Figure 3.27** Capacity by All Scenarios

Next, GHG emission values for all scenarios over the years are given in Figure 3.28. Accordingly, the unavoidable increase in the reference scenario draws attention once again. If we take a look at the other four scenarios, it seems that the rapid decline in Gradual Development in the first years has become slower and more stable after 2030. Conversely, emission values, which decreased more slowly in the first years of modeling in Directed Transition, started to accelerate after 2035. When we look at the relatively similar Societal Commitment and Techno-Friendly scenarios, it is seen that the emission in the TF decreased rapidly from the first years of the modeling, whereas the decrease in the SC remained a bit slower. However, it is seen that these two scenarios achieve zeroized emission values in 2045.

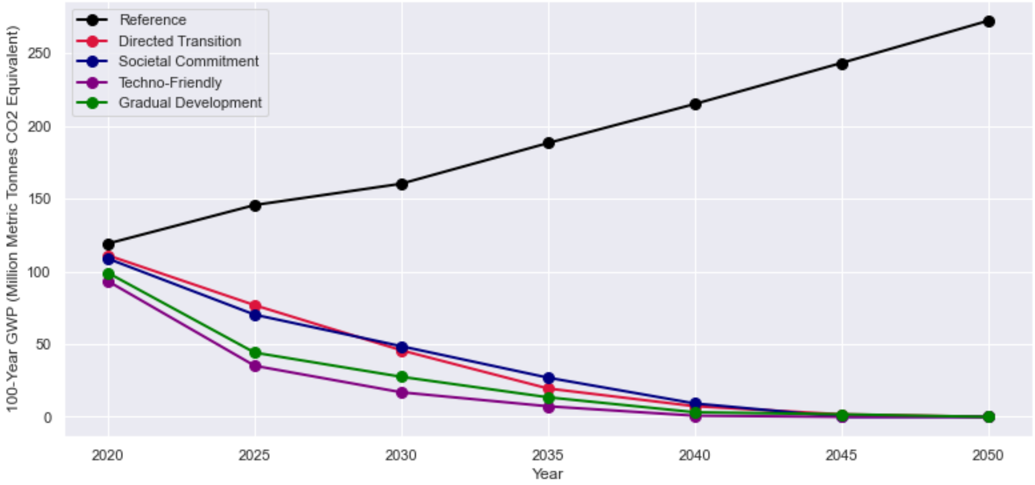


**Figure 3.28** 100-Year GWP by All Scenarios

Finally, the total costs of each scenario are represented in the Figure 3.29. In terms of total cost value, Techno-Friendly scenario is the most expensive one from 2020 until 2035. The reason for this situation can be attributed to the establishment of novel power plants and/or the improvement of existing plants in order to increase the use of new technologies in the early years. From 2035 to 2050, the most expensive scenario is the Societal Commitment. The reason why the Techno-Friendly scenario has left its place can be interpreted as the maintenance cost of the power plants is not as high as the installation costs of the novel plants. Accordingly, if we look at the total costs of the scenarios between the years 2020-2050, it is seen that the Gradual Development scenario is more balanced in terms of cost and is the lowest cost scenario among the four scenarios.

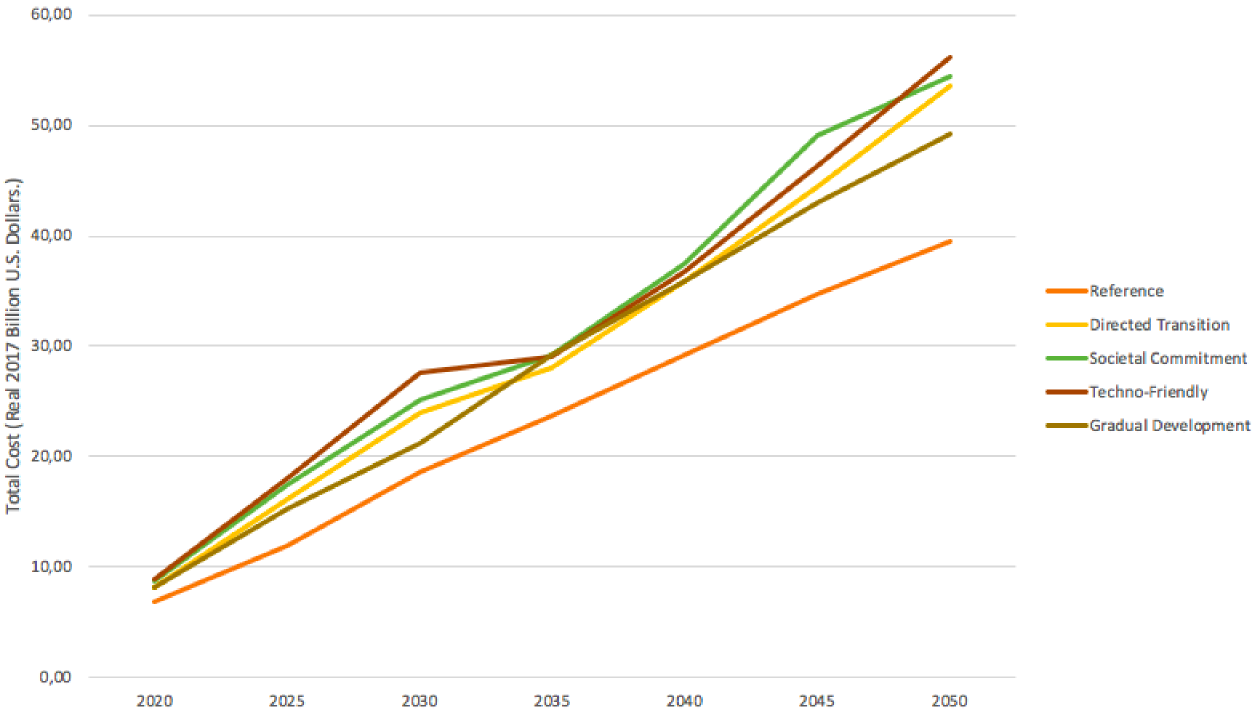


**Figure 3.29** Total Costs by All Scenarios

# 4. CONCLUSION AND DISCUSSIONS

One of the most critical threats affecting human life and our environment, which has increased importance over the years, is global warming. In line with the studies, it has been revealed that one of the most important causes of global warming is greenhouse gases released into the atmosphere. One of the biggest causes of greenhouse gas emissions is the energy sector. In this study, it is aimed to decarbonize Turkey's electricity generation by scenario development. In this direction, five different scenarios were created, and the results were compared. First, a Reference Scenario was created by considering Turkey's current policies. Thanks to this scenario, Turkey's general situation in electricity generation between the years 2020-2050 has been examined. As expected, it has been revealed that if the decision-makers in Turkey do not change their electricity generation strategies, greenhouse gas emissions will gradually increase, and the Paris Agreement targets will not be achieved. At this stage, the idea that if it is desired to make a positive change for the coming years, it is necessary to take a step now has been strengthened. In this direction, four scenarios created by the openENTRANCE project aiming to decarbonize the greenhouse gas emissions of the European Union countries and designed in this direction were taken into account and adapted to the Turkish electricity sector within the scope of this study.

In this context, the first adapted scenario is the Directed Transition scenario. Within the scope of this scenario, the strategies implemented by the decision-makers without the full support of society and without adapting to new technologies are modeled. As a result, carbon emissions in Turkey's electricity generation started to decrease as of 2020, and it was zeroed in 2050. Nevertheless, the decrease in this scenario is slighter, as new technology and social adaptation aspects are missing.

Then, the Societal Commitment scenario was adapted to the Turkish electricity sector. In this scenario, society's adaptation to a greener and more sustainable energy transformation is considered the main parameter. So much so that with the increase in social awareness and sustainability in energy, it is predicted that the energy demand will decrease over the years. Parallel to this, with the increasing tendency towards new technologies and renewable fuels while meeting the energy demand, it has been ensured that all of Turkey's electricity production will be produced from renewable energy sources in 2050. In this context, carbon emissions in electricity generation have decreased since 2020 and zeroed in 2045.

The third scenario is Techno-Friendly. As the name suggests, this scenario is basically based on the adaptation to novel technologies in electricity generation. In addition, it also assumed the positive inclination of the society to these technologies. In this respect, it is similar to the Societal Commitment scenario. However, in this scenario, the use of fossil fuels continued, albeit with technologies that reduce GHG emissions. For this reason, the emissions in the electricity generation sector were only zeroed in 2050, unlike the Societal Commitment scenario.

Finally, the Gradual Development scenario is modeled for the Turkish electricity sector. This scenario can be considered as a mixture of the previous three scenarios. Since the effects of the previous three parameters are modeled together, it can be said that this scenario gives more balanced and slower results. In this context, it has been ensured that all electricity production in Turkey is produced from renewable energy sources in 2050. In addition, GHG emissions, which have been steadily decreasing since 2020, have been zeroed in 2050.

As a result of this study, the decarbonization of Turkey's electricity generation sector was aimed, and the results of the applied scenarios were studied until 2050. In this direction, it has been seen that adaptation to new technologies, social awareness, and incentives of decision-makers are the important rings of the chain in this change. Although these rings give the expected results separately, it has been revealed that they give more balanced and controlled results as expected when taken together as a chain. In this regard, Gradual Development scenarios is considered as more balanced and easier to implement in Turkish electricity sector. When the scenarios are compared in terms of total cost values, the fact that the scenario with the lowest cost is Gradual Development also supports this interpretation. Therefore, to achieve the decarbonization goal in the electricity sector, policy-makers should define greenhouse gas emission reduction targets or carbon prices. For instance, creating a carbon trading system for all sectors and collecting tax from individuals may be useful methods. At the same time giving technology-based support for novel technologies may also be helpful.

