SHURA Energy Transition Center

Net Zero 2053: A Roadmap for the Turkish Electricity Sector

About SHURA Energy Transition Center

SHURA Energy Transition Center, founded by the European Climate Foundation (ECF), Agora Energiewende and Istanbul Policy Center (IPC) at Sabancı University, contributes to decarbonisation of the energy sector via an innovative energy transition platform. It caters to the need for a sustainable and broadly recognized platform for discussions on technological, economic, and policy aspects of Türkiye's energy sector. SHURA supports the debate on the transition to a low-carbon energy system through energy efficiency and renewable energy by using fact-based analysis and the best available data. Taking into account all relevant perspectives by a multitude of stakeholders, it contributes to an enhanced understanding of the economic potential, technical feasibility, and the relevant policy tools for this transition.

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Disclaimer

This report and the assumptions made within the scope of the study have been drafted based on different scenarios and market conditions as of 2022 mid-year. Since these assumptions, scenarios and the market conditions are subject to change, it is not warranted that the forecasts in this report will be the same as the actual figures. The institutions and the persons who have contributed to the preparation of this report cannot be held responsible for any commercial gains or losses that may arise from the divergence between the forecasts in the report and the actual values.

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LIST OF ABBREVIATIONS

BaU	Business-as-Usual scenario
BECCS	Bioenergy carbon capture and storage
bpkm	Billion passenger kilometer
btkm	Billion tonne kilometer
boe	Barrel of oil equivalent
CBAM	Carbon Border Adjustment Mechanism
CCGT	Combined cycle power plants
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP27	27th United Nations Climate Change Conference
DRI	Direct reduced iron
EPDK	Energy Markets Regulatory Authority
EU	European Union
EV	Electric vehicles
GDP	Gross domestic product
GHG	Greenhouse gas
GT	Gas turbine
$GtCO_2$	One billion tonnes of carbon dioxide
GW	Gigawatt
GWh	Gigawatt hour
HDV	Heavy Duty Vehicles
ICE	Internal combustion engine
IEA	International Energy Agency
IMF	The International Monetary Fund
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
km	Kilometer
LCOE	Levelized cost of electricity
LDV	Light Duty Vehicles
MENR	Ministry of Energy and Natural Resources
MEUCC	Ministry of Environment, Urbanisation and Climate Change
Mt	Million tonnes

mtoe	Million tonnes of oil equivalent
NDC	Nationally Determined Contributions
NZ2053	Net Zero 2053 Scenario
OECD	Organisation for Economic Co-operation and Development
OPEC	Organisation of the Petroleum Exporting Countries
PtX	Power to X
PV	Photovoltaic
RES	Renewable energy sources
SMR	Small modular reactor
TCCB	Presidency of the Republic of Türkiye
TCMB	Central Bank of the Republic of Türkiye
TÜİK	Turkish Statistical Institute
TPP	Thermal Power Plant
TWh	Terawatt-hour
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
USGS	United States Geological Survey
VRES	Variable renewable energy sources
WACC	Weighted average cost of capital
WB	World Bank
WEO	World Energy Outlook

Key Messages

- **Türkiye can achieve 2053 net-zero emission goal through maximum integration of renewable energy sources (RES) into the system as well as increased levels of energy efficiency and electrification in end-use sectors.** The results of the study show that power generation from renewable energy is the most competitive option in meeting the increasing electricity demand in terms of cost, as well as the most effective way to reduce carbon emissions. The share of renewable energy in power generation constantly increases, reaching 90% in 2053.

- **Thanks to the reduction in energy intensity, Türkiye can achieve its net zero carbon goal without sacrificing economic growth and welfare.** With strong economic growth potential and the assumption that production will shift to high value-added and less energy-intensive products, the total energy demand increases until 2030 in parallel to the increased economic activity and then energy demand starts to decline due to the effect of electrification and energy efficiency although the economy continues to grow. In the study, it was concluded that by 2053, the final energy demand will be close to 2020 levels.

- **With the use of grid flexibility options, a high ratio of variable renewable energy sources can be integrated into the power grid.** In 2053, the share of solar and wind energy in total electricity generation will increase to 77%. In such system where the production from variable resources are very high, several grid flexibility options such as battery energy storage (30 GW/120 GWh), pumped hydro (3.2 GW) and electrolyzers (70 GW) are used. Additionally, the expansion of transmission and distribution grids are also taken into account.

- **It is possible to reach net zero emissions in sectors that are hard to decarbonize with direct electrification via the use of green hydrogen and other clean fuels.** Indirect electrification through the use of green hydrogen and other e-fuels (Power-to-X) will play a crucial role in the decarbonization of the transport and industrial sectors given their current reliance on fossil-fuels. Electrolyser capacities increase to 5.5 GW in 2035 and to 70 GW in 2053.

- **Between 2020 and 2055, an annual average of 15 billion USD (US$) worth of investments in the electricity sector is required to reach the net-zero emission level.** Between 2020 and 2055, a total of 526 billion US$ worth of investments, which includes the projected capacity expansions in electricity generation plants and grid as well as installing new storage systems is needed. It is expected that investment demand will trigger production in different areas, particularly domestic equipment production and installation, and contribute to growth. As a result of the investments, energy imports will decrease from its current level of 69% to 9% in 2053.

Executive Summary

With the signing of the Paris Climate Accords in 2015, a global majority of countries committed to taking action to mitigate global warming ideally below 1.5°C. In accordance, the European Commission approved the European Green Deal in 2020, which is a strategic policy program that aligns economic and social development with the aim of making the European Union (EU) climate neutral by 2050. The Deal includes a Carbon Border Adjustment Mechanism (CBAM), which enforces a carbon tax for third-party exports into the EU beginning in 2026. Motivated by the emerging global environment toward achieving climate neutrality by mid-century, Türkiye announced its "Green Deal Action Plan" in July 2021, which comprises targets and actions to transform Türkiye into a more sustainable and circular economy. In October 2021, Türkiye took significant steps in the fight against climate change by ratifying the Paris Agreement and, shortly thereafter, pledging to reach net-zero GHG emissions by 2053. These developments represent a decisive turning point for Türkiye's energy and climate policies. In this regard, the focus is currently on providing a new energy transition policy platform to design the necessary policies and action plans that enable economy-wide GHG emission reductions.

Türkiye requires a comprehensive energy transition roadmap that addresses economic and climate resilience, as well as environmental and human health. For the energy transition, the focus should be on reducing GHG emissions in buildings, transport and industry, which are the largest energy consumers. One of the most utilised strategies to achieve this is through electrification, which can be integrated to the system either directly (e.g., electric vehicles (EV), heat pumps etc.) or indirectly (e.g., green hydrogen or e-fuels produced by electrolysis). Yet, this strategy can only be successful if electricity generation is decarbonized first. In that regard, the power sector stands as the backbone for economy-wide decarbonization to achieve net-zero emissions.

By the end of 2022, approximately 54% (56 GW) of Türkiye's installed power capacity is based on renewable energy sources. When total electricity generation is considered, the share of the renewables is almost 40%, demonstrating that the Turkish electricity system is already on a successful transition to low-carbon technologies.

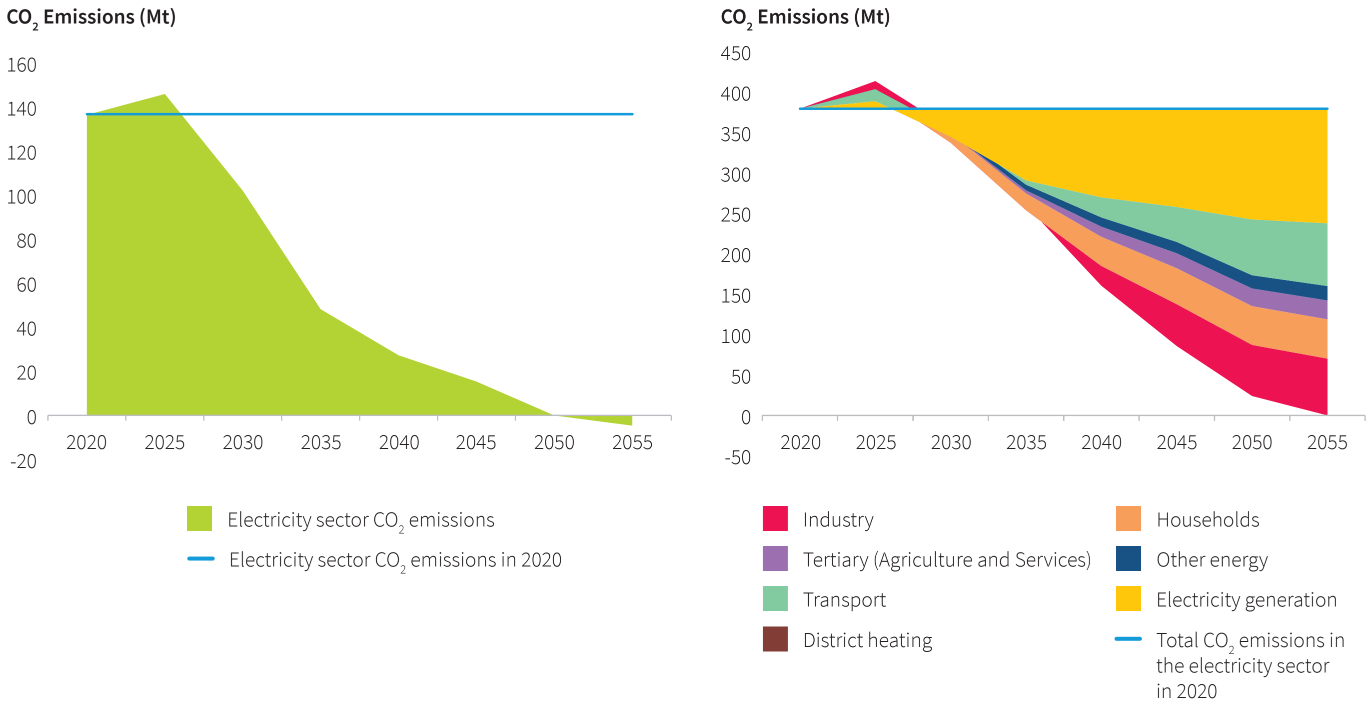
However, it should also be noted that electricity accounts for only 20% of total energy consumption in Türkiye, while the remaining share comes from the energy use in the buildings, transportation sector and manufacturing industry. All things considered, in order to mitigate the effects of climate change and ensure supply security, Türkiye needs to take decisive steps not only in the power sector but all other sectors as well.

The global fossil fuel crisis, which was triggered by the ongoing effects of Covid-19 pandemic and exacerbated by the Russian-Ukrainian conflict in 2022, further highlights the importance of energy transition. The crisis brought about a steep increase in energy prices throughout 2022. Shortages in primary energy sources led to cuts in the energy supply. High energy prices put households and business under pressure, and are nourishing the inflation. Therefore, 2022 has also demonstrated the social risk of relying on fossil fuels, which mostly need to be imported. Within this context, the crisis has increased awareness for the benefits of utilizing local renewable energy resources for energy affordability and energy supply security as well as environmental concerns. To combat climate change, Türkiye has made important progress in setting up new institutional frameworks, which needs to be followed by economy-wide transformation across all sectors and policy areas, focusing on the net-zero carbon emission commitment.

It is from this perspective that SHURA Energy Transition Center presents this study that explores the role of the power sector in the transition to a totally decarbonized Turkish energy system. This study assesses the evolution of energy demand across all sectors while considering energy efficiency improvements, additional demand from end-use electrification, and green hydrogen required to achieve net-zero carbon emissions. The transition pathway of the electricity system that supplies total demand is then examined, and includes an in-depth analyses of system security and costs.