# APPENDIX A: INSTALLED CAPACITY MAPS BY CITIES

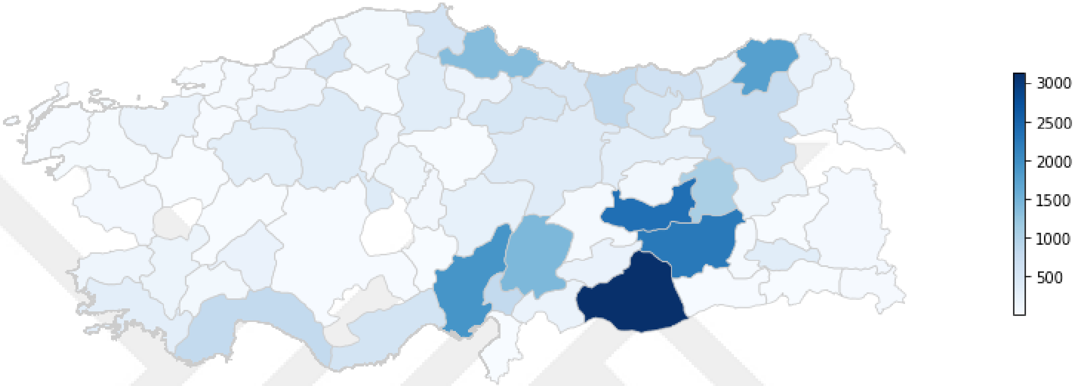


**Figure A.1** Installed Capacity of Hydro Power Plants in Turkey, 2017 by City (MW)

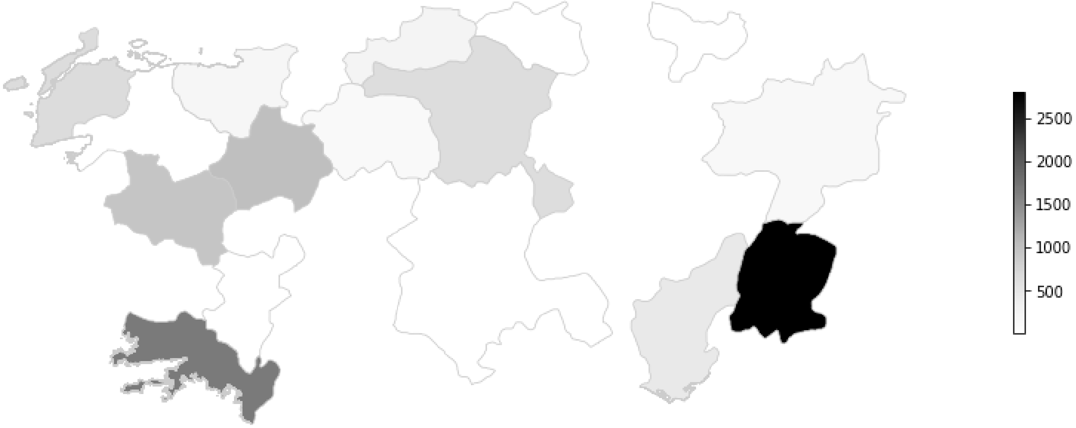


**Figure A.2** Installed Capacity of Lignite Power Plants in Turkey, 2017 by City (MW)

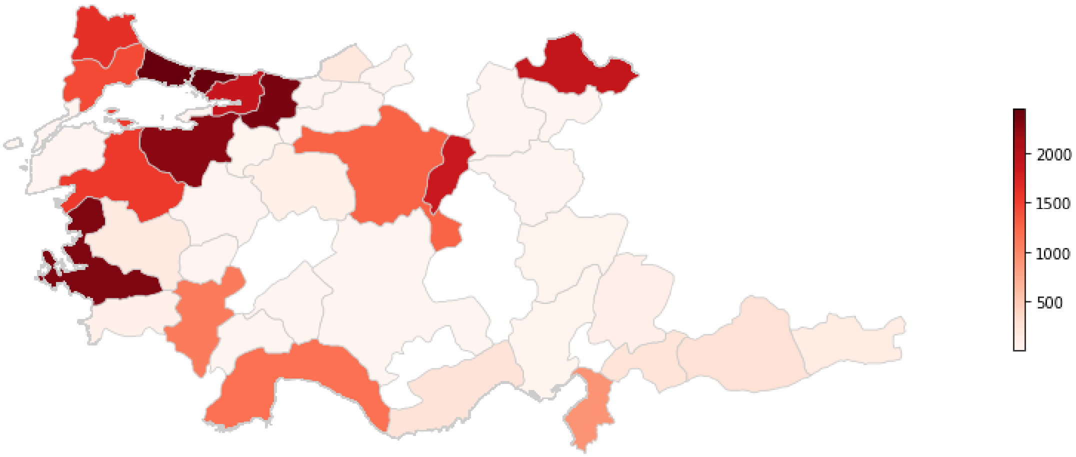


**Figure A.3** Installed Capacity of Natural Gas Power Plants in Turkey, 2017 by City (MW)

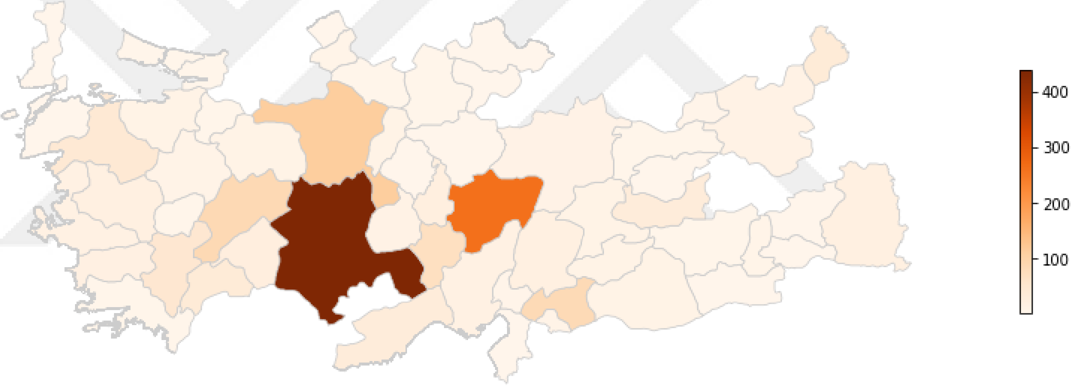


**Figure A.4** Installed Capacity of Solar Power Plants in Turkey, 2017 by City (MW)

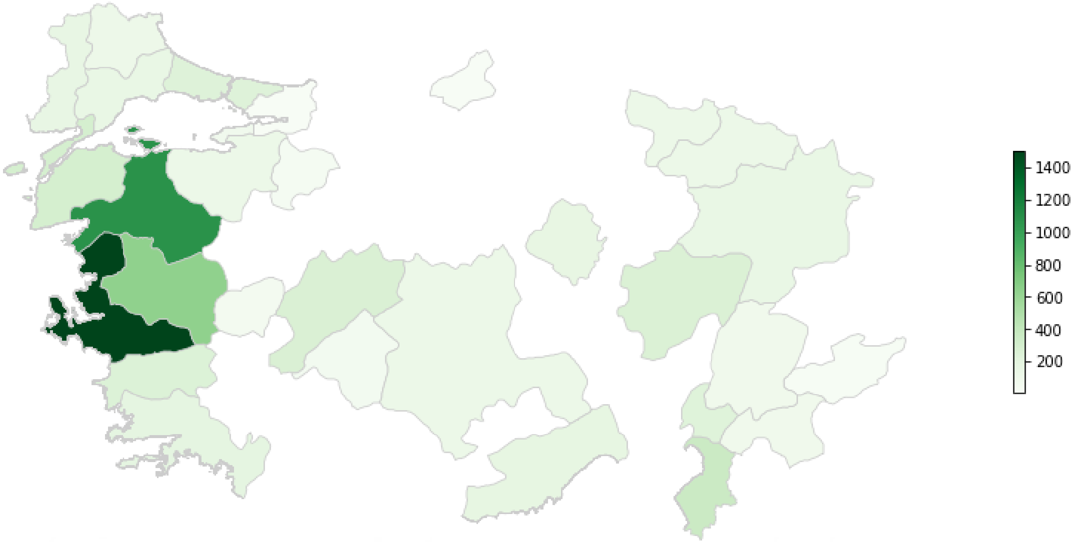


**Figure A.5** Installed Capacity of Wind Power Plants in Turkey, 2017 by City (MW)

# APPENDIX B: POWER PLANTS IN TURKEY

**Table B.1** Power Plants in Turkey by Fuel and Technology in 2017

| **Fuels and Technologies** | **Sum of Installed Capacities (MW)** |
|---|---|
| **Asphaltite** | **405** |
| Fluidized bed | 405 |
| **Biomass** | **535.68** |
| Anaerobic digestion biogas+gas engine | 354.72 |
| Cogeneration | 0.66 |
| Steam turbine biomass solid conventional | 180.3 |
| **Natural Gas** | **25850** |
| CHP- Combined cycle conventional | 734.81 |
| CHP- Internal combustion engine | 13.65 |
| CHP- Steam turbine | 78.29 |
| Combined-cycle | 24174.25 |
| Steam turbine | 849 |
| **Fuel Oil** | **1086.67** |
| Cogeneration | 42.96 |
| Combined-cycle | 1043 |
| **Hydro** | **28561.333** |
| Lake large scale hydroelectricity | 26953.3 |
| Lake medium scale hydroelectricity | 1590.47 |
| Lake very small hydroelectricity | 17.563 |

**Table B.2** Power Plants in Turkey by Fuel and Technology in 2017 cont'd

| **Fuels and Technologies** | **Sum of Installed Capacities (MW)** |
|---|---|
| **Imported Coal** | **9019.4** |
| CHP- Supercritical | 24 |
| Subcritical | 2135.4 |
| Supercritical | 6860 |
| **Geothermal** | **1305.47** |
| Geothermal hydrothermal with flash power plants | 1305.47 |
| **Coal** | **52** |
| Fluidized bed | 52 |
| **Lignite** | **9025.5** |
| CHP- Supercritical | 25.64 |
| Fluidized bed | 992.86 |
| Subcritical | 8007 |
| **Wind** | **7257.12** |
| Wind onshore 3 high | 7257.12 |
| **Solar** | **1633.974** |
| Solar PV roof <0.1 MW | 2.124 |
| Solar PV roof 0.1-10 MWp | 823.85 |
| Solar PV utility scale fixed systems large >10 MW | 808 |
| **Hard Coal** | **300** |
| Subcritical | 300 |
| **Total** | **85032.147** |

# APPENDIX C: LEAP MODEL OF TURKEY

**Table C.1** Time Slices of the LEAP Model

| **Time Slices** | **Number of Hours** | **Total Prod (MW)** | **% of Total Annual Prod** |
|---|---:|---:|---:|
| January Weekday Day | 242 | 9.352.451,68 | 3,2266% |
| January Weekday Night | 286 | 8.922.107,58 | 3,0781% |
| January Weekend Day | 99 | 3.208.786,17 | 1,1070% |
| January Weekend Night | 117 | 3.423.385,46 | 1,1811% |
| February Weekday Day | 220 | 8.324.066,91 | 2,8718% |
| February Weekday Night | 260 | 8.159.542,58 | 2,8150% |
| February Weekend Day | 88 | 2.848.890,50 | 0,9829% |
| February Weekend Night | 104 | 3.096.014,78 | 1,0681% |
| March Weekday Day | 299 | 10.399.266,67 | 3,5877% |
| March Weekday Night | 253 | 7.467.070,70 | 2,5761% |
| March Weekend Day | 104 | 3.124.854,71 | 1,0781% |
| March Weekend Night | 88 | 2.485.642,02 | 0,8575% |
| April Weekday Day | 260 | 8.764.676,77 | 3,0238% |
| April Weekday Night | 220 | 6.432.640,10 | 2,2193% |
| April Weekend Day | 130 | 3.793.540,68 | 1,3088% |
| April Weekend Night | 110 | 3.058.706,12 | 1,0553% |
| May Weekday Day | 273 | 9.275.410,08 | 3,2000% |
| May Weekday Night | 231 | 6.767.257,57 | 2,3347% |
| May Weekend Day | 130 | 3.813.040,77 | 1,3155% |
| May Weekend Night | 110 | 3.036.282,11 | 1,0475% |