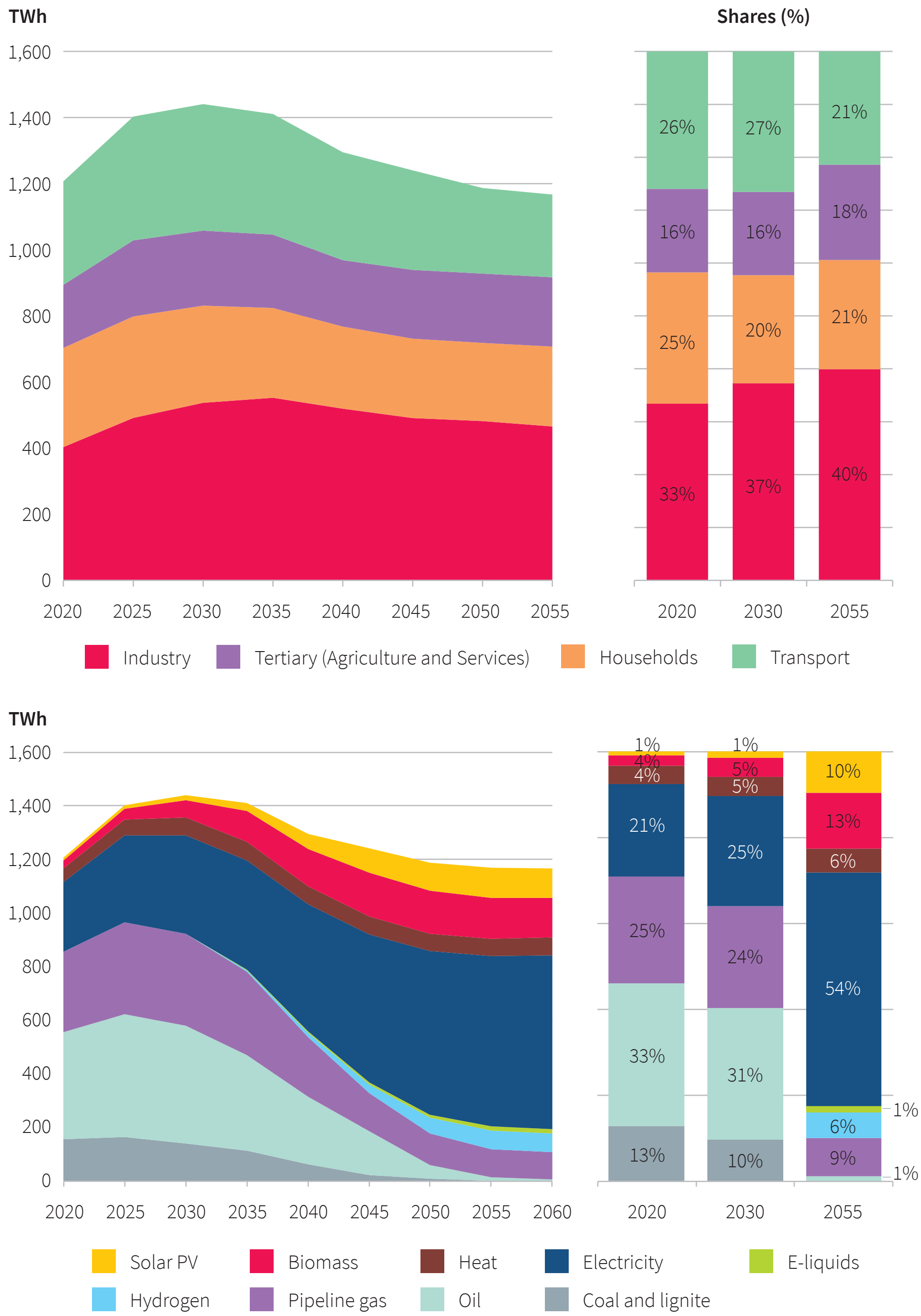
Türkiye's goal to reach net-zero carbon emissions by 2053 is achievable through the displacement of fossil fuels by renewable energy, improved energy efficiency and increased electrification in end-use sectors. The Net-Zero 2053 (NZ2053) scenario shows total carbon emissions peaking in 2025 and then declining by 37.2% in 2035 compared to 2025 levels (Figure 1-right). This early decline in emissions is driven mainly by the power sector (Figure 1-left), which rapidly phases down coal in its transition to renewables. Between 2020 and 2030, the operating hours are reduced for the most inefficient coal and lignite power plants, the pace of which is further accelerated after 2030 due to the implementation of a regulated coal phase out. After 2040, the electrification of the transport sector and introduction of e-fuels further reduces emissions. In the residential sector, the introduction of heat pumps significantly reduces cumulative emissions. Beyond 2050, the power sector contributes to negative emissions through the use of biomass coupled with carbon capture and storage (CCS). This helps counterbalance the residual emissions from other sectors and is an essential component to achieving economy-wide net-zero emissions.

Figure 1: *CO_2 emissions reductions from the electricity sector (left) and the total CO_2 emissions (right)*



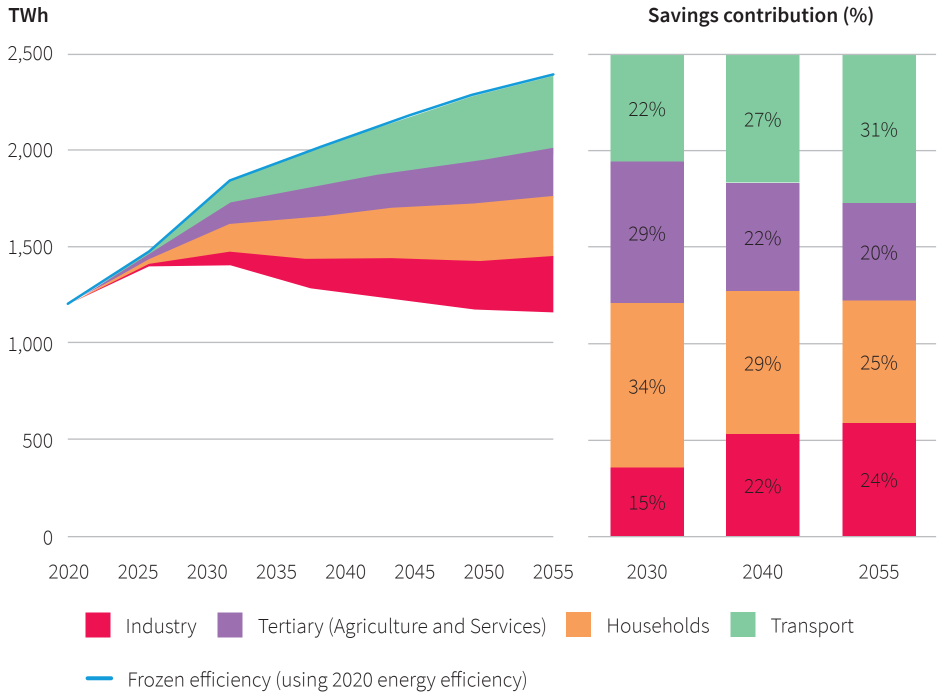
The macro-economic assumptions adopted in this analysis consider substantial economic growth of Türkiye over the entire projection period. Türkiye is assumed to retain its manufacturing capacity, while manufacturing will shift towards producing higher value-added and less energy intensive products. It is expected that construction grows in parallel with the population growth, the reduction in the number of people per residence and the infrastructure investment requirements, while the production of the construction materials will cater to the needs of the domestic market. It is foreseen that transport activity rises with increasing gross domestic product (GDP). **Türkiye's total energy demand continues to grow until 2030 due to increased economic activity. Despite the steady economic growth, energy demand in 2053 declines to 2020 levels thanks to the effects of electrification and energy efficiency improvements (Figure 2).**

Figure 2: *Total energy demand by sector (top) and by fuel type (bottom)*



Energy efficiency is one of the key drivers for decarbonization of the entire economy. In industry, final energy consumption is projected to peak by 2035 in line with the growing industrial production. Afterwards, energy demand in industry declines due to electrification and a shift to less energy intensive processes and manufacturing. One of the main pathways to reducing industrial energy demand is process improvements for waste heat recovery. In the model, additional process-wide improvements in several industries are considered, including the modification of clinker to cement ratios to reduce the energy and emission intensity of cement production. Other assumptions include the maximisation of recycling (secondary) production for all industries where possible. For the residential sector, energy savings are predominately enabled by building renovations that largely reduce heating and cooling demands. Additionally, new electronic appliances and cooling systems are assumed to be A+++-class of energy efficiency. In the model it is evaluated that the entire stock of existing buildings will need to undergo deep refurbishments by 2040. In transport, the shift to electric vehicles (EV) drives the greatest proportion of energy efficiency improvements. While approximately 80% of energy wasted in traditional combustion engines, battery electric vehicles are significantly more efficient, losing only about 10% of the electricity supplied (Kirk, 2022).

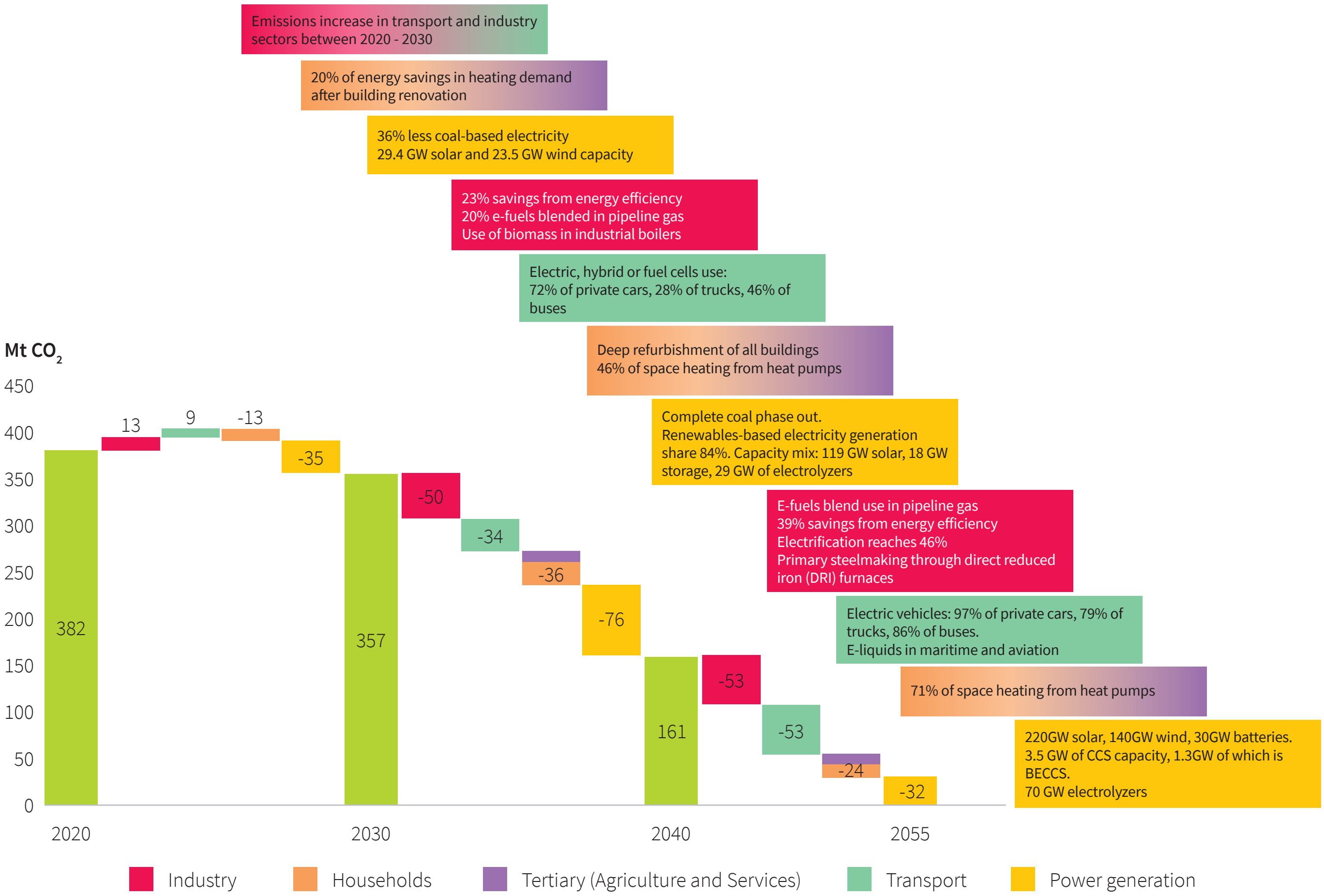
Figure 3: *Energy savings* by sector*



** Computed by freezing the efficiency level of 2020 for the same economic activity.*

Total emissions decrease relatively slowly, by 6.4%, until 2030 (Figure 4), after which emissions drop rapidly due to ceasing electricity production from coal and lignite power plants in the system by 2035. The expansion of renewable energy capacities largely covers increasing electricity demand, and together with the introduction of system flexibility options (i.e. energy storage), renewables displace fossil fuels as these resources are unable to compete on the whole-sale market. The full commissioning of the Akkuyu Nuclear Power Plant by 2030 also contributes to emissions reductions and gradual coal-phase out. By 2030, the power sector makes up the majority of the 24.6 million tonnes total net carbon reductions. Between 2030 and 2040, decarbonization occurs in all sectors. The power sector contributes to a total of 110 million tonnes CO_2 reduced between 2020 and 2040, which is almost half of the emission reductions achieved in that time period. After 2040, electrification of the transport and residential sectors increases in addition to the accelerated transition to e-fuels in the pipeline gas to achieve net-zero carbon emissions in 2053.

Figure 4: *NZ2053 scenario CO_2 emission reduction projections*

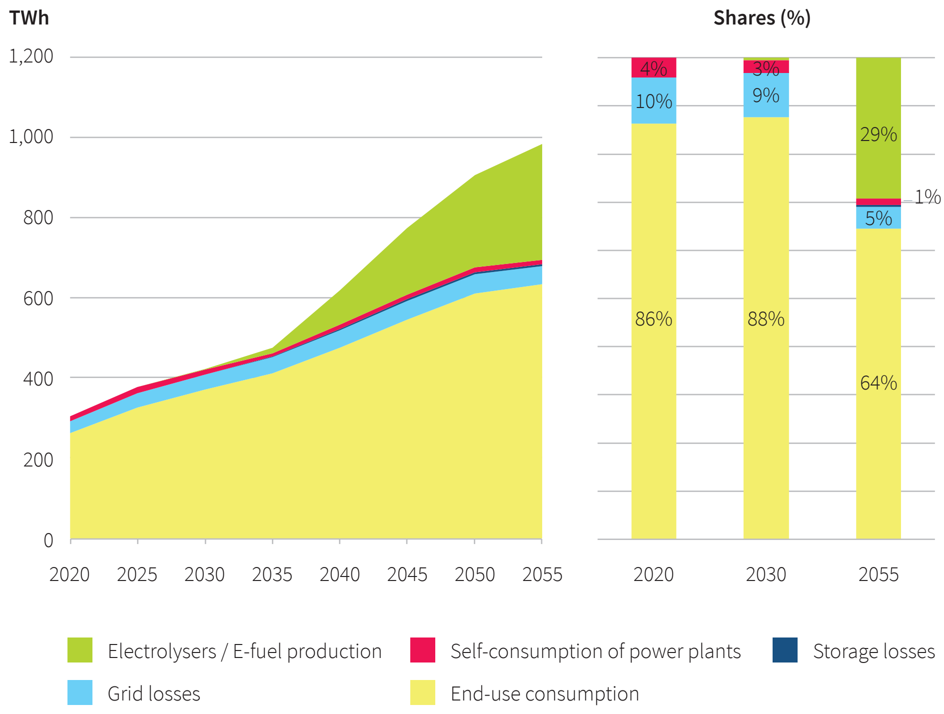


Achieving Türkiye's net-zero target would bring net economic benefits but will require a comprehensive set of public and private sector investments across the economy. The pathway towards a net-zero energy system for Türkiye does not rely on reduced consumption or stagnant economic growth. Rather, the Turkish economy is assumed to grow on average by 3.3% per year through to 2055. This relies on a comprehensive set of public and private sector investments that redesign Türkiye's electricity and transport systems in addition to building refurbishment, while also modernizing the industrial processes and construction. In addition to reducing greenhouse gas (GHG) emissions, these measures contribute to improved human and environmental health and welfare gains across Turkish society and drive the shift in moving Türkiye from a developing to a high-income economy.