**Table C.2** Time Slices of the LEAP Model cont'd

| **Time Slices** | **Number of Hours** | **Total Prod (MW)** | **% of Total Annual Prod** |
|---|---:|---:|---:|
| June Weekday Day | 320 | 10.736.784,19 | 3,7042% |
| June Weekday Night | 160 | 4.940.672,26 | 1,7045% |
| June Weekend Day | 160 | 4.393.372,47 | 1,5157% |
| June Weekend Night | 80 | 2.221.951,96 | 0,7666% |
| July Weekday Day | 336 | 13.399.712,86 | 4,6229% |
| July Weekday Night | 168 | 6.005.444,59 | 2,0719% |
| July Weekend Day | 160 | 5.564.584,97 | 1,9198% |
| July Weekend Night | 80 | 2.723.681,90 | 0,9397% |
| August Weekday Day | 336 | 13.356.998,60 | 4,6082% |
| August Weekday Night | 168 | 5.958.312,65 | 2,0556% |
| August Weekend Day | 160 | 5.517.067,93 | 1,9034% |
| August Weekend Night | 80 | 2.628.933,88 | 0,9070% |
| September Weekday Day | 266 | 9.844.374,08 | 3,3963% |
| September Weekday Night | 190 | 6.101.010,63 | 2,1048% |
| September Weekend Day | 154 | 4.609.459,21 | 1,5903% |
| September Weekend Night | 110 | 3.165.837,49 | 1,0922% |
| October Weekday Day | 308 | 10.476.911,91 | 3,6145% |
| October Weekday Night | 220 | 6.513.650,39 | 2,2472% |
| October Weekend Day | 126 | 3.739.395,04 | 1,2901% |
| October Weekend Night | 90 | 2.539.614,69 | 0,8762% |
| November Weekday Day | 308 | 11.149.970,81 | 3,8467% |
| November Weekday Night | 220 | 6.881.448,77 | 2,3741% |
| November Weekend Day | 112 | 3.549.701,88 | 1,2246% |
| November Weekend Night | 80 | 2.393.991,99 | 0,8259% |
| December Weekday Day | 231 | 8.985.225,85 | 3,0999% |
| December Weekday Night | 273 | 8.953.319,40 | 3,0889% |
| December Weekend Day | 110 | 3.695.480,48 | 1,2749% |
| December Weekend Night | 130 | 3.986.700,24 | 1,3754% |
| **TOTAL** | **8760** | **289.787.245,08** | **99,9765%** |

**Table C.3** Fixed Operating and Maintenance Costs of Electricity Generation Technologies Considered in JRC-EU-TIMES (eur2010/kW)

| **JRC-EU TIMES Technology** | **Fixed Operating and Maintenance Costs** | | | |
|---|---|---|---|---|
| | **2010** | **2020** | **2030** | **2050** |
| Hard Coal Subcritical | 27 | 27 | 27 | 27 |
| Hard Coal Supercritical | 34 | 34 | 34 | 33 |
| Hard Coal Fluidized Bed | 50 | 50 | 50 | 50 |
| Hard Coal IGCC | 55 | 50 | 45 | 37 |
| Lignite Subcritical | 33 | 33 | 33 | 33 |
| Lignite Supercritical | 39 | 39 | 43 | 45 |
| Lignite Fluidized Bed | 55 | 50 | 45 | 37 |
| Lignite IGCC | 48 | 43 | 39 | 32 |
| Natural Gas Steam Turbine | 19 | 19 | 19 | 19 |
| Natural Gas OCGT Peak Device Advanced | 17 | 17 | 17 | 17 |
| Natural Gas Combined Cycle | 26 | 21 | 20 | 20 |
| Natural Gas OCGT Peak Device Conventional | 12 | 12 | 12 | 12 |
| Nuclear 3rd Generation LWR Planned | 43 | 43 | 43 | 43 |
| Nuclear 4th Generation Fast Reactor | 91 | 85 | 80 | 69 |
| Wind Onshore 1 Low | 32 | 25 | 23 | 20 |
| Wind Onshore 2 Medium | 34 | 27 | 24 | 21 |
| Wind Onshore 3 High | 36 | 29 | 27 | 25 |
| Wind Onshore 4 Very High | 40 | 32 | 29 | 27 |
| Hydro Lake Small <1MW | 18 | 18 | 18 | 18 |
| Hydro Lake Medium 1-10MW | 14 | 14 | 14 | 14 |
| Hydro Lake Large >10MW | 12 | 12 | 12 | 12 |
| Hydro Run of River | 15 | 17 | 16 | 16 |

**Table C.4** Fixed Operating and Maintenance Costs of Electricity Generation Technologies Considered in JRC-EU-TIMES cont'd (eur2010/kW)

| **JRC-EU TIMES Technology** | **Fixed Operating and Maintenance Costs** | | | |
|---|---|---|---|---|
| | **2010** | **2020** | **2030** | **2050** |
| Solar PV Large | 47 | 13 | 12 | 10 |
| Solar PV Roof <0.1MW | 55 | 21 | 17 | 12 |
| Solar PV Roof 0.1-10MW | 51 | 16 | 13 | 10 |
| Solar PV High Concentration | 104 | 40 | 32 | 22 |
| Solar CSP | 104 | 89 | 72 | 37 |
| Biomass Steam Turbine | 107 | 91 | 81 | 71 |
| Biomass Anaerobic Digestion | 130 | 127 | 125 | 120 |
| Geothermal Flash | 84 | 77 | 70 | 70 |
| Geothermal Enhanced | 350 | 280 | 210 | 210 |
| Coal CHP Subcritical | 33 | 33 | 33 | 33 |
| Coal CHP Supercritical | 52 | 48 | 41 | 41 |
| Lignite CHP Subcritical | 40 | 40 | 40 | 40 |
| Lignite CHP Supercritical | 57 | 54 | 49 | 49 |
| Natural Gas CHP Steam Turbine | 21 | 21 | 21 | 21 |
| Natural Gas CHP Combined Cycle | 26 | 25 | 24 | 24 |
| Natural Gas CHP Internal Combustion | 18 | 18 | 18 | 18 |

**Table C.5** Specific Investment Costs of Electricity Generation Technologies Considered in JRC-EU-TIMES (eur2010/kW)

| **JRC-EU TIMES Technology** | **Specific Investments Costs (overnight)** | | | |
|---|---|---|---|---|
| | **2010** | **2020** | **2030** | **2050** |
| Hard Coal Subcritical | 1365 | 1365 | 1365 | 1365 |
| Hard Coal Supercritical | 1705 | 1700 | 1700 | 1700 |
| Hard Coal Fluidized Bed | 2507 | 2507 | 2507 | 2507 |
| Hard Coal IGCC | 2758 | 2489 | 2247 | 1830 |
| Lignite Subcritical | 1552 | 1552 | 1552 | 1552 |
| Lignite Supercritical | 1856 | 1856 | 1856 | 1856 |
| Lignite Fluidized Bed | 2758 | 2489 | 2247 | 1830 |
| Lignite IGCC | 3009 | 2716 | 2451 | 1996 |
| Natural Gas Steam Turbine | 750 | 750 | 750 | 750 |
| Natural Gas OCGT Peak Device Advanced | 568 | 568 | 568 | 568 |
| Natural Gas Combined Cycle | 855 | 855 | 855 | 855 |
| Natural Gas OCGT Peak Device Conventional | 486 | 486 | 476 | 472 |
| Nuclear 3rd Generation LWR Planned | 5000 | 5000 | 5000 | 5000 |
| Nuclear 4th Generation Fast Reactor | | | | 4400 |
| Wind Onshore 1 Low | 1300 | 1200 | 1050 | 950 |
| Wind Onshore 2 Medium | 1400 | 1270 | 1190 | 1110 |
| Wind Onshore 3 High | 1600 | 1380 | 1270 | 1190 |
| Wind Onshore 4 Very High | 1700 | 1430 | 1320 | 1240 |
| Hydro Lake Small <1MW | 1800 | 1800 | 1800 | 1800 |
| Hydro Lake Medium 1-10MW | 1400 | 1400 | 1400 | 1400 |
| Hydro Lake Large >10MW | 1200 | 1200 | 1200 | 1200 |
| Hydro Run of River | 1454 | 1712 | 1575 | 1575 |

**Table C.6** Specific Investment Costs of Electricity Generation Technologies Considered in JRC-EU-TIMES cont'd (eur2010/kW)

| **JRC-EU TIMES Technology** | **Specific Investment Costs (overnight)** | | | |
|---|---|---|---|---|
| | **2010** | **2020** | **2030** | **2050** |
| Solar PV Large >10MW | 3165 | 895 | 805 | 650 |
| Solar PV Roof <0.1MW | 3663 | 1420 | 1135 | 775 |
| Solar PV Roof 0.1-10MW | 3378 | 1065 | 850 | 675 |
| Solar PV High Concentration | 6959 | 2698 | 2157 | 1473 |
| Solar CSP | 5200 | 2960 | 2400 | 1840 |
| Biomass Steam Turbine | 3069 | 2595 | 2306 | 2018 |
| Biomass Anaerobic Digestion | 3713 | 3639 | 3566 | 3426 |
| Geothermal Flash | 2400 | 2200 | 2000 | 2000 |
| Geothermal Enhanced | 10000 | 8000 | 6000 | 6000 |
| Coal CHP Subcritical | 1646 | 1645 | 1638 | 1638 |
| Coal CHP Supercritical | 2657 | 2441 | 2053 | 2053 |
| Lignite CHP Subcritical | 1872 | 1863 | 1863 | 1853 |
| Lignite CHP Supercritical | 2810 | 2567 | 2130 | 2130 |
| Natural Gas CHP Steam Turbine | 1182 | 1180 | 1157 | 1157 |
| Natural Gas CHP Combined Cycle | 823 | 822 | 816 | 816 |
| Natural Gas CHP Internal Combustion | 606 | 604 | 593 | 593 |

**Table C.7** Used Electricity Generation Technologies Considered in JRC-EU-TIMES

| **Fuel** | **The JRC-EU-TIMES Technology** |
|---|---|
| Asphaltite | Fluidized Bed |
| Coal | Fluidized Bed |
| | Subcritical |
| | IGCC |
| | IGCC Pre Comb. Capture |
| | Supercritical and Post Comb. Capture |
| | Supercritical and Oxyfueling Capture |
| | CHP Subcritical |
| | CHP Supercritical and Post Comb. Capture |
| | CHP Supercritical and Oxyfueling Capture |
| | CHP Integrated Gasification and Post Comb. Capture |
| | CHP Integrated Gasification and Pre Comb. Capture |
| | CHP Integrated Gasification and Oxyfueling Capture |
| Imported Coal | Subcritical |
| | Supercritical |
| | CHP Supercritical |