A large portion of the investments considering the power sector will be directed into restructuring the electricity system to be based predominantly on renewables. Combined with renewable energy, the advantages imparted by energy efficiency gains in all sectors pave the way for reduced carbon and energy intensities of production. Türkiye's trade balance improves significantly, and energy import dependency drops from 69% in 2020 to just 9% in 2053.

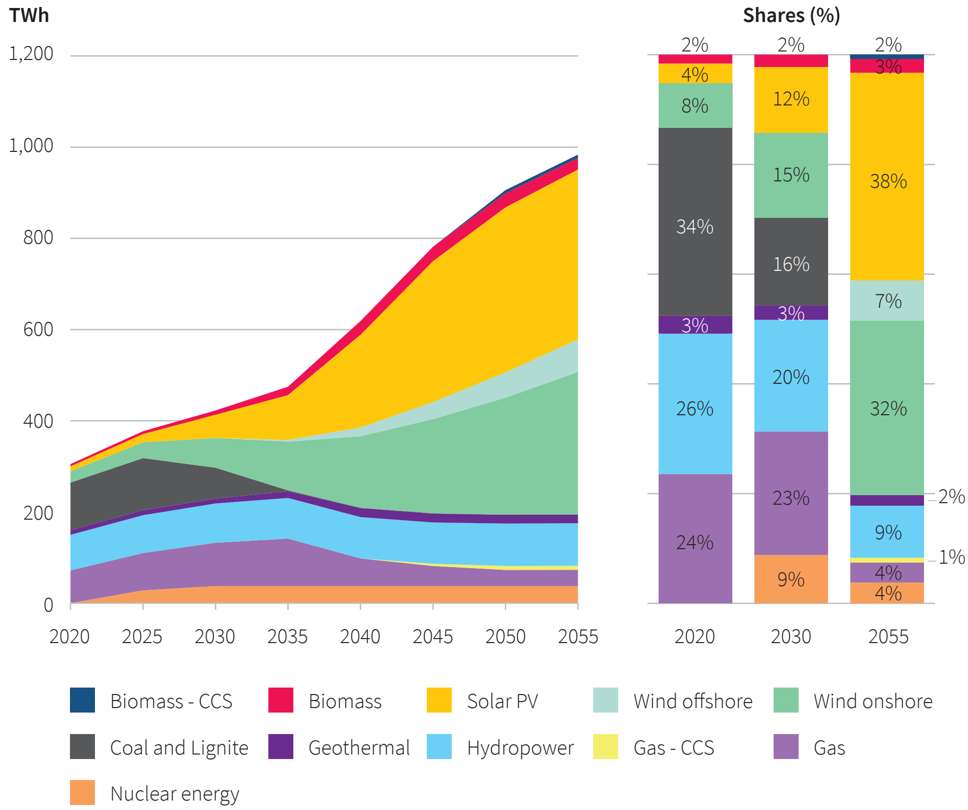
The electrification of end-use sectors and the domestic production of e-fuels results in a rapid increase in electricity demand. The share of electricity in total final energy demand (electrification ratio) is approximately 54% in 2053. Electrification is highest in the tertiary (agriculture and services) sector, where electricity supplies 61% of final energy in 2053 and is followed by the residential (60%), transport (58%) and industrial (46%) sectors. As end-use sectors transition from fossil fuels to electricity, ensuring that the electricity used is supplied by low-carbon or zero emission sources is paramount. Modelling results demonstrate that renewable energy technologies will be able to generate sufficient electricity for this purpose. In 2053, the electricity system will heavily rely on variable renewable energy resources (VRES) such as wind (including offshore) and solar, whose share in the total electricity generation grows to 77% (757 TWh). To balance their variable generation profiles, significant energy storage systems enable grid integration. The main storage systems considered in the model include pumped hydro, batteries, and electrolysers (Power-to-X systems), which increases the flexibility of the grid and ensure system stability. Demand side responses are provided in this analysis through electric vehicles and smart charging systems. Battery and pumped-hydro storage systems will be used primarily for daily balancing, while the usage of green hydrogen and/or e-fuels supply seasonal storage. By 2053, the total electricity demand (Figure 5) is expected to reach 982 TWh, of which 29% (287 TWh) will be used for the production of green hydrogen and e-fuels. The end-use final electricity demand is expected to be approximately 2.4 times more than the 2020 levels.

Figure 5: *Total electricity consumption*



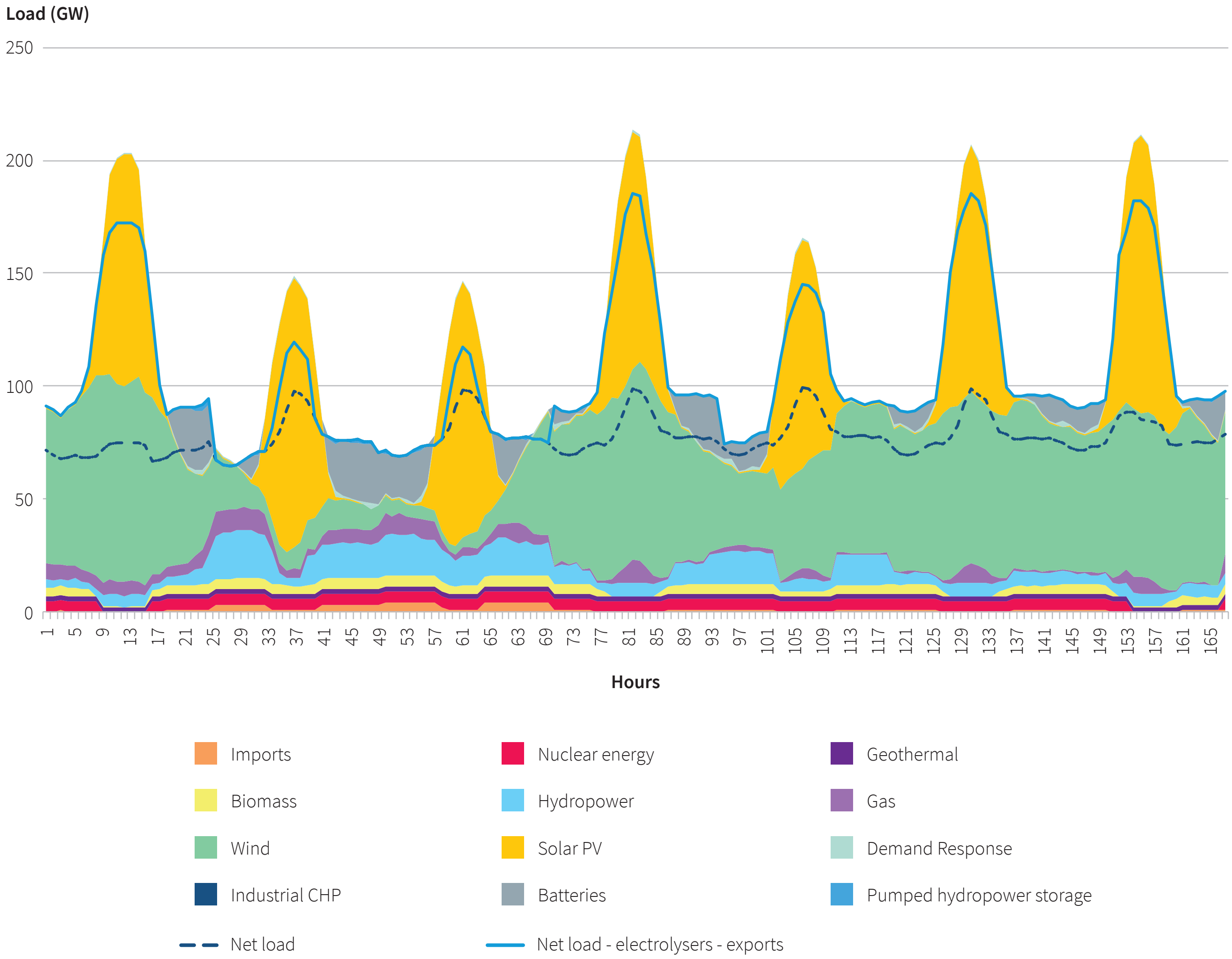
In the net-zero system of 2053, the share of the renewable energy of total electricity generation exceeds 90%. The development of Türkiye's offshore wind potential begins in 2030. The delay in offshore wind development is due mainly to current technology costs which affect the trend in the levelized cost of electricity (LCOE). On the other hand, onshore wind installed capacity reaches 38 GW by 2035. Thereafter, 20 GW is installed in each 5-year period, resulting in a total onshore wind capacity of 120 GW in 2055. Solar PV installed capacities reach 57 GW in 2035 and 220 GW in 2055. By 2053, some 33 GW of energy storage systems (pumped hydro and batteries) will ensure system stability and reliability. The capacity of the batteries deployed in the model reach 30 GW/120 GWh, corresponding to 4-hour discharge at maximum output. The electrolysers needed to produce green hydrogen will start being deployed in 2030 and reach 5.5 GW total capacity in 2035. In order to meet increasing demand for e-fuels, electrolyser deployment increases rapidly thereafter and totals 70 GW by 2053. Dispatchable generators total 92.5 GW in 2053, and guarantee system security and stability in cooperation with the flexibility provided by storage, transmission interconnections, and demand response. Electrolyers, which are expected to function in times of high renewables based electricity generation, add crucial additional system flexibility. E-fuels (e.g., synthetic methane, biogas and green hydrogen) are gradually phased into the natural gas network, and ultimately completely replace natural gas by 2053. Combined cycle gas turbine (CCGT) plants using e-fuels will then be operated as reserve capacity in the electricity system (Figure 6).

Figure 6: *Electricity generation by technology*



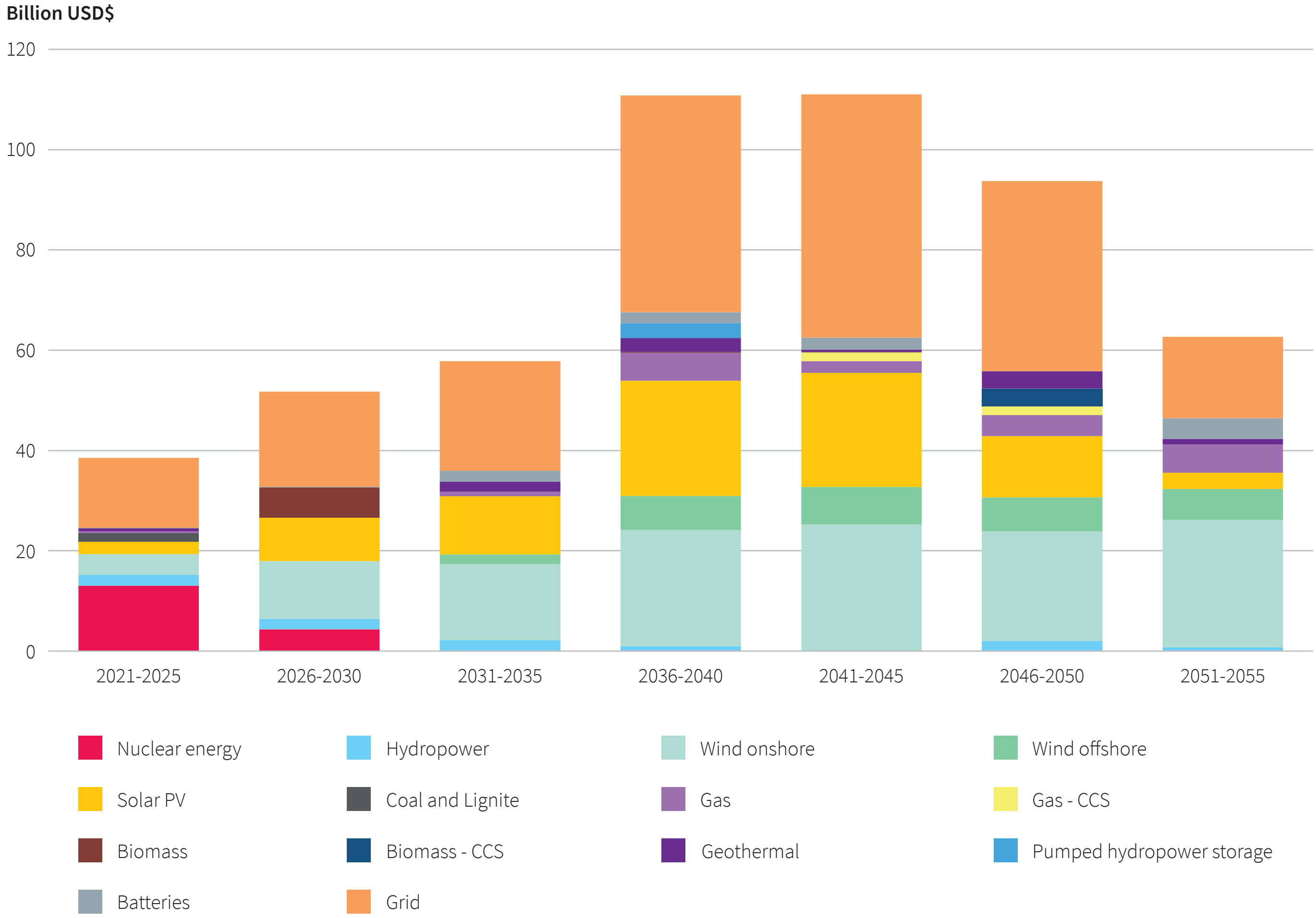
The Turkish power system in 2053 remains stable and reliable even with the vast amount of power generated by variable renewables. System reliability under various load conditions was tested on an hourly basis by the model (Figure 7). In addition to the energy storage systems, other dispatchable renewable generators (i.e., hydro, biomass and geothermal) keep the balance between supply and demand. Hourly simulations indicate that the system can deliver the demand requirements even under load stress conditions with the help of electrolysers and energy storage systems (i.e., pumped storage and batteries). Electrolysers are required to produce e-fuels and provide flexibility to the system. These units will operate flexibly at hours of highest availability of renewable energy, primarily during noon when the solar PV production is at highest. In the model, the demand side participation of the electric vehicles through smart charging provides a similar flexibility.

Figure 7: *Hourly electricity generation profile of a typical week*



The large expansion of new solar, wind and storage capacities create significant investment opportunities for the private sector. Investments increase especially after 2035 due to the growth in electricity demand driven by the electrification of demand across all sectors, while investments into grid infrastructure help manage the influx of variable renewables. Between 2020 and 2055, an annual average of 15 billion USD worth of investments is required. Of the 526 billion USD investment over the entire projection period, 62% is for installing new power plants and storage systems and the rest for grid development. Investment rates decline after 2050 as the growth in energy demand slows and the system nears net-zero (Figure 8).

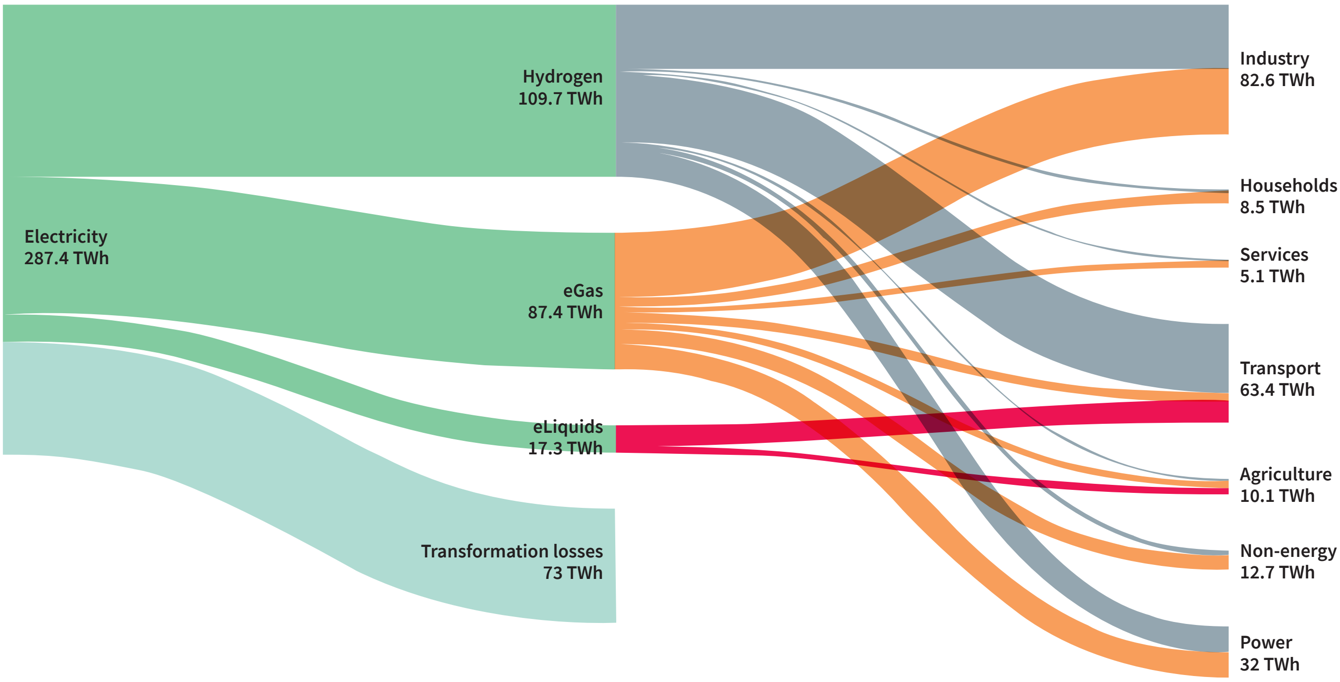
Figure 8: *Investments in the electricity sector (5-year periods)*



Indirect electrification through the use of green hydrogen and other e-fuels (Power-to-X) will play a crucial role in the decarbonization of the transport and industrial sectors given their current reliance on fossil-fuels. Power-to-X technologies are used especially in those sectors that depend on high temperature heat processes or where high energy densities are required. In the NZ2053 scenario, the shift to e-fuels in industry starts in 2035 with fossil-fuels completely phasing out in this sector by 2050. Correspondingly, Türkiye's gas network will also transition to e-fuel alternatives.

In transport, 71% of the passenger cars and 41% of the buses and trucks will either battery or plug-in hybrid electric vehicles (PHEV) by 2040. Between 2040 and 2045, all new passenger cars and vans will be either electric or fuel cell vehicles. In addition to this, e-fuels become necessary for transportation modes where electrification is not feasible, typically for travelling long distances. As such, green hydrogen is directed to around 10% of public road transport, 17% in Light Duty Vehicles (LDV) and 30% in Heavy Duty Vehicles (HDV) in 2053. Electrolysis-based e-liquids such as synthetic kerosene and ammonia are used in aviation and maritime transport respectively. The shares of e-fuels and green hydrogen in industry and transport are limited before 2030 but increase rapidly afterwards due to the expected technological advancements, drops in the technology costs and acceptance of the Power-to-X technologies both in in the world and Türkiye. In 2053, the share of green hydrogen and other e-fuels in total energy demand corresponds to approximately 15%.

Figure 9: *E-fuel production and sectoral consumption by type in 2053*



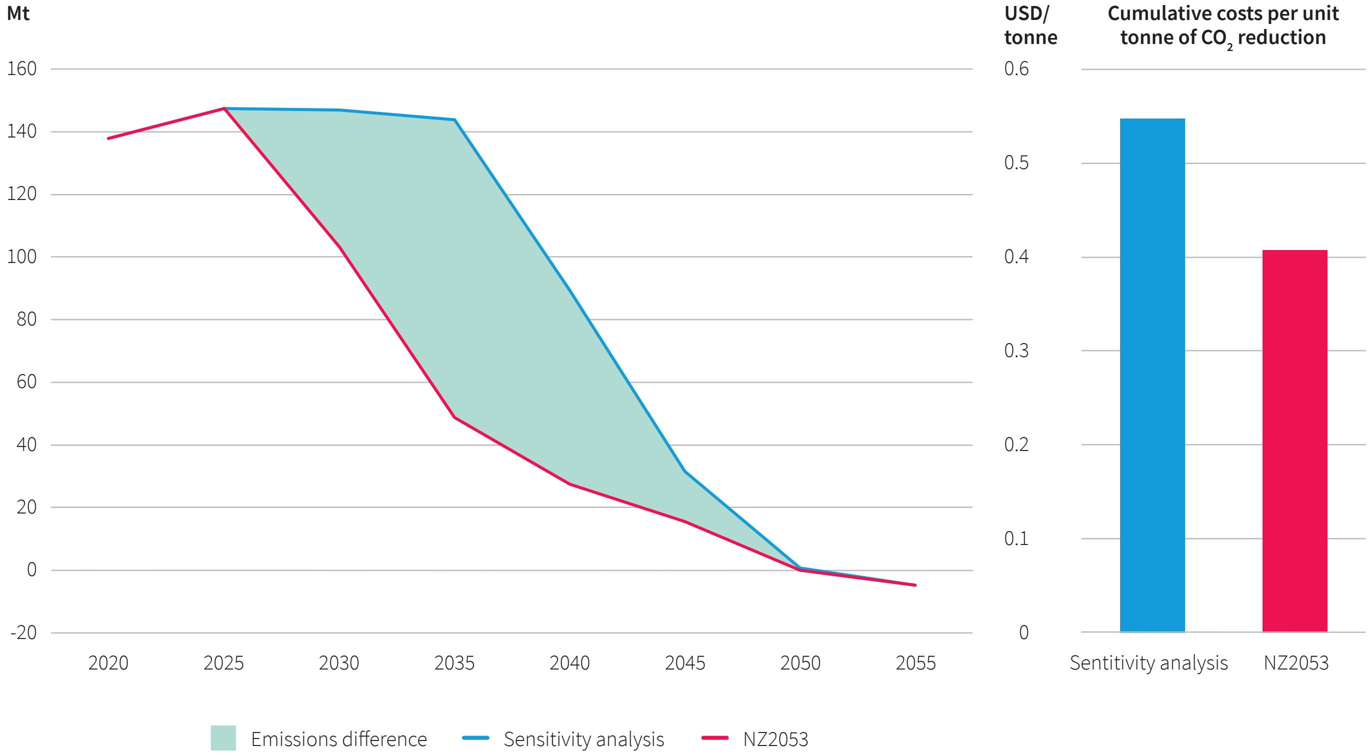
To fuel the indirect electrification requirements (considering hydrogen and e-fuel production), nearly 70 GW of electrolyser capacity is installed by 2053. The main advantages of having electrolyser capacity in the power system are that these units can utilize the excess amount of energy produced from solar PV and wind power plants, which would have otherwise been curtailed, to produce e-fuels and to keep the grid stable as the produced e-fuels can be utilised as a form of seasonal energy storage. In the model, the production of e-fuels is optimized simultaneously with the peak of renewable electricity generation. However, the production and then combustion of e-fuels involves significant conversion losses (approximately 50%); therefore, e-fuels should be used only where strictly necessary, but still can act as weekly or seasonal storage also for electricity.

Delaying immediate actions in decarbonizing the energy sector makes achieving Türkiye's net-zero target by 2053 significantly more challenging and poses considerably higher implementation risks. Within the scope of this work, a sensitivity analysis was conducted whereby the system achieves net zero by 2053, but the necessary changes are implemented with a delay. The sensitivity analysis demonstrates that running coal and lignite plants beyond 2035 increases cumulative carbon emissions while the continued presence of fossil fuels making

the transition more difficult, renewables deployment. By delaying action, an additional 59 GW wind and solar will need to be deployed over the last 13 years of the transition that would otherwise been distributed between 2020 and 2040 as observed in the NZ2053 scenario. Furthermore, continuing coal and lignite use until 2045 and then exercising a coal to gas switch results in an increase in natural gas imports and energy import expenditures over the projection period. When climate actions are delayed, the cumulative energy import costs between 2031-2055 are 20% higher than in the NZ2053 scenario. The continuing import dependency also increases the risk of exposure to fluctuations in the international fossil fuel prices. Additionally, further delaying the integration of renewable energy plants into the power system due to the existing fossil fuel power plants in the system, increases the total system costs. Furthermore, in order to reach net zero in the sensitivity analysis, over 200 GW of new renewable capacity, mostly solar and wind, will need to be deployed between 2040 and 2050, the implementation of which is nearly impossible considering supply of finance, labor and equipment.

Above all, delaying the transformation of the power system due to various impediments, increases Türkiye's cumulative emissions from the power sector by 46% and cumulative system costs per tonne of CO_2 reduction approximately by 34% in 2053 (Figure 10).

Figure 10: *Comparison of the cumulative emissions and the cumulative system costs per unit tonne of CO_2 reduced during the projection period*



Both the NZ2053 and the sensitivity analysis results show that it is imperative that the power sector reaches negative emissions between 2050 and 2055 to counterbalance the residual emissions persistent in the industry and transport sectors.

1. Introduction

Globally, there is an increasing trend in greenhouse gas (GHG) emissions, which is also contributed by the increase in energy consumption. Although with the Covid-19 pandemic the global carbon dioxide (CO_2) emissions dropped extraordinarily (5.8%) in 2020, the levels of carbon emissions started to rise again by the end of 2020 (IEA, 2021). In addition to the impact of the pandemic on the global economy, conflict between Russia and Ukraine in 2022 also highlighted the importance of securing the energy supply for many countries. With the disruption of supply chain and accessing the primary energy resources, the energy prices have seen an unprecedented rise, which eventually brought the focus back to the renewable energy resources and hence the energy transition goals.

Global framework agreements such as the Kyoto Protocol and later the Paris Agreements aim fighting against global warming and thus climate change, have an unquestionable impact on the speed of implementing country-specific energy transition plans. In this direction, the European Commission approved the European Green Deal in 2020, which is a strategic program integrating economic and social development with the aim of becoming climate neutral by 2050. The European Green Deal includes a Carbon Border Adjustment Mechanism (CBAM) effective after 2026, which enforces a carbon tax for third-party imports. Motivated by the emerging global environment toward achieving net-zero greenhouse gas (GHG) emissions goal by mid-century, Türkiye undertook a significant step in line with its intention to mitigate the negative impacts of climate change by publishing the “Green Deal Action Plan” in July, 2021. This document comprises of targets and actions to transform the Turkish economy to a more sustainable and circular economy. In October 2021, Türkiye took significant steps in contributing to the global fight against climate change by ratifying the Paris Agreement and subsequently announcing its pledge to achieve an economy with net zero GHG emissions by 2053.

The most recent data on Türkiye’s GHG emissions, published by the Turkish Statistical Institute (TÜİK), indicates that in 2020, the overall emissions were approximately 523.9 million tonnes (Mt) of carbon dioxide equivalent (CO_2e) (TÜİK, 2022). Although the Covid-19 pandemic caused a significant decline in global GHG emissions, Türkiye’s GHG emissions in 2020 increased by 3.1% over 2019 levels. The revised Nationally Determined Contribution (NDC) that was announced during the 27th United Nations Climate Conference (COP27) in Egypt, targets a 41% GHG emission reduction in 2030 when compared to the reference scenario. The reference scenario projects that by 2030, Türkiye’s GHG emissions will increase more than twice of the 2020 level and reach 1.18 billion tonnes of CO_2e, and with the targeted 41% reduction, will be reduced to approximately 482 Mt CO_2e. On the other hand, this reduction rate means that by 2030, Türkiye’s total emissions will increase by 32% when compared to 2020 and reach 698 Mt CO_2e.[1] The revised NDC also foresees an emission peak in 2038. If GHG emissions continue to rise until 2038, a challenging transition path lies before Türkiye in order to reach the net-zero emissions target by 2053.