**Table C.8** Used Electricity Generation Technologies Considered in JRC-EU-TIMES cont'd

| **Fuel** | **The JRC-EU-TIMES Technology** |
|---|---|
| Fuel Oil | Combined Cycle |
| | Cogeneration |
| Natural Gas | Combined Cycle |
| | Combined Cycle and Post Comb. Capture |
| | Steam Turbine |
| | OCGT Peak Device Advanced |
| | OCGT Peak Device Conventional |
| | CHP Combined Cycle |
| | CHP Combined Cycle Advanced |
| | CHP Combined Cycle and Post Comb. Capture |
| | CHP Combined Cycle Pre Comb. Capture |
| | CHP Combined Cycle and Oxyfueling Capture |
| | CHP Steam Turbine |
| | CHP Internal Combustine |
| Nuclear | 3rd Generation Non-Planned |
| | 3rd Generation LWR-Planned |
| | 4th Generation Fast Reactor |
| Geothermal | Flash |
| | Enhanced Geothermal Systems |
| Ocean | Wave |
| | Tidal Energy Stream and Range |
| Wood | Steam Turbine |
| | Steam Turbine2 |
| | Organic Ranking Cycle |

**Table C.9** Used Electricity Generation Technologies Considered in JRC-EU-TIMES cont'd

| **Fuel** | **The JRC-EU-TIMES Technology** |
|---|---|
| Lignite | Fluidized Bed |
| | Subcritical |
| | Supercritical |
| | Supercritical and Post Comb. Capture |
| | Supercritical and Oxyfueling Capture |
| | IGCC |
| | IGCC Pre Comb. Capture |
| | CHP Subcritical |
| | CHP Supercritical |
| | CHP Supercritical and Post Comb. Capture |
| | CHP Supercritical and Oxyfueling Capture |
| | CHP Integrated Gasification Post Comb. Capture |
| | CHP Integrated Gasification Pre Comb. Capture |
| | CHP Integrated Gasification and Oxyfueling Capture |
| Wind | Onshore 1 Low |
| | Onshore 2 Medium |
| | Onshore 3 High |
| | Onshore 4 Very High |
| | Offshore 1 Low |
| | Offshore 2 Medium |
| | Offshore 3 High |
| | Offshore 4 Very High |

**Table C.10** Used Electricity Generation Technologies Considered in JRC-EU-TIMES cont'd

| **Fuel** | **The JRC-EU-TIMES Technology** |
|---|---|
| Solar | PV Utility Scale Fixed Systems Large >10 MW |
| | PV Roof <0.1MWp |
| | PV Roof 0.1-10 MWp |
| | PV High Concentration |
| | CSP |
| Biomass | Cogeneration |
| | Anaerobic Digestion Biogas + Gas Engine |
| | IGCC |
| | With Carbon Sequestration |
| Hydro | Lake Very Small Expensive Hydroelectricity <1 MW |
| | Lake Very Small Cheap Hydroelectricity <1 MW |
| | Lake Medium Scale Expensive Hydroelectricity1-10 MW |
| | Lake Medium Scale Cheap Hydroelectricity 1-10 MW |
| | Lake Large Scale Expensive Hydroelectricity >10 MW |
| | Lake Large Scale Cheap Hydroelectricity >10 MW |
| | Run of Rive Hydroelectricity |
| Waste | Steam Turbine Municipal Waste |
| | Anaerobic Digestion Sludges |
| | Internal Combust Biogas |

**Table C.11** Annual Electricity Demand Projections (TWh)

| **Year** | **Low Demand Scenario** | **Reference Scenario** | **High Demand Scenario** |
|---|---|---|---|
| 2017 | 268.4 | 266 | 264.2 |
| 2018 | 280.6 | 279 | 277.8 |
| 2019 | 292.8 | 292 | 291.4 |
| 2020 | 305 | 305 | 305 |
| 2021 | 317.2 | 318 | 318.6 |
| 2022 | 329.4 | 331 | 332.2 |
| 2023 | 341.6 | 344 | 345.8 |
| 2024 | 353.8 | 357 | 359.4 |
| 2025 | 366 | 370 | 373 |
| 2026 | 378.2 | 384 | 388.4 |
| 2027 | 390.4 | 398 | 403.8 |
| 2028 | 402.6 | 412 | 419.2 |
| 2029 | 414.8 | 426 | 434.6 |
| 2030 | 427 | 440 | 450 |
| 2031 | 438.6 | 453.4 | 465.4 |
| 2032 | 450.2 | 466.8 | 480.8 |
| 2033 | 461.8 | 480.2 | 496.2 |
| 2034 | 473.4 | 493.6 | 511.6 |
| 2035 | 485 | 507 | 527 |
| 2036 | 497 | 523.8 | 548.8 |
| 2037 | 509 | 540.6 | 570.6 |
| 2038 | 521 | 557.4 | 592.4 |
| 2039 | 533 | 574.2 | 614.2 |

**Table C.12** Annual Electricity Demand Projections (TWh) cont'd

| **Year** | **Low Demand Scenario** | **Reference Scenario** | **High Demand Scenario** |
|---|---|---|---|
| 2040 | 545 | 591 | 636 |
| 2041 | 557 | 607.8 | 657.8 |
| 2042 | 569 | 624.6 | 679.6 |
| 2043 | 581 | 641.4 | 701.4 |
| 2044 | 593 | 658.2 | 723.2 |
| 2045 | 605 | 675 | 745 |
| 2046 | 617 | 691.8 | 766.8 |
| 2047 | 629 | 708.6 | 788.6 |
| 2048 | 641 | 725.4 | 810.4 |
| 2049 | 653 | 742.2 | 832.2 |
| 2050 | 665 | 759 | 854 |

**Table C.13** Technical Lifetime Data of The JRC-EU TIMES Technologies Considered in This Study

| **The JRC- EU TIMES Technology** | **Technical Lifetime (Years)** |
|---|---|
| Hard Coal Subcritical | 35 |
| Hard Coal Supercritical | 35 |
| Hard Coal Fluidized Bed | 35 |
| Hard Coal IGCC | 30 |
| Lignite Subcritical | 35 |
| Lignite Supercritical | 35 |
| Lignite Fluidized Bed | 35 |
| Lignite IGCC | 30 |
| Natural Gas Steam Turbine | 35 |
| Natural Gas OCGT Peak Device Advanced | 15 |
| Natural Gas Combined Cycle | 25 |
| Natural Gas OCGT Peak Device Conventional | 15 |
| Nuclear 3rd Generation LWR Planned | 50 |
| Nuclear 4th Generation Fast Reactor | 50 |
| Wind Onshore 1 Low | 25 |
| Wind Onshore 2 Medium | 25 |
| Wind Onshore 3 High | 25 |
| Wind Onshore 4 Very High | 25 |
| Hydro Lake Very Small <1MW | 75 |
| Hydro Lake Medium 1-10MW | 75 |
| Hydro Lake Large >10MW | 75 |
| Hydro Run of River | 75 |

**Table C.14** Technical Lifetime Data of The JRC-EU TIMES Technologies Considered in This Study cont'd

| **The JRC- EU TIMES Technology** | **Technical Lifetime (Years)** |
|---|---|
| Solar PV Large >10MW | 30 |
| Solar PV Roof <0.1MW | 30 |
| Solar PV Roof 0.1-10MW | 30 |
| Solar PV High Concentration | 30 |
| Solar CSP | 30 |
| Biomass Steam Turbine | 20 |
| Biomass Anaerobic Digestion | 25 |
| Geothermal Flash | 30 |
| Geothermal Enhanced | 30 |
| Coal CHP Subcritical | 25 |
| Coal CHP Supercritical | 30 |
| Lignite CHP Subcritical | 25 |
| Lignite CHP Supercritical | 30 |
| Natural Gas CHP Steam Turbine | 25 |
| Natural Gas CHP Combined Cycle | 25 |
| Natural Gas CHP Internal Combustion | 25 |

# APPENDIX D: NUMERICAL RESULTS OF REFERENCE SCENARIO

**Table D.1** Reference Scenario (REF) Outputs by Feedstock Fuel

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 8.51 | 6.74 | 4.97 | 3.19 | 1.40 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 31.03 | 31.03 | 124.13 | 124.13 | 124.13 | 124.13 | 124.13 |
| Wind Onshore 3 High | 103.70 | 162.10 | 220.51 | 278.91 | 337.31 | 395.72 | 454.12 |
| Solar PV Roof >10MW | 22.07 | 48.67 | 75.26 | 101.86 | 128.46 | 155.05 | 181.65 |
| Solar PV Roof <0.1MW | 1.39 | 3.68 | 5.97 | 8.26 | 10.56 | 12.85 | 15.14 |
| Solar PV Roof 0.1-10MW | 22.18 | 48.76 | 75.34 | 101.91 | 128.49 | 155.07 | 181.65 |
| Biomass Anaerobic Digestion | 0.00 | 0.51 | 0.36 | 0.34 | 0.34 | 0.34 | 1.19 |
| Biomass Steam Turbine | 0.00 | 0.25 | 0.29 | 0.20 | 0.20 | 0.20 | 0.58 |
| Natural Gas CC | 103.02 | 69.85 | 11.48 | 9.40 | 7.99 | 7.63 | 5.69 |
| Natural Gas Steam Turbine | 4.57 | 1.58 | 1.17 | 0.81 | 0.97 | 0.48 | 0.33 |
| Natural Gas CHP Steam Turbine | 0.97 | 0.62 | 0.16 | 0.07 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP CC | 13.67 | 2.58 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP Internal Comb | 0.18 | 0.09 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table D.2** Reference Scenario (REF) Outputs by Feedstock Fuel cont'd

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Fuel Oil CC | 0.00 | 0.42 | 0.28 | 0.14 | 0.00 | 0.00 | 0.00 |
| Fuel Oil Cogeneration | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hydro Large Scale Expensive | 345.93 | 384.14 | 422.36 | 460.57 | 498.79 | 537.00 | 575.22 |
| Hydro Medium Scale Expensive | 21.07 | 21.07 | 21.07 | 21.07 | 21.07 | 21.07 | 21.07 |
| Hydro Small Scale Expensive | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Imported Coal Subcritical | 53.87 | 53.87 | 53.87 | 53.87 | 53.87 | 53.87 | 53.38 |
| Imported Coal Supercritical | 154.31 | 123.62 | 74.35 | 53.85 | 27.89 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.67 | 0.63 | 0.18 | 0.26 | 0.46 | 0.54 | 0.59 |
| Geothermal Flash | 42.70 | 52.14 | 61.58 | 71.02 | 80.46 | 89.90 | 99.34 |
| Coal Fluidized Bed | 1.05 | 0.80 | 0.47 | 0.25 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 4.32 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 195.07 | 342.78 | 481.14 | 681.82 | 855.43 | 954.10 |
| Lignite Fluidized Bed | 21.45 | 13.58 | 7.50 | 5.52 | 4.45 | 2.35 | 2.66 |
| Lignite Subcritical | 170.97 | 139.77 | 109.61 | 77.94 | 48.25 | 47.53 | 46.60 |
| Lignite CHP Supercritical | 0.64 | 0.46 | 0.12 | 0.08 | 0.06 | 0.00 | 0.00 |
| **Total** | **1128.5** | **1362.3** | **1614.1** | **1855.1** | **2157.2** | **2459.4** | **2761.6** |