[1] https://www.bloomberg.com/news/articles/2022-11-15/turkey-s-climate-plan-points-to-32-rise-in-emissions-by-2030

In Türkiye, energy-related emissions constitute 70% of the total GHG emissions (TÜİK, 2022). In addition to this large share, due to the ever-increasing energy demand, the energy sector is in a key position to reach the net zero target. There is an 8% increase in primary energy consumption in 2021 when compared to the previous year (MENR, 2022) and the final energy consumption levels in 2021 increased 9% to reach 123 million toe (mtoe), with electricity constituting approximately 20% of this consumption. The increase in energy and electricity consumption resulted from a strong post Covid-19 recovery, especially in energy intensive sectors. The other important factor that played a role in this increase is the sustained long-term energy demand growth in line with Türkiye's general economic and demographic trends.

Considering that energy is key to both economic development and climate action, Türkiye needs to develop a strong energy transition roadmap that is vital for both economic and climate resilience, as well as the environment and human health. In this respect, after setting up necessary institutional frameworks, it is critical to prepare an economy-wide "net zero roadmap" where all sectors and policy areas, focus on the net zero pledge and to define sectoral pathways, necessary policies and interim targets within this scope. In this context, it will also be significant to define interim targets and related action plans together with policy mechanisms in climate and energy policies. This, in turn, provides Türkiye a great opportunity to undergo a transformation that would pave the way for achieving the net-zero carbon emission reduction target via the use of its vast potential in energy efficiency and renewable energy resources. In addition to renewable energy and energy efficiency, another critical pillar of the energy transition is electrification. Since the increase in electrification is of great importance in the decarbonization of economy-wide sectors, the electricity sector is expected to play an essential role in the energy transition and decarbonization of other sectors.

SHURA Energy Transition Center has been conducting data-based analyses and extensive studies that investigates the energy transition pathway of Türkiye with an outlook of 2030. In May 2018, SHURA published the "Increasing the Share of Renewables in Türkiye's Power System" report which demonstrated that Türkiye's power system has technical and economic ability to integrate up to 50% renewables (including 30% share in wind and solar energy) at relatively limited additional costs until 2026. The "Integration of Renewable Energy into the Turkish Electricity System" report published in April 2022 demonstrated that the renewables share could be as high as 70% in the power system with acceptable levels of operational challenges (i.e., the redispatch and curtailment levels remain below 5% of the annual production) until 2030. Within this report, the share of solar and wind energy resources in production rises to 35%. In the report, it is noted that as the share of variable renewables (VRES) in the total electricity generation mix increases, the power system needs to be accompanied with imperative grid flexibility options.

The "Socioeconomic Impact of the Power System Transition in Türkiye" study of SHURA, a macroeconomic modelling exercise comparing a SHURA transition scenario with a baseline scenario by 2030, was published in June 2021. The SHURA scenario assumes at least 50% share of renewable energy in the power generation mix, 30% of which consists of wind and solar.

The scenario also includes 10% improvement in energy efficiency in comparison to the reference scenario taking into account the projections of the National Energy Efficiency Plan and the Ministry of Energy and Natural Resources (MENR), in addition to partial electrification in transportation (assuming 2.5 million electric vehicles and 1 million charging points) and heating (with 2 million heat pumps and increased share of smart homes). In the study, it was found that the economic benefits of the SHURA scenario were three times as large as the economic costs. On the socioeconomic front, probable shifts in production and employment from less efficient sectors to more efficient and high technology intensive sectors was observed; necessitating a closer look at just transition policies.

These studies conducted by SHURA focused on levelling electricity sector CO_2 emissions by 2030. Türkiye's adoption of a net-zero emissions target by 2053 necessitates an extensive analysis of the roadmap to decarbonise the electricity sector, from generation to end-use demand, taking into account macroeconomic trends and new technologies.

With the goal to achieve an economy with net-zero carbon emission in 2053, the study initially focuses on assessing the current and future total energy demand as well as analysing the energy supply to meet this demand, in order to assess the supply potential of Türkiye's power system. Additionally, the study focuses on the role of the electricity sector within a totally decarbonised energy system by 2053 and in this context, reviews the technical and economic feasibility of Türkiye's energy transition. In that regard, the study uses a model that has the ability to produce long-term projections, taking into account the significant parameters in economic development, sectoral energy demand and electrification of sectors. The study also examines the reliability and stability of the power system by modelling various cases (e.g., high variable energy generation) with supply-demand simulations to understand the merit order changes when reaching the net-zero carbon emissions target. Within the scope of this analysis, 2030 is considered as the intermediate target year to assess the implications of the speed of decarbonization efforts in reaching the 2053 net-zero target.

While assessing the possible roadmaps for Türkiye to reach a net-zero carbon emission economy by 2053 and to decarbonise the entire energy system, particularly the emissions in the electricity sector, the developments in the main elements of energy transition; i.e. renewable energy, energy efficiency and electrification, were also considered. The main output of the study is the "2053 Net-Zero (NZ2053) Scenario", which includes the results of a roadmap for energy transition in Türkiye to achieve economy-wide net-zero carbon emissions. A sensibility analysis was also conducted within the study to understand the technical and economic consequences of a slower energy transition.

In the report; Section 2 presents the methodology, macroeconomic outlook and sectoral activity projections; Section 3 consists of the modelling tool and general assumptions; Section 4 provides the Net-Zero 2053 (NZ2053) scenario scope; Section 5 includes NZ2053 scenario results; Section 6 summarises the sensitivity analysis results, which shows the impact of a slower energy transition in the economy; and section 7 presents the conclusions. Additionally, detailed assumptions are presented in the Annexes.


NET
ZERO

2. Methodology

As is known, Türkiye has demonstrated its determination in the fight against climate change by pledging to achieve net-zero GHG emissions by 2053. In this regard, the main purpose of this current report is to analyse a possible pathway for the entire economy to reach zero carbon emission with a focus on the electricity sector within the next three decades, in line with Türkiye's commitment to turn climate neutral by 2053. The decarbonization of the electricity sector for an emerging economy with sustained activity growth rates, rising population, and growing income levels, implies various technical, economic, and policy challenges. Having focused on the electricity sector, which will play a key role in an economy-wide decarbonization, this study also aims to capture the complex interlinkages between energy supply and demand, while representing the key dynamics that will shape the future of power markets[2]. The transition to a decarbonised electricity sector requires the adoption of ambitious policies and clean technologies in both the demand and supply side of the energy system.

In the study, total energy demand is modelled by considering the development of sectoral activities, population and Gross Domestic Product (GDP) growth, electrification as well as energy efficiency potential until 2053. Then, the gross electricity demand is determined by the electrification ratios in all sectors, energy efficiency potential, and the rate of e-fuel use in the end-use sectors. In that regard, the study is based on an advanced energy system model that makes a detailed analysis of the demand and the supply in line with the net-zero carbon emissions target.

The following sections explains the tools and associated methodology adopted to model the power system in order for Türkiye to achieve the 2053 net-zero carbon emission target. These sections also provide information regarding the modelled development of the supply and demand dynamics, technology development, costs, and investment needs.

2.1 Outline of the Study

This study is based on a quantitative modelling work, which simulates the Turkish power system with its current specifics. The features of the modelling tool used in the study are explained in Section 2.2.

The main stages of the study are as follows:

Identifying the key parameters of the analysis
The model inputs and general assumptions are determined by taking into account the general data within publicly available resources for Türkiye and international benchmark studies (e.g., International Energy Agency (IEA), World Economic Outlook (WEO), etc.), while feedback from the stakeholders is considered in certain stages. Within the study, two stakeholder meetings were organised, the first of which aimed identifying the general assumptions for the model, whereas the second meeting aimed to discuss the preliminary findings.

[2] Examples are the conversion of fuels used in demand sectors, the increase of renewable energy-based capacity in electricity generation, storage and flexibility requirements, energy pricing, etc.

The main parameters used in the analysis include parameters from both the supply and demand sides, such as the existing power supply capacities, technical potential for the power supply, international fuel prices, macroeconomic projections (e.g. GDP, population growth etc.), sectoral projections and so on. In the study, carbon emission projections in all sectors are investigated by considering existing and developing carbon abatement technologies and potential for negative emissions (i.e. through carbon capture and storage (CCS) units to be used in biomass power plants) as well as sector integration.

Once the basic assumptions and data are finalised, the model is run with 5-year intermediary time steps with a focus on the mid-term target of 2030. The assessment also considers the technologies, such as the battery storage systems, electric vehicles (EVs), heat pumps, green hydrogen etc. and their estimated cost projections, as economy-wide electrification level would in turn determine the speed of the energy transition.

Assessing the electricity demand

In the study, the total annual energy consumption until 2053 and the electricity demand in this consumption are calculated, taking into account the population, economic and sectoral growth estimations, electrification level and the potential of sectoral savings via energy efficiency. When the overall electricity demand is computed, the hourly simulations are developed based on the sectoral demand projections and the flexibility of the demand.

The computation of the annual total electricity demand in end-user sectors is conducted via analysing the industry, transportation, residential, agriculture and service sectors in detail. In this computation, potential for energy efficiency and electrification levels are considered in all end-user sectors. Likewise, the integration level of Power-to-X (PtX) technology is assessed in each sector, with a focus on the industry and transport sectors. Additionally, in the transport sector, the modal shift assessment is conducted together with the share of the electric vehicles assumptions. With respect to the projected electricity demand, the daily and seasonal demand shift until 2053 is also analysed in the study. As for the hourly electricity demand simulations, various parameters including the GDP projections, population, energy efficiency and electrification potential, the current and historical electricity demand profiles are utilised. The hourly electricity demand is simulated on a sectoral level and possible impact of the demand-side participation potential is also included in the analysis when possible.

Identifying the power system supply-side parameters

Considering the global trends in technology costs as well as the projected cost changes, the power supply development of Türkiye is modelled toward 2053. In that regard, the analysis considered the existing power plants in Türkiye, renewable energy potential on a regional level and other technical parameters such as load increase/reduction rates of power plants and minimum load levels. A “carbon value” strategy is adopted to evaluate the possible impact of carbon emitting technologies. The power supply capacity development is then modelled, which would enable achieving both the total end-user electricity demand and the net-zero carbon emission target by 2053.

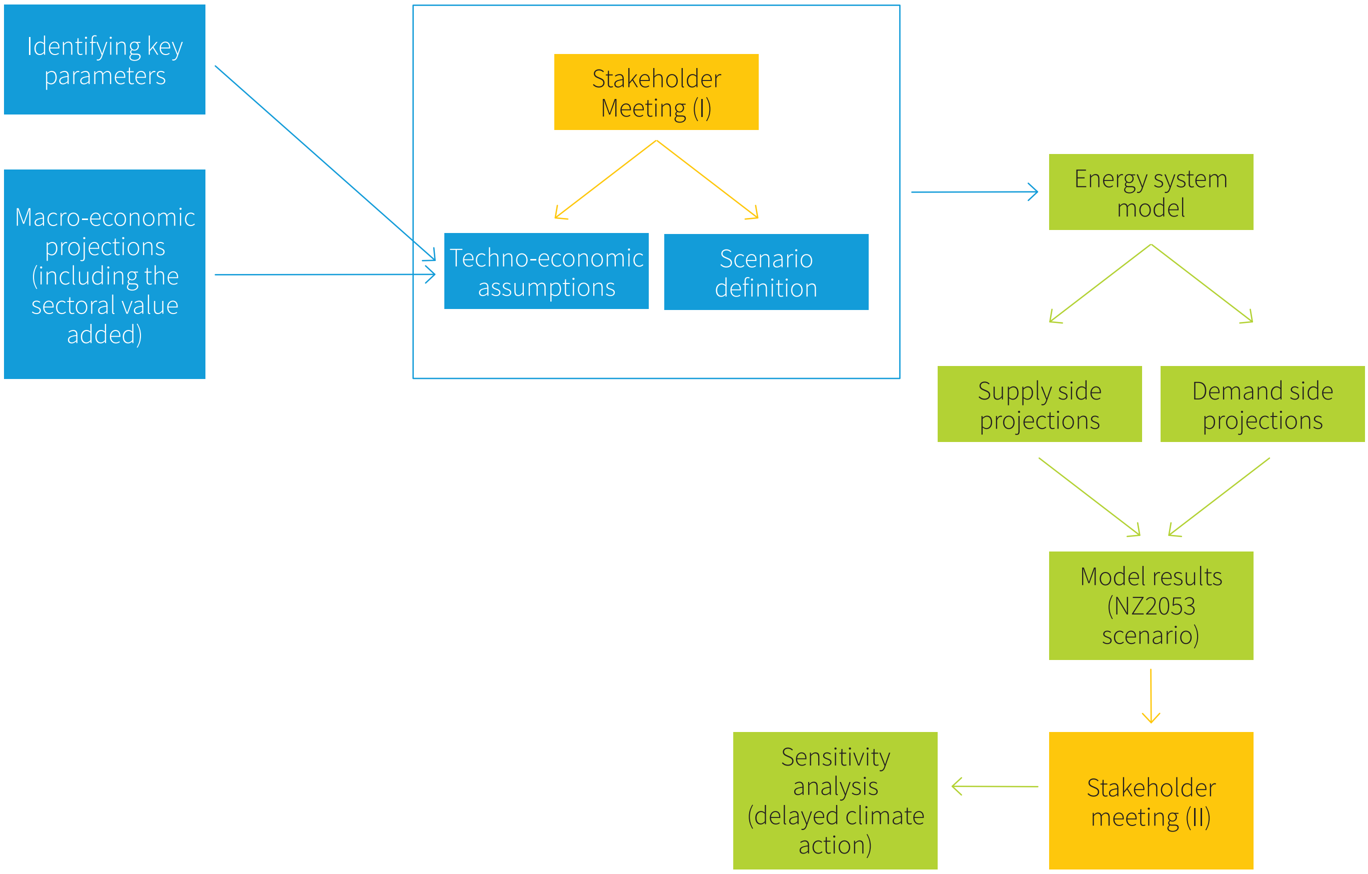
Analysis of net-zero carbon emissions by 2053 for the energy system

To analyse the net-zero pathway for Türkiye by 2053 requires an hourly market model that considered all factors such as the power system security and resilience due to the increased leves of distributed energy resources (rooftop solar, back of the meter battery, electric vehicles, heat pump etc.) and utility-scale renewable power plants with variable generation across the country. The model optimizes the investments in supply, in other words, the plants that need to enter the system in order to achieve net-zero carbon emissions in 2053, the generation mix, energy storage and electrolyser investments, in terms of system safety and cost. The economic and technical details are defined to the model in accordance to the emission targets.