**Table D.3** Reference Scenario (REF) Capacity

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 0.36 | 0.29 | 0.21 | 0.14 | 0.06 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 1.20 | 1.20 | 4.80 | 4.80 | 4.80 | 4.80 | 4.80 |
| Wind Onshore 3 High | 10.96 | 17.13 | 23.31 | 29.48 | 35.65 | 41.83 | 48.00 |
| Solar PV Roof >10MW | 2.92 | 6.43 | 9.94 | 13.46 | 16.97 | 20.49 | 24.00 |
| Solar PV Roof <0.1MW | 0.18 | 0.49 | 0.79 | 1.09 | 1.39 | 1.70 | 2.00 |
| Solar PV Roof 0.1-10MW | 2.93 | 6.44 | 9.95 | 13.47 | 16.98 | 20.49 | 24.00 |
| Biomass Anaerobic Digestion | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 |
| Biomass Steam Turbine | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |
| Natural Gas CC | 19.75 | 12.66 | 5.29 | 5.00 | 5.00 | 5.00 | 5.00 |
| Natural Gas Steam Turbine | 0.76 | 0.60 | 0.73 | 0.60 | 0.60 | 0.60 | 0.60 |
| Natural Gas CHP Steam Turbine | 0.07 | 0.05 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP CC | 0.51 | 0.15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP Internal Comb | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil CC | 0.92 | 0.69 | 0.46 | 0.23 | 0.00 | 0.00 | 0.00 |
| Fuel Oil Cogeneration | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |

**Table D.4** Reference Scenario (REF) Capacity cont'd

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Hydro Large Scale Expensive | 28.87 | 32.06 | 35.24 | 38.43 | 41.62 | 44.81 | 48.00 |
| Hydro Medium Scale Expensive | 1.59 | 1.59 | 1.59 | 1.59 | 1.59 | 1.59 | 1.59 |
| Hydro Small Scale Expensive | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Hydro Large Scale Cheap | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.66 |
| Imported Coal Subcritical | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 |
| Imported Coal Supercritical | 6.13 | 4.90 | 3.68 | 2.45 | 1.23 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Geothermal Flash | 1.50 | 1.84 | 2.17 | 2.50 | 2.83 | 3.17 | 3.50 |
| Coal Fluidized Bed | 0.05 | 0.03 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 7.13 | 15.93 | 22.84 | 31.98 | 39.77 | 44.87 |
| Lignite Fluidized Bed | 0.92 | 0.81 | 0.69 | 0.58 | 0.46 | 0.46 | 0.46 |
| Lignite Subcritical | 7.23 | 5.93 | 4.63 | 3.34 | 2.04 | 2.04 | 2.04 |
| Lignite CHP Supercritical | 0.02 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| **Total** | **89.79** | **103.17** | **122.22** | **142.74** | **165.92** | **189.45** | **215.24** |

**Table D.5** Reference Scenario (REF) 100-Year GWP

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 0.53 | 0.40 | 0.29 | 0.18 | 0.08 | 0.00 | 0.00 |
| Natural Gas Steam Turbine | 0.61 | 0.21 | 0.15 | 0.11 | 0.13 | 0.06 | 0.04 |
| Natural Gas CHP Steam Turbine | 0.14 | 0.09 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP Internal Comb | 0.03 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil Cogeneration | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Subcritical | 15.52 | 14.97 | 14.46 | 14.30 | 14.14 | 13.99 | 13.71 |
| Imported Coal Supercritical | 39.62 | 30.74 | 17.92 | 12.98 | 6.72 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.19 | 0.17 | 0.05 | 0.07 | 0.12 | 0.14 | 0.15 |
| Coal Fluidized Bed | 0.27 | 0.20 | 0.11 | 0.06 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 1.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 59.08 | 101.22 | 142.07 | 201.33 | 252.59 | 281.73 |
| Lignite Fluidized Bed | 6.39 | 3.89 | 2.07 | 1.49 | 1.18 | 0.61 | 0.68 |
| Lignite Subcritical | 53.85 | 42.80 | 32.66 | 23.07 | 14.18 | 13.88 | 13.52 |
| Lignite CHP Supercritical | 0.16 | 0.11 | 0.03 | 0.02 | 0.01 | 0.00 | 0.00 |
| **Total** | **118.65** | **152.68** | **168.98** | **194.36** | **237.90** | **281.28** | **309.83** |

# APPENDIX E: NUMERICAL RESULTS OF DIRECTED TRANSITION SCENARIO

**Table E.1** Directed Transition (DT) Outputs by Feedstock Fuel

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 8.51 | 6.58 | 4.70 | 2.98 | 1.03 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 31.03 | 31.03 | 124.13 | 124.13 | 124.13 | 123.01 | 0.00 |
| Wind Onshore 1 Low | 2.75 | 7.34 | 11.93 | 16.51 | 21.10 | 25.69 | 10.03 |
| Wind Onshore 2 Medium | 3.01 | 8.03 | 13.04 | 18.06 | 23.08 | 28.10 | 15.98 |
| Wind Onshore 3 High | 118.32 | 201.09 | 283.86 | 366.64 | 449.41 | 532.18 | 518.88 |
| Solar PV Roof >10MW | 33.08 | 78.03 | 122.97 | 167.91 | 212.86 | 257.80 | 301.96 |
| Solar PV Roof <0.1MW | 5.52 | 14.69 | 23.86 | 33.03 | 42.21 | 51.38 | 33.50 |
| Solar PV Roof 0.1-10MW | 33.19 | 78.12 | 123.04 | 167.97 | 212.89 | 257.82 | 300.79 |
| Solar CSP | 1.00 | 2.68 | 4.35 | 6.02 | 7.69 | 9.37 | 6.87 |
| Biomass Cogeneration | 0.00 | 0.30 | 0.50 | 0.46 | 0.88 | 7.85 | 1.28 |
| Biomass Anaerobic Digestion | 0.00 | 1.08 | 1.43 | 1.75 | 3.28 | 22.93 | 3.37 |
| Biomass Steam Turbine | 0.00 | 0.33 | 0.20 | 0.34 | 0.20 | 2.57 | 1.12 |
| Natural Gas CC | 63.61 | 75.67 | 13.84 | 12.23 | 15.05 | 3.12 | 0.00 |
| Natural Gas Steam Turbine | 7.33 | 5.51 | 1.98 | 1.37 | 1.21 | 0.38 | 0.00 |
| Natural Gas CHP Steam Turbine | 1.23 | 0.97 | 0.14 | 0.08 | 0.00 | 0.00 | 0.00 |

**Table E.2** Directed Transition (DT) Outputs by Feedstock Fuel cont'd

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Natural Gas CHP CC | 4.52 | 1.44 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP Internal Comb | 0.22 | 0.15 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil CC | 0.00 | 0.42 | 0.28 | 0.14 | 0.00 | 0.00 | 0.00 |
| Fuel Oil Cogeneration | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hydro Large Scale Expensive | 345.93 | 384.14 | 422.36 | 460.57 | 498.79 | 537.00 | 554.07 |
| Hydro Medium Scale Expensive | 25.17 | 32.01 | 38.86 | 45.70 | 52.54 | 59.38 | 66.23 |
| Hydro Small Scale Expensive | 2.62 | 6.60 | 10.58 | 14.55 | 18.53 | 22.51 | 17.40 |
| Hydro Large Cheap | 0.00 | 0.00 | 0.00 | 0.00 | 17.66 | 181.78 | 977.33 |
| Hydro Run of River Hydroelectricity | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Subcritical | 46.27 | 31.00 | 30.04 | 23.09 | 15.73 | 8.01 | 0.00 |
| Imported Coal Supercritical | 144.53 | 92.34 | 71.92 | 59.84 | 27.58 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 2.66 | 0.67 | 0.14 | 0.42 | 0.45 | 0.35 | 0.00 |
| Geothermal Flash | 42.70 | 52.14 | 61.58 | 71.02 | 80.46 | 89.90 | 66.22 |
| Coal Fluidized Bed | 4.07 | 0.79 | 0.40 | 0.23 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 3.36 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 2.46 | 75.15 | 62.31 | 55.60 | 49.22 | 22.17 | 0.00 |
| Lignite Fluidized Bed | 21.85 | 19.12 | 12.48 | 9.22 | 5.13 | 8.29 | 0.00 |
| Lignite Subcritical | 170.39 | 137.39 | 72.04 | 75.03 | 32.12 | 32.51 | 0.00 |
| Lignite CHP Supercritical | 0.65 | 0.48 | 0.08 | 0.13 | 0.07 | 0.00 | 0.00 |
| Waste Internal Combust Biogas | 0.00 | 0.00 | 0.00 | 0.00 | 3.91 | 5.27 | 0.00 |
| **Total** | **1128.5** | **1362.3** | **1614.1** | **1855.1** | **2157.2** | **2459.4** | **2875.1** |

**Table E.3** Directed Transition (DT) Capacity

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite FB | 0.36 | 0.29 | 0.21 | 0.14 | 0.06 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 1.20 | 1.20 | 4.80 | 4.80 | 4.80 | 4.80 | 4.80 |
| Wind Onshore 1 Low | 0.55 | 1.45 | 2.36 | 3.27 | 4.18 | 5.09 | 6.00 |
| Wind Onshore 2 Medium | 0.45 | 1.21 | 1.97 | 2.73 | 3.48 | 4.24 | 5.00 |
| Wind Onshore 3 High | 12.51 | 21.26 | 30.00 | 38.75 | 47.50 | 56.25 | 65.00 |
| Solar PV Roof >10MW | 4.37 | 10.31 | 16.25 | 22.19 | 28.12 | 34.06 | 40.00 |
| Solar PV Roof <0.1MW | 0.73 | 1.94 | 3.15 | 4.36 | 5.58 | 6.79 | 8.00 |
| Solar PV Roof 0.1-10MW | 4.39 | 10.32 | 16.26 | 22.19 | 28.13 | 34.06 | 40.00 |
| Solar CSP | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Biomass Cogeneration | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Biomass Anaerobic Digestion | 0.50 | 0.75 | 1.00 | 1.25 | 1.50 | 1.75 | 2.00 |
| Biomass ST | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 1.00 |
| Natural Gas CC | 19.75 | 12.66 | 5.29 | 5.00 | 5.00 | 3.27 | 0.82 |
| Natural Gas ST | 0.76 | 0.60 | 0.72 | 0.60 | 0.60 | 0.47 | 0.40 |
| Natural Gas CHP ST | 0.07 | 0.05 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 |
| Fuel Oil CC | 0.92 | 0.69 | 0.46 | 0.23 | 0.00 | 0.00 | 0.00 |
| Hydro Large Expensive | 28.87 | 32.06 | 35.24 | 38.43 | 41.62 | 44.81 | 48.00 |
| Hydro Medium Expensive | 1.90 | 2.42 | 2.93 | 3.45 | 3.97 | 4.48 | 5.00 |
| Hydro Small Expensive | 0.20 | 0.50 | 0.80 | 1.10 | 1.40 | 1.70 | 2.00 |
| Hydro Large Cheap | 0.00 | 0.00 | 0.00 | 0.00 | 1.47 | 15.17 | 81.56 |
| Imported Coal Subcritical | 1.94 | 1.62 | 1.29 | 0.97 | 0.65 | 0.32 | 0.00 |
| Imported Coal Supercritical | 6.13 | 4.90 | 3.68 | 2.45 | 1.23 | 0.00 | 0.00 |
| Geothermal Flash | 1.50 | 1.84 | 2.17 | 2.50 | 2.83 | 3.17 | 3.50 |
| Coal Fluidized Bed | 0.05 | 0.03 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 1.97 | 7.55 | 11.23 | 14.78 | 14.78 | 14.78 |
| Lignite Fluidized Bed | 0.92 | 0.81 | 0.69 | 0.58 | 0.46 | 0.46 | 0.46 |
| Lignite Subcritical | 7.23 | 5.93 | 4.63 | 3.34 | 2.04 | 2.04 | 2.04 |
| **Total** | **96.42** | **115.69** | **142.56** | **170.9** | **202.7** | **241.38** | **334.13** |

**Table E.4** Directed Transition (DT) 100-Year GWP

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 0.53 | 0.39 | 0.27 | 0.17 | 0.06 | 0.00 | 0.00 |
| Natural Gas Steam Turbine | 0.97 | 0.73 | 0.26 | 0.18 | 0.16 | 0.05 | 0.00 |
| Natural Gas CHP Steam Turbine | 0.18 | 0.14 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP Internal Comb | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil Cogeneration | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Subcritical | 13.33 | 10.56 | 8.33 | 6.13 | 4.13 | 2.08 | 0.00 |
| Imported Coal Supercritical | 39.68 | 23.42 | 13.34 | 14.42 | 6.65 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.19 | 0.18 | 0.04 | 0.11 | 0.11 | 0.09 | 0.00 |
| Coal Fluidized Bed | 0.27 | 0.20 | 0.10 | 0.06 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 1.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 16.70 | 47.93 | 21.85 | 15.40 | 14.75 | 0.00 |
| Lignite Fluidized Bed | 6.51 | 5.47 | 3.44 | 2.49 | 1.36 | 2.16 | 0.00 |
| Lignite Subcritical | 53.67 | 42.07 | 21.46 | 12.20 | 9.44 | 9.49 | 0.00 |
| Lignite CHP Supercritical | 0.16 | 0.12 | 0.02 | 0.03 | 0.02 | 0.00 | 0.00 |
| Waste Internal Combust Biogas | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.03 | 0.00 |
| **Total** | **116.56** | **100.01** | **69.21** | **57.66** | **39.35** | **30.65** | **0.00** |

# APPENDIX F: NUMERICAL RESULTS OF SOCIETAL COMMITMENT SCENARIO

**Table F.1** Societal Commitment (SC) Outputs by Feedstock Fuel

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 8.51 | 6.74 | 4.97 | 3.13 | 1.05 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 31.03 | 31.03 | 124.13 | 124.13 | 119.95 | 0.00 | 0.00 |
| Wind Onshore 1 Low | 2.29 | 6.12 | 9.94 | 13.76 | 17.58 | 13.42 | 19.07 |
| Wind Onshore 2 Medium | 3.01 | 8.03 | 13.04 | 18.06 | 23.08 | 19.26 | 25.49 |
| Wind Onshore 3 High | 122.62 | 212.56 | 302.50 | 392.44 | 482.38 | 572.32 | 630.14 |
| Wind Onshore 4 Very High | 0.00 | 0.00 | 0.00 | 80.53 | 243.70 | 660.67 | 801.90 |
| Solar PV Roof >10MW | 33.08 | 78.03 | 122.97 | 167.91 | 212.86 | 226.19 | 228.38 |
| Solar PV Roof <0.1MW | 3.46 | 9.19 | 14.92 | 20.65 | 26.38 | 26.98 | 30.38 |
| Solar PV Roof 0.1-10MW | 34.57 | 81.79 | 129.01 | 176.22 | 223.44 | 260.78 | 286.44 |
| Solar PV High Concentration | 0.77 | 2.06 | 3.35 | 4.64 | 5.93 | 0.55 | 6.84 |
| Solar CSP | 1.00 | 2.68 | 4.35 | 6.02 | 7.69 | 3.09 | 9.21 |
| Biomass Anaerobic Digestion | 0.00 | 0.24 | 4.14 | 10.10 | 8.69 | 3.09 | 3.58 |
| Biomass Steam Turbine | 0.00 | 0.35 | 1.60 | 2.36 | 3.12 | 0.64 | 0.73 |
| Natural Gas CC | 84.09 | 99.76 | 74.88 | 45.00 | 32.69 | 0.00 | 0.00 |

**Table F.2** Societal Commitment (SC) Outputs by Feedstock Fuel cont'd

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Natural Gas Steam Turbine | 0.36 | 0.60 | 4.67 | 4.54 | 2.37 | 0.00 | 0.00 |
| Natural Gas CHP Steam Turbine | 0.18 | 0.39 | 0.61 | 0.28 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP CC | 13.10 | 3.77 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil CC | 0.00 | 0.00 | 0.28 | 0.14 | 0.00 | 0.00 | 0.00 |
| Hydro Large Scale Expensive | 342.66 | 375.43 | 408.20 | 440.96 | 473.73 | 506.50 | 536.11 |
| Hydro Medium Scale Expensive | 27.58 | 38.44 | 49.29 | 60.15 | 71.00 | 60.54 | 80.96 |
| Hydro Small Scale Expensive | 2.62 | 6.60 | 10.58 | 14.55 | 18.53 | 16.91 | 20.84 |
| Hydro Large Scale Cheap | 0.00 | 0.00 | 0.00 | 0.65 | 0.80 | 0.49 | 0.57 |
| Hydro Run of River Hydroelectricity | 1.03 | 2.75 | 4.47 | 6.19 | 7.91 | 9.63 | 10.31 |
| Imported Coal Subcritical | 44.18 | 29.93 | 14.96 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Supercritical | 157.58 | 131.77 | 105.22 | 69.01 | 24.72 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.67 | 0.68 | 0.54 | 0.47 | 0.36 | 0.00 | 0.00 |
| Geothermal Flash | 41.41 | 48.70 | 55.99 | 63.28 | 70.57 | 77.86 | 79.37 |
| Coal Subcritical | 4.32 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 92.66 | 82.62 | 70.62 | 53.50 | 0.00 | 0.00 |
| Lignite Fluidized Bed | 19.91 | 15.01 | 9.28 | 6.24 | 1.94 | 0.00 | 0.00 |
| Lignite Subcritical | 146.75 | 75.69 | 50.46 | 24.86 | 0.00 | 0.00 | 0.00 |
| Lignite CHP Supercritical | 0.65 | 0.51 | 0.29 | 0.17 | 0.06 | 0.00 | 0.00 |
| **Total** | **1128.5** | **1362.3** | **1614.1** | **1855.1** | **2159.1** | **2459.5** | **2770.6** |

**Table F.3** Societal Commitment (SC) Capacity

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 0.36 | 0.29 | 0.21 | 0.14 | 0.06 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 1.20 | 1.20 | 4.80 | 4.80 | 4.80 | 4.80 | 4.80 |
| Wind Onshore 1 Low | 0.45 | 1.21 | 1.97 | 2.73 | 3.48 | 4.24 | 5.00 |
| Wind Onshore 2 Medium | 0.45 | 1.21 | 1.97 | 2.73 | 3.48 | 4.24 | 5.00 |
| Wind Onshore 3 High | 12.96 | 22.47 | 31.97 | 41.48 | 50.99 | 60.49 | 70.00 |
| Wind Onshore 4 Very High | 0.00 | 0.00 | 0.00 | 6.38 | 19.32 | 69.75 | 76.38 |
| Solar PV Roof >10MW | 4.37 | 10.31 | 16.25 | 22.19 | 28.12 | 34.06 | 40.00 |
| Solar PV Roof <0.1MW | 0.46 | 1.21 | 1.97 | 2.73 | 3.49 | 4.24 | 5.00 |
| Solar PV Roof 0.1-10MW | 4.57 | 10.81 | 17.04 | 23.28 | 29.52 | 35.76 | 42.00 |
| Solar PV High Concentration | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Solar CSP | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Biomass Anaerobic digestion | 0.55 | 0.87 | 1.20 | 1.52 | 1.85 | 2.17 | 2.50 |
| Biomass Steam Turbine | 0.22 | 0.30 | 0.37 | 0.45 | 0.52 | 0.59 | 0.67 |
| Natural Gas CC | 20.88 | 15.39 | 10.49 | 5.00 | 4.63 | 3.27 | 3.27 |
| Natural Gas Steam Turbine | 0.74 | 0.55 | 0.78 | 0.60 | 0.45 | 0.45 | 0.45 |
| Natural Gas CHP Steam Turbine | 0.07 | 0.05 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP CC | 0.51 | 0.15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil CC | 0.92 | 0.69 | 0.46 | 0.23 | 0.00 | 0.00 | 0.00 |
| Hydro Large Scale Expensive | 28.59 | 31.33 | 34.06 | 36.80 | 39.53 | 42.27 | 45.00 |
| Hydro Medium Scale Expensive | 2.08 | 2.90 | 3.72 | 4.54 | 5.36 | 6.18 | 7.00 |
| Hydro Small Scale Expensive | 0.20 | 0.50 | 0.80 | 1.10 | 1.40 | 1.70 | 2.00 |
| Hydro Run of River Hydroelectricity | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Imported Coal Subcritical | 1.78 | 1.19 | 0.59 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Supercritical | 6.25 | 5.22 | 4.20 | 2.80 | 1.40 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Geothermal Flash | 1.46 | 1.72 | 1.97 | 2.23 | 2.49 | 2.74 | 3.00 |
| Coal CHP Subcritical | 0.00 | 3.32 | 3.32 | 3.32 | 3.32 | 3.32 | 3.32 |
| Lignite Fluidized Bed | 0.87 | 0.67 | 0.46 | 0.31 | 0.15 | 0.00 | 0.00 |
| Lignite Subcritical | 6.20 | 3.20 | 2.13 | 1.07 | 0.00 | 0.00 | 0.00 |
| Waste Internal Combust Biogas | 0.00 | 0.00 | 2.68 | 7.01 | 7.01 | 7.01 | 7.01 |
| **Total** | **96.7** | **117.6** | **144.7** | **175.2** | **213.6** | **290.1** | **325.6** |