Sensitivity analysis

The sensitivity analysis examines the consequences of a delay in energy transition and climate action in terms of carbon budget and costs, assuming the same sectoral activity and same levels of total energy demand. The main purpose of this analysis is to investigate the technical and economic feasibility of postponing energy transition and emission reduction targets needed to reach the net-zero target during the remaining 30-year period.

Figure 11: *Project flow-chart*



2.2 Modelling Tool

The study was conducted by the CompactPRIMES[3] model, which is a market-equilibrium model of the energy system that combines the engineering and microeconomic foundations. The model is both actor-oriented and market-oriented since it represents the decisions for both the individual actors regarding the demand and supply of energy as well as balancing the decisions in simultaneous markets cleared by prices. In this respect, energy demand in the model is not the outcome of technology simulations or statistical relationships, but by considering sectoral activity, energy efficiency and electrification levels. The model is adapted for Türkiye energy system considering the existing power plants and other technical parameters. Additionally, the model was calibrated using the 2020 Energy Balance Tables that were published by the Turkish Republic Ministry of Energy and Natural Resources (MENR). The model considers the time period between 2020 and 2055, which is run by 5-year projection periods.

The model examines the energy use of all sectors (industry, residential, transportation, agriculture and services sectors) and the technologies involved. All sectoral development is modelled and further divided into sub-sectors and energy processes. For each process, useful service is covered by energy commodities, attached to technology types, based on their costs, technical characteristics, and consumer preferences. In this context, energy carriers are considered imperfect substitutes for some energy processes. In the model, energy efficiency is simulated via various ways which include electrification of end-use sectors, building renovations or recovery of waste heat in the industrial processes.

An inter-temporal optimization module is incorporated in the model, which considers the electricity generation in the electricity sector, heat supply and the production of e-fuels. The module optimizes the capacity expansion and system operation based on constraints on either the resources, power plants or the power system. To ensure the grid stability and power system reliability, the model computes the demand for ancillary services and storage requirements endogenously, linking them directly to the electricity generated by variable renewables.

The model estimates the prices for electricity, heat, and e-fuels endogenously, which also drive the equilibrium of the energy demand and supply. In principle, all estimated prices recover the costs of energy supply. Nevertheless, electricity prices are calculated considering load profiles and marginal supply costs.

2.3 Demand and Power Generation Analysis

The model simulates the annual power system operation and reserve requirements using the defined representative weeks. The granularity used in the study is 4 typical weeks, further disaggregated into 672 typical hours. This level of detail is necessary to capture the daily, weekly, and seasonal variability of load and generation patterns from the variable renewable sources. As part of validating the model, it was run with historical seasonal data for the first two-week time period.

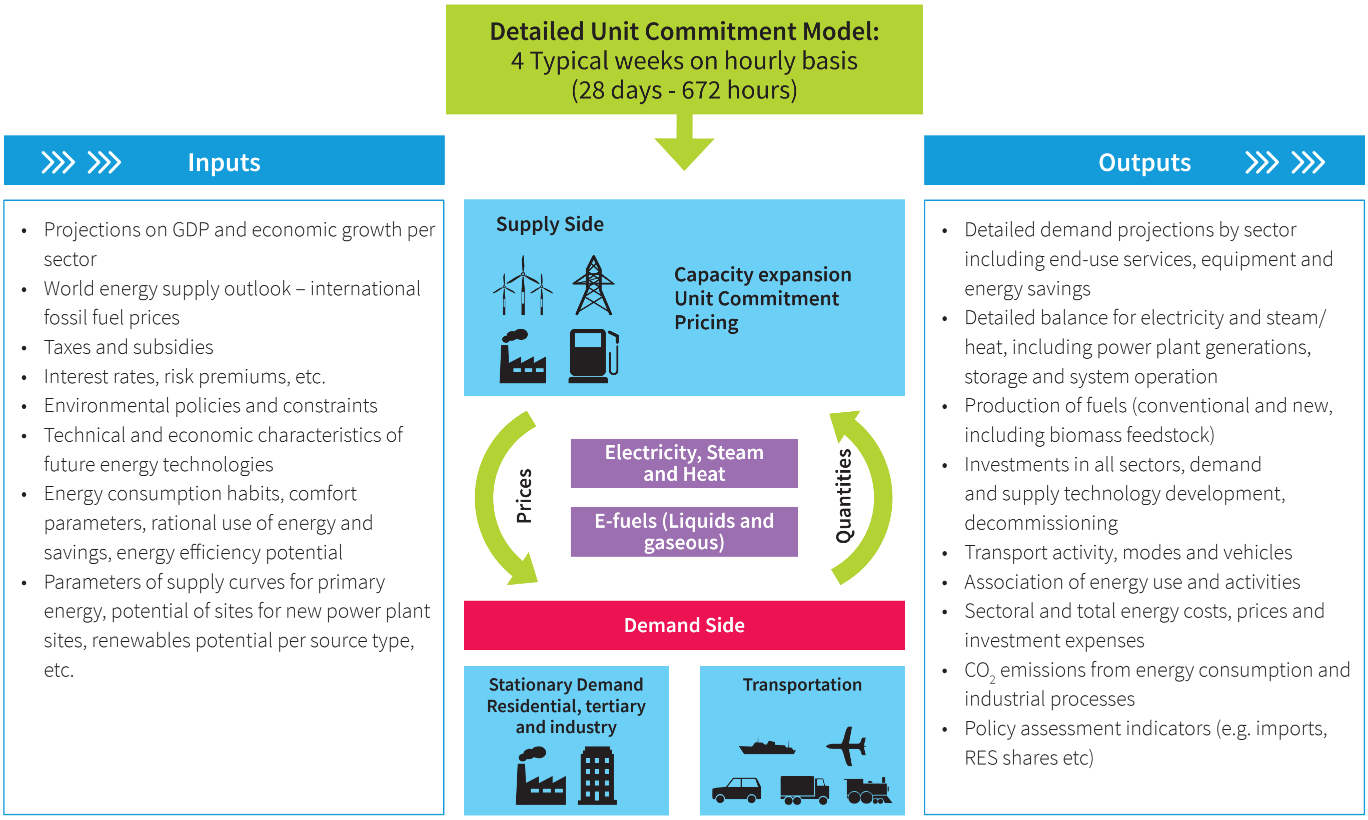
[3] CompactPRIMES is a model developed and maintained by E3Modelling SA. It is a single country version of the PRIMES model which is widely used for the European Union (EU) and other European countries.
For further information: https://e3modelling.com/modelling-tools/

Table 1: *Frequency of typical days used in the model*

Typical days	Hours	Frequency [weeks]
Winter	168	25
Summer	168	25
High demand	168	1
Renewable power plants low generation performance	168	1
Total	**672**	**52**

The data include the average power load profiles as well as the generation profiles of wind, solar and hydropower plants. For the wind energy power plants, the used daily load profile was adjusted to reflect the daily variability, which cannot be captured via the average seasonal values. The frequency of the analysis for typical seasons are assumed to be 25 weeks. The remaining two weeks represent the extreme cases. The first one considers a week with the lowest electricity generation from renewable energy sources and the other considers a week with the highest electricity demand.

Figure 12: *CompactPRIMES model and the interconnections between modules*



3. Modelling and General Assumptions

It is of importance to calibrate the model against the most current publicly available data sources to evaluate a net-zero pathway for Türkiye by 2053. In that regard, the publicly available data sources used in the study includes the Turkish Statistical Institute (TÜİK), International Energy Agency (IEA), United Nations Framework Convention on Climate Change (UNFCCC), United States Geological Survey (USGS) publications, World Steel Association and so on. Additionally, the model was calibrated based on the 2020 Energy Balance Tables that were published by the Ministry of Energy and Natural Resources (ETKB, 2021).

At the time of the study, the 2021 Energy Balance Tables were not available and hence 2020 data were used for the model calibration. Several checks regarding the impact of the Covid-19 pandemic were conducted on the data prior to the calibrations. In that regard, it was assessed that the economic stagnation caused by the pandemic had insignificant impact on the energy intensity of Türkiye, which in turn made it possible to utilise from the 2020 energy balance dataset. Regarding the electricity sector, the gross power generation in 2020 was just above 300 terawatt hours (TWh). This is close to the levels observed in 2018 and 2019, in which the variable renewable energy sources retained their shares. In the analysis, it was also found that the transportation sector was the most affected sector due to the travel restrictions and lockdowns (Yükseltan et al., 2022). In order to account for this impact in transport, the rate of using public passenger vehicles was adjusted to a lower level to fine-tune the actual energy consumption in 2020 in the model. As for the projection year (2053), this rate was reset to average the benchmark levels. To model the transformation of the energy system, it is of importance to envisage the new, cutting-edge and emerging technologies including their performance as well as their current and expected future costs. In the model, a detailed database of energy demand and power supply technologies are present which are used as inputs to the model. Considering the new technologies, the expected learning rates are defined in the model, which paves the way for increasing competitiveness between technologies over time.

Concerning the demand projections, the model includes a total of 98 energy uses, which are covered by 149 technologies. These include industrial machinery (e.g., furnaces, kilns, smelters, motors), heating technologies and building appliances, public and private vehicles. The associated costs and efficiencies of the technologies were derived from the ASSET study (De Vita et.al., 2020), and the European Union (EU) Reference 2020 Scenario.

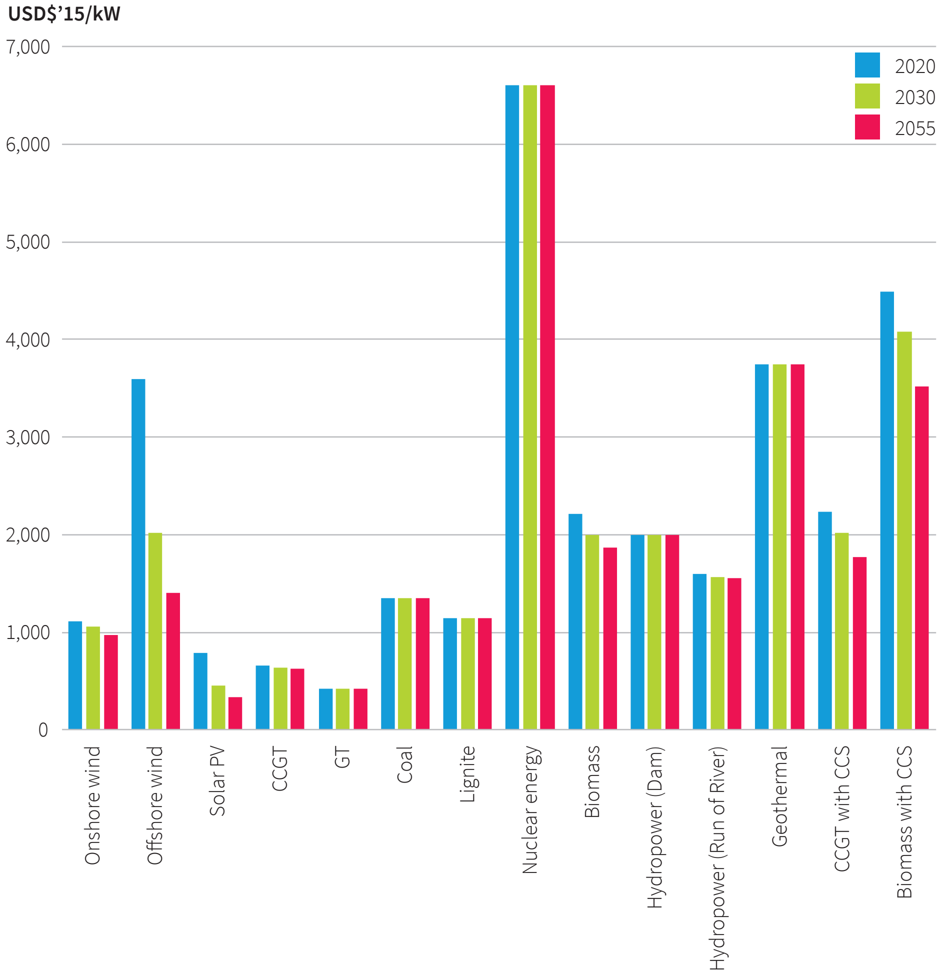
Within the model, a power module is present which includes a total of 33 technologies for electricity generation and energy storage, and a total of three processes (i.e., Power to X (PtX) to produce green hydrogen, e-gas and e-liquids) to produce e-fuels. Publicly available data provided by the Energy Markets Regulatory Authority on licensed and unlicensed power plant capacities in Türkiye's energy mix was also used in the model, (EPDK, 2022). Existing thermal capacities are included in the model at the highest detail possible for main activity producers, with distinct representation of each plant. Due to the total quantities of the unlicensed solar PV plants as well as other licensed renewable energy power plants, an aggregation methodology was adopted based on the technology (e.g. wind, grid-wide solar PV, etc.) and commissioning year of the relevant power plants.

Techno-economic assumptions for the electricity sector are based on extensive literature research, mainly based on the EU Reference 2020 Scenario, ASSET studies (De Vita et al., 2020), and IEA World Energy Outlook (IEA, 2021) adopted for the EU and Türkiye. In the model, it is assumed that the falling capital costs of variable RES (wind onshore and solar PV) observed since 2010 will continue throughout the projection period. Among the current power generation technologies, the cost reduction is notable especially for solar PV considering the economies of scale, production efficiency and market competition. Additionally, the costs associated to the energy storage technologies, such as batteries, are assumed to reduce over time, which in turn increases the possible applications of installing solar PV and wind power plants together with accompanying energy storage solutions. Considering the applications of new technologies, such as green hydrogen and carbon capture and storage (CCS), it is assumed in the model that innovations revolving around these technologies will cause cost reductions and productions will be scaled. As for the existing technologies such as natural gas and coal power plants, it is assumed that the technological advancements are matured and hence the capital costs will remain the same in the coming years. When concerned with the nuclear power plants, a review of publicly available data on the capital costs was conducted and prolonged installation periods together with environmental precautions were considered. The small modular reactor (SMR) technology is not included in the model as the technology is still under development.

The weighted average cost of capital (WACC), an input value for the power generation, is assumed to be 8.5%[4] in the study. Furthermore, coal and lignite power plants are considered to have an additional risk premium of 2.5% within the context of a net-zero target. With this implication, the behavioural change of investors can be simulated, which foresees a reluctance to invest in fossil fuel (carbon emitting) power plants. The risk premium increases the annual capital costs and quantifies the reluctance of investors in financing projects such as new coal power plants, due to possible decarbonization policies (e.g., carbon pricing).

[4] For further details on this assumption see the Annexes.

Figure 13: *Projections on the cost evolution of the power generation technologies*



3.1 Framework assumptions

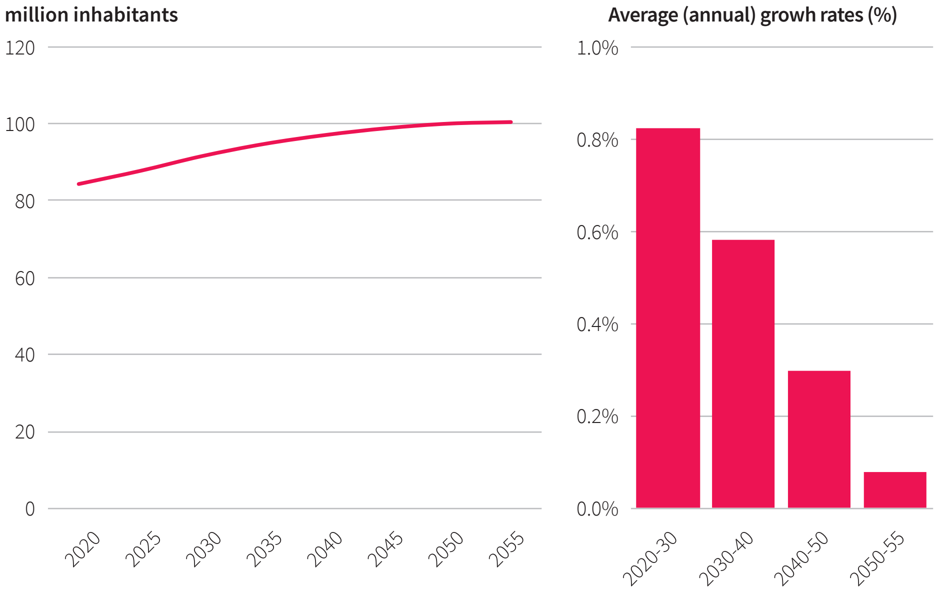
3.1.1 Macroeconomic outlook

The macroeconomic outlook provides the framework assumptions for Türkiye's economic and demographic evolution in the coming decades. The outlook shows the structure of sectors and activities of the Turkish economy in the future, in line with overall economic growth and population dynamics, drawing on recent demographic and economic projections from publicly available resources published by the national and international official institutions.

Türkiye's population which has been growing consistently throughout the 21st century reached 84.3 million of people in 2020. This study uses the low growth scenario of TÜİK until 2040, and the medium variant of United Nations (UN) projections for the subsequent period. Population increases in the course of the projection period, even though at a diminishing rate over time.

The diminishing rate of population growth is a result of the completion of the demographic transition accompanying the initial stages of economic development. In the initial stages, improved health and welfare reduce death rates while fertility declines at a slower pace, resulting in fast population growth. In later stages, with Türkiye's transition from a lower to an upper middle-income country, over the past 20 years, the total fertility rate has been declining by an average 1.7% annually, leading to a slower population growth. The decline in the population growth rate is expected to continue over the next 30 years due to high urbanization rates and an ageing population. Between 2020 and 2030 population growth rates are estimated at 0.83%, and set to decrease slightly the decade after (0.58% in 2030-2040), and drop to 0.3% in 2040-2050. Population peaks at 100 million by 2050 and stabilizes on this level in the next decade. In this study, population estimates are assumed to be the same for both the Net-Zero 2053 (NZ2053) scenario and the sensitivity analysis.

Figure 14: *Demographic projections*



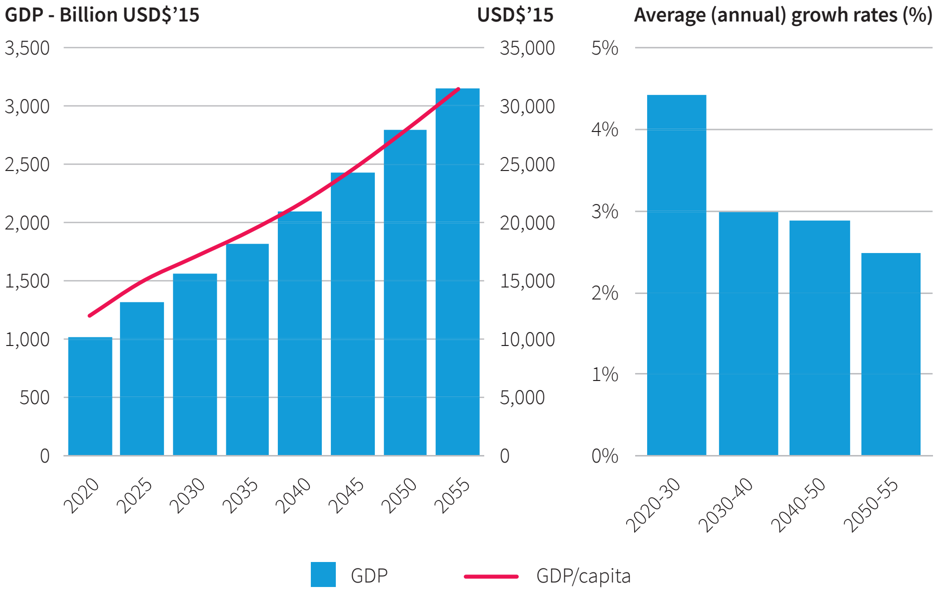
Türkiye's economy registered sustained and strong growth in 2000 - 2020, expanding cumulatively by 45%, or 4.6% annually. Growth peaked between 2010 and 2015 above 7%, but in the following years the rate contracted to 3.3% due to macroeconomic instability and COVID-19 restrictions (IMF, 2022). As observed in other emerging market economies, Türkiye did not enter an economic recession during the COVID-19 outbreak[5].

The Turkish economy retains a strong manufacturing industry base; by 2020 the share of industry and energy in gross value added stood at 21%[6]. Average annual growth in value added in industry between 2000 and 2020 was 5% and its share over the period was between 18% - 20%. Agricultural value added grew by 3% per annum though its share declined from 11% to 7.5% with the shift to activities of higher complexity and value added. Construction grew by 6% annually and its share increased from 6% to 7.5% reflecting population growth and high infrastructure investment rates. There was a significant shift from agriculture to both construction and services sectors, whereby services sector grew by 5% annually with their share in value added remaining around 63% through the time period of 2000 and 2020.

[5] World Economic Outlook, October 2022.
[6] Gross value added based on TÜİK

Following the slowdown of Covid-19 pandemic, the Turkish economy experienced a steep recovery, and rapid growth is projected also for 2022[7], despite high energy prices and disruption of value chains, caused by the Russia-Ukraine war. This study assumes that the economy sustains strong – although slower – growth in the next decades, as Türkiye transitions from an emerging to a high-income country. Between 2022 and 2030 the economy is expected to expand at an average annual rate of 4.4% and decelerate afterwards due to demographic stabilization and lower investment rates. On average for the period of 2020-2055 average annual growth is projected at 3.3% (Figure 15). Estimates for the current decade are forecasts retrieved from the World Bank (2023-2024) and International Monetary Fund (IMF) (2025-2027). For the longer period, long term baseline projections of Organization for Economic Cooperation and Development (OECD) were used (OECD, 2018).

Figure 15: *Economic growth projections*



With growing Gross Domestic Product (GDP) and income, the structure of the economy changes. These changes are associated with increasing contribution of services to GDP and diversification of industrial production. In this study, Türkiye is assumed to retain its manufacturing capacity, but it is projected that the knowledge-intensive sectors like engineering, pharmaceuticals etc. will drive the industrial growth. The share of knowledge-intensive industries to value added in the manufacturing industry is expected to rise to 46% in 2055 from 28% in 2020, whereas that of energy-intensive (metals, cement, petrochemical, paper) industries to decline to 12% in 2055 from 18% in 2020. The decoupling of physical activity from economic growth is also projected. Future products are expected to be less capital intensive but more sophisticated, adding value through human capital and innovation. This trend affects all sectors, including traditional industries. This shift in industrial activity will contribute significantly to reducing energy and carbon intensity.

[7] GDP, quarterly, TÜİK

3.1.2 Sectoral projections

Türkiye has a diverse manufacturing sector spanning food, textiles, construction materials, chemicals/petrochemicals, basic metals, machinery/equipment, and automotive industries. Nevertheless, Turkish industry is characterized by the predominance of low and low-medium technology with low value-added products in its output composition. While production in many strategic sectors is insufficient to meet the needs of the domestic market causing import dependency in intermediate and end products, overcapacity much exceeding domestic demand in energy intensive sectors triggers low value added and import-dependent exports. The low- technology low-value trap has been recognized in national policy and strategy documents as a major structural factor limiting economic growth and increasing Türkiye's foreign trade deficit. Main policy documents, such as the 10th and 11th five-year national development plans stress the need for industrial transformation. Projections of industrial activity are based on this move toward higher technology level and higher value-added sectors and products together with the potentials presented by the green industrial transformation paradigm, also recognized in national policy documents.

The change in industrial composition implied by the foregoing frame has been reflected in the projections made in this study. It has been assumed that the share of lower value added and lower technology sectors with high energy intensity will decline as production in higher technology, higher value added and less energy intensive sectors will grow faster.

Another projection is a general movement toward less energy intensive and higher value-added products within sectors that are traditionally classified as low technology. The assumptions consider both the possible development of domestic demand and trends and opportunities in external markets.

In low and medium-low technology products, such as fast-moving consumer products and some consumer durables, growth rates are expected to decline due to already high penetration levels. Export growth in low and low-medium technology sectors whose value added is limited in comparison to energy content and transport costs, such as long iron and steel products (used in building construction) and non-metallic minerals, especially cement, is expected to decline. It is assumed that the high growth rates in Turkish exports of these products, whose share in international trade tends to be very low and domestic production capacity in export markets grows fast, will be temporary and export shares will revert to long-term averages. On the other hand, in medium-high and high technology sectors both domestic and foreign demand are expected to continue to grow at least at their previous rates. Increases in growth and new capacity are also expected in sectors whose domestic production is insufficient to meet growing domestic demand, such as chemicals and flat iron and steel products (used in machinery, electrical appliances, and automotive). In addition, new manufacturing needs arising from the energy transition itself will lead to growth in medium high and high technology products, such as renewable energy and energy efficiency equipment, energy storage systems, electric vehicles and other appliances, green materials and end use products. Digitalization will also be a major driver of the growth of these manufacturing areas.

The industrial projections in this study reflect an awareness of the foregoing characteristics of Turkish industry and represent a move toward higher technology and higher value-added manufacturing enabling sustained GDP growth over the 35-year period. From a de-carbonization perspective, the resulting industrial mix, especially after 2030, is less energy intensive and more prone to electrification than the current composition. As of 2020, the share of the manufacturing sector in total sectoral value added is 21% and the share of medium-high and high technology products in manufacturing value added is 35%. Projections in this study indicate that with the movement toward higher technology products, the share of manufacturing in total sectoral value added (including industry, services and agriculture) will go up to 26.5% by 2040 and stabilize at 23% by 2055. The share of medium-high and high technology products in total sectoral value added is assumed to reach 40.8% by 2030 and 59.2% by 2055.

Table 2: *Projected share of selected sectors in industrial value-added by technology*

	2020	2030	2040	2055
Low Technology	34.3%	31.7%	26.0%	20.7%
Food and Beverage	10.8%	9.4%	7.7%	6.0%
Textiles	10.0%	9.4%	7.5%	5.8%
Apparel	5.6%	6.0%	5.5%	4.5%
Paper and Paper Products	3.2%	3.1%	2.3%	1.8%
Other	4.7%	3.9%	3.0%	2.7%
Medium-Low Technology	31.0%	27.5%	24.0%	20.0%
Refinery Products	1.3%	1.1%	0.8%	0.5%
Rubber and Plastics	6.1%	5.5%	4.2%	3.2%
Glass, Ceramics and Cement	5.7%	5.3%	4.5%	3.6%
Basic Metals	8.7%	7.1%	5.8%	4.7%
Fabricated Metal Products	7.4%	7.1%	7.4%	6.8%
Other	1.7%	1.4%	1.3%	1.2%
Medium-High Technology	29.3%	33.2%	39.9%	45.7%
Chemicals	6.9%	7.2%	7.7%	6.9%
Electrical Equipment	5.8%	5.9%	6.4%	6.4%
Machinery	6.6%	8.7%	11.5%	12.8%
Motor Vehicles, Trailers, Semi-Trailers	8.2%	8.4%	9.5%	8.8%
Other Transport Equipment	1.8%	1.4%	1.2%	1.1%
Other (clean energy technologies, advanced materials, etc.)	0.0%	1.6%	3.7%	9.7%
High Technology	5.4%	7.6%	10.0%	13.5%
Pharmaceuticals	2.6%	2.6%	2.6%	2.3%
Computer, Electronic and Optical products	1.9%	2.8%	3.6%	2.5%
Air and Spacecraft and Related Machinery	0.9%	0.9%	1.1%	1.2%
Other (advanced digital and green products)	0.0%	1.3%	2.6%	6.5%

Hard to decarbonize sectors; basic metals (including iron and steel, non-ferrous metals and fabricated metal products), non-metallic minerals (glass, cement and ceramics), and chemicals (chemicals, petrochemicals, fertilizers and plastics), which constitute about 6% of total sectoral value added, account for 20% of primary energy consumption and 24% of demand side CO_2 emissions. While total value added in these sectors is relatively low compared to the value of production, continued activity is considered essential and strategic for continued steady economic development. A strategy of selective growth in these sectors with emphasis on higher value added and less energy intensive products geared mainly toward meeting domestic demand is foreseen in the projections. The domestic construction sector, which is the main driver of growth in much of these products, including long steel, cement, ceramics and glass, is expected to grow by 135% during 2020-2055. The main assumptions in key energy intensive sectors are presented below.