**Table F.4** Societal Commitment (SC) 100-Year GWP

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 0.53 | 0.40 | 0.29 | 0.18 | 0.06 | 0.00 | 0.00 |
| Natural Gas Steam Turbine | 0.05 | 0.08 | 0.62 | 0.60 | 0.31 | 0.00 | 0.00 |
| Natural Gas CHP Steam Turbine | 0.03 | 0.06 | 0.09 | 0.04 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP Internal Comb | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil Cogeneration | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Subcritical | 12.73 | 8.32 | 4.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Supercritical | 40.46 | 32.77 | 25.36 | 16.64 | 5.96 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.19 | 0.18 | 0.14 | 0.12 | 0.09 | 0.00 | 0.00 |
| Coal Fluidized Bed | 0.27 | 0.20 | 0.13 | 0.06 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 1.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 28.06 | 24.40 | 20.85 | 15.80 | 0.00 | 0.00 |
| Lignite Fluidized Bed | 5.93 | 4.30 | 2.56 | 1.69 | 0.52 | 0.00 | 0.00 |
| Lignite Subcritical | 46.22 | 23.18 | 15.03 | 7.36 | 0.00 | 0.00 | 0.00 |
| Lignite CHP Supercritical | 0.16 | 0.12 | 0.07 | 0.04 | 0.01 | 0.00 | 0.00 |
| Waste Internal Combust Biogas | 0.00 | 0.00 | 0.03 | 0.13 | 0.12 | 0.00 | 0.00 |
| **Total** | **107.91** | **97.67** | **72.73** | **47.71** | **22.87** | **0.00** | **0.00** |

# APPENDIX G: NUMERICAL RESULTS OF TECHNO-FRIENDLY SCENARIO

**Table G.1** Techno Friendly (TF) Outputs by Feedstock Fuel

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 8.51 | 6.74 | 4.97 | 2.99 | 0.62 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 31.03 | 31.03 | 124.13 | 123.64 | 115.06 | 60.46 | 0.00 |
| Wind Onshore 1 Low | 2.29 | 6.12 | 9.94 | 13.76 | 17.58 | 21.41 | 15.31 |
| Wind Onshore 2 Medium | 3.01 | 8.03 | 13.04 | 18.06 | 23.08 | 28.10 | 24.80 |
| Wind Onshore 3 High | 122.62 | 212.56 | 302.50 | 392.44 | 482.38 | 572.32 | 580.47 |
| Wind Onshore 4 Very High | 33.77 | 79.86 | 125.95 | 172.04 | 218.13 | 264.22 | 270.91 |
| Solar PV Roof <0.1MW | 3.46 | 9.19 | 14.92 | 20.65 | 26.38 | 32.11 | 30.77 |
| Solar PV Roof 0.1-10MW | 34.57 | 81.79 | 129.01 | 176.22 | 223.44 | 270.66 | 293.64 |
| Solar PV High Concentration | 0.77 | 2.06 | 3.35 | 4.64 | 5.93 | 7.22 | 6.91 |
| Solar CSP | 1.00 | 2.68 | 4.35 | 6.02 | 7.69 | 9.37 | 9.25 |
| Biomass Anaerobic Digestion | 0.00 | 1.21 | 1.66 | 2.18 | 39.73 | 47.77 | 3.91 |
| Biomass Steam Turbine | 0.00 | 0.75 | 1.07 | 1.43 | 20.94 | 18.79 | 1.12 |
| Natural Gas CC | 129.40 | 124.17 | 47.10 | 18.65 | 7.30 | 2.80 | 0.00 |
| Natural Gas Steam Turbine | 0.00 | 0.10 | 0.95 | 1.21 | 0.33 | 0.00 | 0.00 |
| Natural Gas CHP Steam Turbine | 0.46 | 0.88 | 0.41 | 0.10 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP CC | 9.95 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table G.2** Techno Friendly (TF) Outputs by Feedstock Fuel cont'd

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Natural Gas CHP Internal Comb | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil CC | 0.00 | 0.42 | 0.28 | 0.14 | 0.00 | 0.00 | 0.00 |
| Hydro Large Scale Expensive | 342.66 | 375.43 | 408.20 | 440.96 | 473.73 | 506.50 | 536.00 |
| Hydro Medium Scale Expensive | 27.58 | 38.44 | 49.29 | 60.15 | 71.00 | 81.86 | 70.38 |
| Hydro Small Scale Expensive | 2.62 | 6.60 | 10.58 | 14.55 | 18.53 | 22.51 | 20.80 |
| Hydro Large Scale Cheap | 0.00 | 0.00 | 0.00 | 78.36 | 167.29 | 292.25 | 749.53 |
| Hydro Run of River Hydroelectricity | 1.03 | 2.75 | 4.47 | 6.19 | 7.91 | 9.63 | 11.03 |
| Imported Coal Subcritical | 53.55 | 53.87 | 53.87 | 51.08 | 21.74 | 5.62 | 0.00 |
| Imported Coal Supercritical | 119.33 | 51.18 | 15.14 | 9.33 | 2.40 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.67 | 0.68 | 0.62 | 0.59 | 0.22 | 0.20 | 0.00 |
| Geothermal Flash | 46.57 | 62.46 | 78.35 | 94.24 | 110.13 | 126.02 | 136.73 |
| Coal Fluidized Bed | 1.07 | 0.80 | 0.53 | 0.25 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 4.32 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 163.24 | 187.17 | 133.66 | 61.16 | 46.93 | 0.00 |
| Lignite Fluidized Bed | 20.42 | 15.32 | 10.21 | 4.85 | 0.00 | 0.00 | 0.00 |
| Lignite Subcritical | 127.23 | 23.65 | 11.83 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lignite CHP Supercritical | 0.56 | 0.28 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Waste Internal Combust Biogas | 0.00 | 0.00 | 0.19 | 6.61 | 34.48 | 35.50 | 0.00 |
| **Total** | **1128.5** | **1362.3** | **1614.1** | **1855.1** | **2157.2** | **2462.3** | **2761.6** |

**Table G.3** Techno Friendly (TF) Capacity

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 0.36 | 0.29 | 0.21 | 0.14 | 0.06 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 1.20 | 1.20 | 4.80 | 4.80 | 4.80 | 4.80 | 4.80 |
| Wind Onshore 1 Low | 0.45 | 1.21 | 1.97 | 2.73 | 3.48 | 4.24 | 5.00 |
| Wind Onshore 2 Medium | 0.45 | 1.21 | 1.97 | 2.73 | 3.48 | 4.24 | 5.00 |
| Wind Onshore 3 High | 12.96 | 22.47 | 31.97 | 41.48 | 50.99 | 60.49 | 70.00 |
| Wind Onshore 4 Very High | 4.46 | 10.55 | 16.64 | 22.73 | 28.82 | 34.91 | 41.00 |
| Solar PV Roof <0.1MW | 0.46 | 1.21 | 1.97 | 2.73 | 3.49 | 4.24 | 5.00 |
| Solar PV Roof 0.1-10MW | 4.57 | 10.81 | 17.04 | 23.28 | 29.52 | 35.76 | 42.00 |
| Solar PV High Concentration | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Solar CSP | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Biomass Anaerobic Digestion | 0.55 | 0.87 | 1.20 | 1.52 | 1.85 | 2.17 | 2.50 |
| Biomass Steam Turbine | 0.25 | 0.38 | 0.50 | 0.63 | 0.75 | 0.88 | 1.00 |
| Natural Gas CC | 20.98 | 15.65 | 10.33 | 5.00 | 5.00 | 5.00 | 5.00 |
| Natural Gas Steam Turbine | 0.57 | 0.09 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| Natural Gas CHP Steam Turbine | 0.07 | 0.05 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP CC | 0.37 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP Internal Comb | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil CC | 0.92 | 0.69 | 0.46 | 0.23 | 0.00 | 0.00 | 0.00 |

**Table G.4** Techno Friendly (TF) Capacity cont'd

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Fuel Oil Cogeneration | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| Hydro Large Scale Expensive | 28.59 | 31.33 | 34.06 | 36.80 | 39.53 | 42.27 | 45.00 |
| Hydro Medium Scale Expensive | 2.08 | 2.90 | 3.72 | 4.54 | 5.36 | 6.18 | 7.00 |
| Hydro Small Scale Expensive | 0.20 | 0.50 | 0.80 | 1.10 | 1.40 | 1.70 | 2.00 |
| Hydro Large Scale Cheap | 0.00 | 0.00 | 0.00 | 6.54 | 13.96 | 24.39 | 74.40 |
| Hydro Run of River Hydroelectricity | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Imported Coal Subcritical | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 |
| Imported Coal Supercritical | 4.73 | 2.03 | 0.60 | 0.40 | 0.20 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Geothermal Flash | 1.64 | 2.20 | 2.76 | 3.32 | 3.88 | 4.44 | 5.00 |
| Coal Fluidized Bed | 0.05 | 0.03 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 5.80 | 8.24 | 8.24 | 8.24 | 8.24 | 8.24 |
| Lignite Fluidized Bed | 0.86 | 0.65 | 0.43 | 0.22 | 0.00 | 0.00 | 0.00 |
| Lignite Subcritical | 5.38 | 1.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lignite CHP Supercritical | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Waste Internal Combust Biogas | 0.00 | 0.00 | 0.17 | 2.01 | 2.01 | 2.01 | 2.01 |
| **Total** | **94.81** | **116.04** | **144.36** | **175.59** | **211.68** | **251.27** | **330.71** |

**Table G.5** Techno Friendly (TF)100-Year GWP

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 0.53 | 0.40 | 0.29 | 0.17 | 0.04 | 0.00 | 0.00 |
| Natural Gas Steam Turbine | 0.00 | 0.01 | 0.13 | 0.16 | 0.04 | 0.00 | 0.00 |
| Natural Gas CHP Steam Turbine | 0.07 | 0.13 | 0.06 | 0.01 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP Internal Comb | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil Cogeneration | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Subcritical | 15.43 | 14.97 | 14.46 | 13.56 | 5.71 | 1.46 | 0.00 |
| Imported Coal Supercritical | 30.64 | 12.73 | 3.65 | 2.25 | 0.58 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.19 | 0.18 | 0.16 | 0.15 | 0.06 | 0.05 | 0.00 |
| Coal Fluidized Bed | 0.27 | 0.20 | 0.13 | 0.06 | 0.00 | 0.00 | 0.00 |
| Coal Subcritical | 1.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 49.44 | 55.27 | 39.47 | 18.06 | 13.86 | 0.00 |
| Lignite Fluidized Bed | 6.08 | 4.39 | 2.81 | 1.31 | 0.00 | 0.00 | 0.00 |
| Lignite Subcritical | 40.07 | 7.24 | 3.52 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lignite CHP Supercritical | 0.14 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Waste Internal Combust Biogas | 0.00 | 0.00 | 0.00 | 0.03 | 0.17 | 0.17 | 0.00 |
| **Total** | **94.77** | **89.76** | **80.48** | **57.18** | **24.65** | **15.54** | **0.00** |

# APPENDIX H: NUMERICAL RESULTS OF GRADUAL DEVELOPMENT SCENARIO

**Table H.1** Gradual Development (GD) Outputs by Feedstock Fuel

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 8.51 | 6.67 | 4.77 | 2.72 | 0.72 | 0.00 | 0.00 |
| Nuclear 3rd Gen LWR Planned | 31.03 | 31.03 | 124.13 | 124.13 | 124.13 | 124.13 | 95.79 |
| Wind Onshore 2 Medium | 3.01 | 8.03 | 13.04 | 18.06 | 23.08 | 28.10 | 33.11 |
| Wind Onshore 3 High | 126.92 | 224.03 | 321.13 | 418.24 | 515.35 | 612.45 | 709.56 |
| Solar PV Roof >10MW | 35.15 | 83.53 | 131.91 | 180.30 | 225.08 | 277.07 | 325.45 |
| Solar PV Roof <0.1MW | 2.77 | 7.35 | 11.94 | 16.52 | 20.45 | 25.69 | 30.27 |
| Solar PV Roof 0.1-10MW | 35.26 | 83.62 | 131.99 | 179.43 | 216.65 | 277.09 | 325.45 |
| Solar PV High Concentration | 0.77 | 2.06 | 3.35 | 4.56 | 4.69 | 7.22 | 8.51 |
| Solar CSP | 1.00 | 2.68 | 4.35 | 5.91 | 6.09 | 9.37 | 11.04 |
| Biomass Anaerobic Digestion | 0.00 | 1.21 | 1.66 | 2.25 | 2.33 | 27.99 | 63.07 |
| Biomass Steam Turbine | 0.00 | 0.58 | 0.60 | 0.48 | 0.83 | 7.94 | 18.90 |
| Natural Gas CC | 103.58 | 53.75 | 4.36 | 3.21 | 1.94 | 0.73 | 0.00 |
| Natural Gas Steam Turbine | 2.28 | 2.53 | 1.37 | 1.14 | 0.88 | 0.20 | 0.00 |
| Natural Gas CHP Steam Turbine | 0.30 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Natural Gas CHP CC | 16.86 | 6.62 | 0.77 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fuel Oil CC | 0.00 | 0.42 | 0.28 | 0.14 | 0.00 | 0.00 | 0.00 |
| Fuel Oil Cogeneration | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table H.2** Gradual Development (GD) Outputs by Feedstock Fuel cont'd

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Hydro Large Scale Expensive | 342.66 | 375.43 | 408.20 | 440.96 | 473.73 | 506.50 | 539.27 |
| Hydro Medium Scale Expensive | 27.58 | 38.44 | 49.29 | 60.15 | 71.00 | 81.86 | 92.72 |
| Hydro Small Scale Expensive | 2.62 | 6.60 | 10.58 | 14.55 | 18.53 | 22.51 | 26.49 |
| Hydro Large Scale Cheap | 0.00 | 0.00 | 30.47 | 108.47 | 236.64 | 316.47 | 452.83 |
| Hydro Run of River Hydroelectricity | 1.03 | 2.75 | 4.47 | 6.19 | 7.91 | 9.63 | 11.35 |
| Imported Coal Subcritical | 44.39 | 29.93 | 14.69 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Supercritical | 150.50 | 112.87 | 74.87 | 36.19 | 0.00 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.67 | 0.68 | 0.67 | 0.64 | 0.42 | 0.27 | 0.00 |
| Geothermal Flash | 43.99 | 55.58 | 67.17 | 78.76 | 90.35 | 101.94 | 113.53 |
| Coal Fluidized Bed | 1.08 | 0.88 | 0.65 | 0.41 | 0.14 | 0.00 | 0.00 |
| Coal Subcritical | 5.72 | 2.91 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 202.28 | 180.56 | 138.03 | 109.39 | 63.79 | 0.00 |
| Lignite Fluidized Bed | 21.85 | 19.12 | 16.39 | 13.34 | 6.78 | 4.30 | 0.00 |
| Lignite Subcritical | 118.36 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lignite CHP Supercritical | 0.65 | 0.51 | 0.38 | 0.24 | 0.07 | 0.00 | 0.00 |
| **Total** | **1128.5** | **1362.3** | **1614.1** | **1855.1** | **2157.2** | **2505.2** | **2899.2** |

**Table H.3** Gradual Development (GD) Capacity

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Nuclear 3rd Gen LWR Planned | 1.20 | 1.20 | 4.80 | 4.80 | 4.80 | 4.80 | 4.80 |
| Wind Onshore 2 Medium | 0.45 | 1.21 | 1.97 | 2.73 | 3.48 | 4.24 | 5.00 |
| Wind Onshore 3 High | 6.16 | 16.42 | 26.69 | 36.95 | 47.21 | 57.48 | 67.74 |
| Solar PV Roof >10MW | 3.84 | 10.23 | 16.62 | 23.01 | 29.41 | 35.80 | 42.19 |
| Solar PV Roof <0.1MW | 0.36 | 0.97 | 1.57 | 2.18 | 2.79 | 3.39 | 4.00 |
| Solar PV Roof 0.1-10MW | 3.83 | 10.22 | 16.61 | 23.01 | 29.40 | 35.79 | 42.18 |
| Solar PV High Concentration | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Solar CSP | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Biomass Anaerobic Digestion | 0.20 | 0.52 | 0.85 | 1.17 | 1.50 | 1.82 | 2.15 |
| Biomass Steam Turbine | 0.04 | 0.12 | 0.19 | 0.26 | 0.34 | 0.41 | 0.49 |
| Natural Gas Steam Turbine | 0.00 | 0.00 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| Hydro Large Scale Expensive | 1.64 | 4.37 | 7.11 | 9.84 | 12.58 | 15.31 | 18.05 |
| Hydro Medium Scale Expensive | 0.49 | 1.31 | 2.13 | 2.95 | 3.77 | 4.59 | 5.41 |
| Hydro Small Scale Expensive | 0.18 | 0.48 | 0.78 | 1.08 | 1.38 | 1.68 | 1.98 |
| Hydro Large Scale Cheap | 0.00 | 0.00 | 2.54 | 9.05 | 19.75 | 26.41 | 37.79 |
| Hydro Run of River Hydroelectricity | 0.09 | 0.24 | 0.39 | 0.55 | 0.70 | 0.85 | 1.00 |
| Geothermal Flash | 0.25 | 0.65 | 1.06 | 1.47 | 1.88 | 2.29 | 2.70 |
| Coal CHP Subcritical | 0.00 | 7.83 | 12.10 | 12.10 | 12.10 | 12.10 | 12.10 |
| **Total** | **17.7** | **55.1** | **91.6** | **127.7** | **167.9** | **204.1** | **245.1** |

**Table H.4** Gradual Development (GD) 100-Year GWP

| **Branch** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|
| Asphaltite Fluidized Bed | 0.53 | 0.40 | 0.28 | 0.16 | 0.04 | 0.00 | 0.00 |
| Natural Gas Steam Turbine | 0.30 | 0.34 | 0.18 | 0.15 | 0.12 | 0.03 | 0.00 |
| Natural Gas CHP Steam Turbine | 0.04 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Subcritical | 22.79 | 8.32 | 3.94 | 0.00 | 0.00 | 0.00 | 0.00 |
| Imported Coal Supercritical | 38.64 | 28.07 | 18.05 | 8.72 | 0.00 | 0.00 | 0.00 |
| Imported Coal CHP Supercritical | 0.19 | 0.18 | 0.17 | 0.16 | 0.11 | 0.07 | 0.04 |
| Coal Fluidized Bed | 0.28 | 0.22 | 0.16 | 0.10 | 0.03 | 0.00 | 0.00 |
| Coal Subcritical | 1.78 | 0.89 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Coal CHP Subcritical | 0.00 | 56.26 | 53.32 | 40.76 | 32.30 | 18.84 | 0.00 |
| Lignite Fluidized Bed | 6.51 | 5.47 | 4.52 | 3.61 | 1.80 | 1.12 | 0.00 |
| Lignite Subcritical | 37.28 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lignite CHP Supercritical | 0.16 | 0.12 | 0.09 | 0.06 | 0.02 | 0.00 | 0.00 |
| **Total** | **108.49** | **100.90** | **80.70** | **53.72** | **34.42** | **20.05** | **0.00** |

# APPENDIX I: SCENARIO DEVELOPMENT

**Table I.1** Exogenous Capacities for Each Scenario (Thousand MW)

| Resource | 2020 | | | | 2030 | | | | 2040 | | | | 2045 | | | | 2050 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DT | SC | TF | GD | DT | SC | TF | GD | DT | SC | TF | GD | DT | SC | TF | GD | DT | SC | TF | GD |
| Wind | 7.3 | 7.2 | 7.4 | 7.2 | 7.3 | 7.2 | 7.4 | 7.2 | 7.3 | 7.2 | 7.4 | 7.2 | 7.3 | 7.2 | 7.4 | 7.2 | 7.3 | 7.2 | 7.4 | 7.2 |
| Solar | 1.6 | 1.9 | 1.7 | 1.7 | 1.6 | 1.9 | 1.7 | 1.7 | 1.6 | 1.9 | 1.7 | 1.7 | 1.6 | 1.9 | 1.7 | 1.7 | 1.6 | 1.9 | 1.7 | 1.7 |
| Hydro | 28.6 | 28.8 | 28.5 | 28.6 | 28.6 | 28.8 | 28.5 | 28.6 | 28.6 | 28.8 | 28.5 | 28.6 | 28.6 | 28.8 | 28.5 | 28.6 | 28.6 | 28.8 | 28.5 | 28.6 |
| Biomass | 0.5 | 0.6 | 0.5 | 0.4 | 0.5 | 0.6 | 0.5 | 0.4 | 0.5 | 0.6 | 0.5 | 0.4 | 0.5 | 0.6 | 0.5 | 0.4 | 0.5 | 0.6 | 0.5 | 0.4 |
| Geothermal | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| Natural Gas | 21.1 | 22.21 | 22 | 20.4 | 5.5 | 10.3 | 10.3 | 2.6 | 4.6 | 3.5 | 5 | 1.4 | 2.3 | 2.1 | 5 | 1.2 | 0.1 | 2.1 | 5 | 1.1 |
| Nuclear | 1.2 | 1.2 | 1.2 | 1.2 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 |
| Coal | 8.3 | 8.2 | 7.1 | 8.04 | 5.01 | 4.8 | 2.7 | 3.6 | 1.89 | 1.4 | 2.3 | 0.33 | 0.34 | 0.02 | 2.1 | 0.02 | 0.02 | 0.02 | 2.1 | 0.02 |

**Table I.2** Maximum Capacities for Each Scenario (MW)

| Resource | 2017 | | | | 2050 | | | |
|---|---|---|---|---|---|---|---|---|
| | DT | SC | TF | GD | DT | SC | TF | GD |
| Wind | 7257.12 | 7257.12 | 7257.12 | 7257.12 | 76000 | 80000 | 80000 | 81000 |
| Solar | 1634.06 | 1634.06 | 1634.06 | 1634.06 | 88000 | 89000 | 90000 | 92000 |
| Hydro | 28561.3 | 28561.3 | 28561.3 | 28561.3 | 55000 | 55000 | 55000 | 55000 |
| Biomass | 535.02 | 535.02 | 535.02 | 535.02 | 3000 | 3000 | 3500 | 3000 |
| Geothermal | 1305 | 1305 | 1305 | 1305 | 3500 | 3000 | 5000 | 4000 |

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