- **Basic Metals:** Türkiye's production volume in basic metals led by iron and steel grew by 77% during 2005-2021 driven both by long steel demanded by the construction sector and by flat steel demanded by the electrical equipment, machinery and automotive sectors. In Türkiye, secondary steel (produced in electric arc furnaces) has roughly a 69% share in production and primary steel (produced from iron ore in integrated blast furnaces) has a 31% share, which is reverse the current ratios in most major steel producers in the world. About 68% of the steel Türkiye produces is long steel produced from scrap in electric arc furnaces used mainly in the construction sector. While the dominance of production in electric arc furnaces is preferable from an emissions point of view, the product mix emphasizing low value added and highly import dependent construction steel as opposed to flat steel for more advanced uses is contested. There is general agreement that Türkiye needs to increase the share of flat products and reduce the share of long products in its product composition. Growth in production of flat steel will be needed in line with the projected increase in the production of machinery/equipment, consumer durables, automotive (mainly electric vehicles) and renewable energy equipment. Long products, in turn, are projected to grow mainly in parallel to demand in domestic construction with exports tapering off to reduce the need for scrap in low value-added production. Currently, nearly all flat products are produced in blast furnaces; however, along with de-carbonization goals, an increasing share is foreseen to shift to arc furnaces. During 2020-2055 total iron and steel production is assumed to grow by 33% while the share of production in electric arc furnaces remains at around 69%. The share of flat steel in production volume is expected to increase from 30% to 46% while the ratio of value added to production value goes up from 18% to 25%.

- **Glass, cement and ceramics:** Production volume in non-metallic minerals grew by 96% during 2005-2021, driven mainly by construction growth and partly by exports. In the medium term, growth is expected to develop in parallel to both population growth and increase in housing demand with the assumed decrease in average inhabitants per household from 3.3 people per household to 1.7. Share of exports in cement, which has grown to 30% in the past few years due to the decline in the domestic construction market, is expected to return to about 10% as the domestic market recovers. In glass, export growth is expected to slow down due to new capacity investments in regions closer to export markets. In ceramics, development of alternative sustainable products is expected to limit the growth in exports. Overall volume growth in non-metallic minerals over 2020-2055 is expected to be around 94% while growth in value added is projected to be 136%.

- **Chemicals:** Production volume of chemicals, which provides essential inputs to various sectors, grew by 127% during 2005-2021. Türkiye is highly dependent on imports to meet domestic demand in the chemicals sector; imports meet about 65% of domestic demand. Exports tend to be import dependent and low value-added final products and constitute 35% of production. In the medium to long term, it is assumed that as domestic capacity geared toward import substitution increases, share of imports in domestic consumption will decline to 40% and the share of exports in production will decline to 10%. Based on these assumptions, production volume growth is projected as 180% and value-added growth is projected as 259%. The projections take into account investments in the petrochemicals production as well as possibilities in newly developed composite materials for sustainable products.

Engineering sectors, such as machinery, electrical equipment, automotive industry, clean energy technologies, as well as advanced materials, green products and aircraft and related technology are projected to experience the fastest growth in both production and value added during 2020-2055. Current share of these sectors in total manufacturing value added is 25% and is expected to reach 42% by 2055. Growth will be driven by both domestic and foreign demand and will be built upon the competitive advantage offered by low energy intensity and existing and future technical and marketing know-how. These will be enhanced by increased education, regional cooperation and research and development. Value added in the engineering sectors is projected to grow by 582% over 2020-2055. The main assumptions in key engineering sectors are presented below.

- **Electrical Equipment:** Production in electrical equipment grew by 210% over 2005-2021 driven mainly by increased urbanization and access to credit in the domestic market and exports to the EU. Exports currently constitute 70-75% of production and are expected to continue to grow in parallel to increased demand for energy efficient and sustainable products and building renovation. Electrification of heating in buildings and industry, energy storage equipment including batteries and renewable energy related equipment offer potential for new products in both the domestic and export markets. Construction growth and the reduction in inhabitants per household is expected to constitute the basis of sustained growth in the domestic market. Growth over 2020-2055 is projected to be 175% in production and 313% in value added.

- **Machinery:** Production in machinery and equipment grew by 200% during 2005-2021 driven especially by exports which constitute 50% of production. Nevertheless, imports are almost equal to domestic consumption and import dependency is particularly high in sophisticated products while significant capacity development has taken place in production of low and medium technology equipment. The sector is expected to further develop and increase product sophistication with growth over the next thirty years projected to be driven by import substitution and new products triggered by the green transformation, especially electrification of transport and heating. Export potential will also be sustained and overall growth over 2020-2055 is projected to be 420% in production and 630% in value added.

- **Automotive Industry:** Production of motor vehicles grew by 126% during 2005-2021 driven by strong growth in both exports and domestic demand. Türkiye has a long-standing relationship with major global automotive producers and strong international-local partnerships. Future growth is expected to be driven especially by production of electric vehicles where investments for domestic production has been started both by public sector and international/local partnership ventures. Growth in the domestic market is expected to be driven by increased car ownership which is currently low by international averages. During 2020-2055, growth is projected to be 171% in production and 300% in value added.

- **High Technology Sectors:** Growth in medium-high technologies, green transition and increased digitalization are expected to trigger progress in high technology sectors, especially in communication and information technologies, pharmaceuticals and aircraft related industries. Production in pharmaceuticals grew three-fold over 2005-2021 while growth in communication/information technologies and aircraft related industries exceeded 120%. Sustained growth in these sectors driven by both domestic demand and exports is expected and their total share in value added is projected to increase from 5.4% in 2020 to 13.5% in 2055.

Traditional low technology sectors, food/beverage and textiles/apparel, which constitute a major part of production in 2020 are expected to continue to grow albeit at a slower pace with a shift toward higher value-added products. Electrification, direct use of renewable energy sources and circular economy will be the salient trends in the transformation of these sectors. Production growth in food and beverage over 2020-2055 is projected to be 58% and its share in value added is expected to decline from 11% to 6%. In textiles and apparel production growth over 2020-2055 is projected to be 84% and 98% respectively while share in overall value added is expected to decline from 10% to 5.8% in textiles and from 5.6% to 4.5% in apparel.

Table 3: *Projected cumulative growth in value-added at five-year intervals*

	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050	2051-2055
Iron and Steel	29.8%	13.9%	16.3%	4.9%	3.9%	3.4%	1.3%
Non-Ferrous Metals	30.0%	15.1%	18.4%	7.5%	7.2%	6.8%	4.5%
Chemicals	32.8%	39.8%	27.5%	24.2%	13.5%	4.5%	2.9%
Building Materials	38.6%	22.1%	18.6%	7.7%	4.6%	2.7%	1.7%
Paper & Pulp	37.2%	26.5%	10.0%	5.0%	2.5%	1.5%	1.5%
Food, Beverage, Tobacco	32.2%	19.0%	18.4%	4.8%	2.5%	2.5%	1.9%
Engineering	46.7%	40.7%	38.4%	32.3%	21.5%	14.6%	13.6%
Textiles	44.4%	23.5%	17.8%	8.7%	5.3%	1.4%	1.4%
Other Industries	35.1%	23.8%	19.1%	14.8%	14.3%	15.8%	18.1%

3.2 International Fuel Prices

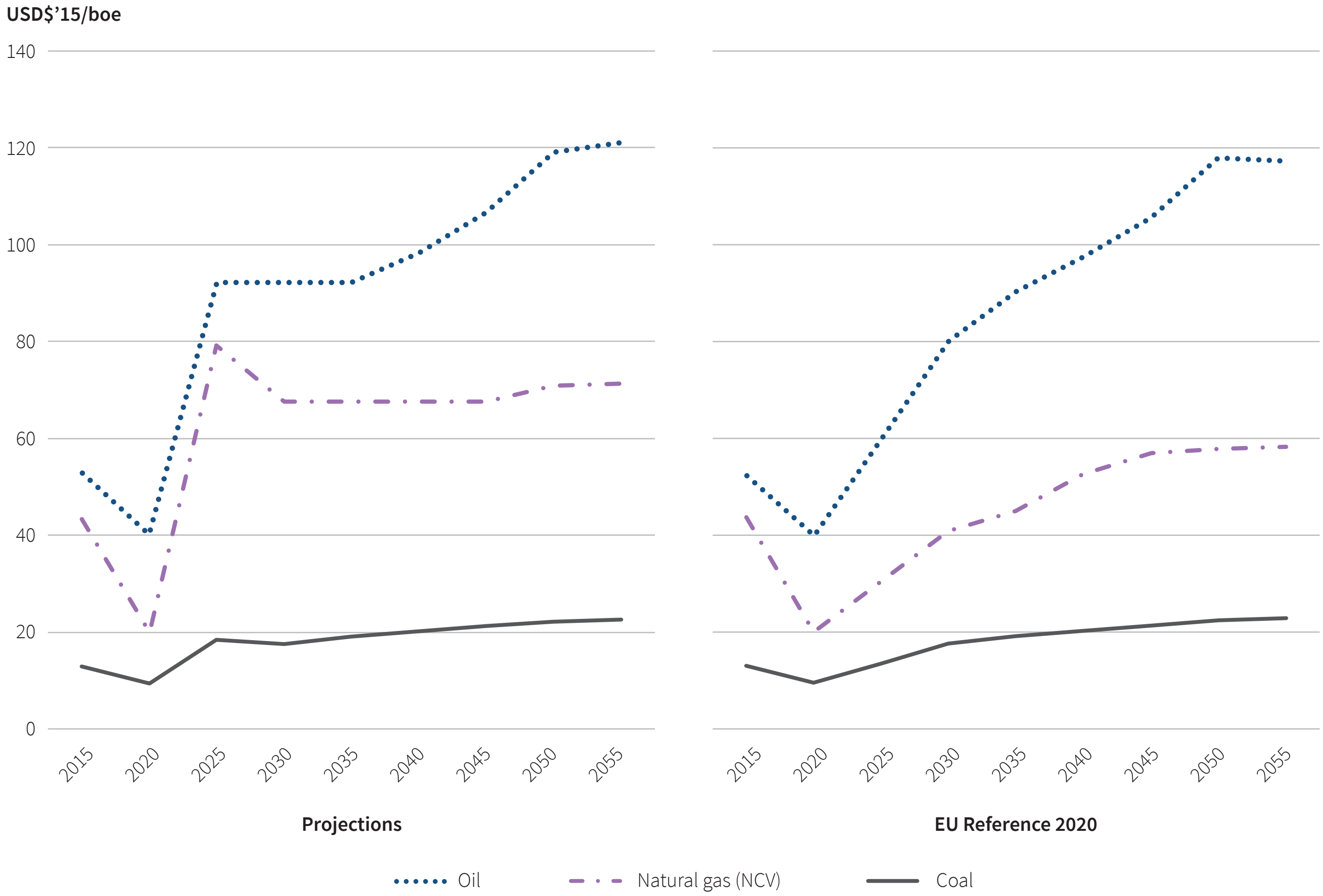
Alongside socio-economic projections, the model uses projections of international energy prices. The international fuel prices influence the domestic fuel prices of fossil fuel-based products e.g. oil products for transport, as well as the natural gas prices for all end users. International fuel prices indirectly influence also the electricity price in so far as power generation uses imported fossil fuels.

International prices depend on several variables, such as future economic growth rates across the world, the development of new technologies, global climate change policies and the strategies of resource holders. These constitute an important marker at the macroeconomic level, as well as for the future of the energy system. Any transition process away from fossil fuels will have to factor in the comparison of the economics of alternative pathways.

Price projections used in the study consider the recent developments on the energy markets, particularly the short-term higher prices. These are based on the developments presented in the REPowerEU document, which were one of the first fuel price projections available until 2050 including the effect of recent developments and were available as of May 2022 (European Commission, 2022). Figure 16 shows price projections between 2020 and 2055 for oil, coal, and natural gas. Oil, natural gas, and coal prices are based on actual data for 2020-2021, combined with estimates of prices in 2022.

After 2022, projected prices are high compared to previous projections (e.g. EU Reference 2020, European Commission, 2021), as it is assumed that a new market equilibrium will stabilise at higher levels. In case of natural gas, current disruptions of supply are assumed to have a permanent effect in the long run price, which is projected to stabilize around 70 US Dollars (US$) per boe after 2035. On the other hand, more recent projections e.g. in the World Energy Outlook 2022 of IEA, suggest that prices will stabilise at lower levels and earlier. However, toward the net zero target, the prices of fossil fuels have increasingly low influence on the modelling results during the transition, as fossil fuels play a dwindling role in the energy system.

Figure 16: *International fossil fuel prices*[8]



Beyond 2035, oil prices continue to rise reflecting the rising cost of production, limited investments in extraction, tapping new supply routes, and geopolitical developments such as the swing supplier strategy of the Organisation of the Petroleum Exporting Countries (OPEC), transportation costs, etc.

National price projections are a combination of international fuel price projections and national historical price developments. The prices of domestically produced fossil fuel prices are based on the costs of extraction augmented with the associated subsidies, or other tariffs and agreements aiming at maintaining the competitiveness of domestically produced resources. In Türkiye, lignite is produced and consumed domestically and is not traded. Historical prices used in the modelling are based on primarily on the World Bank (WB) Commodity Outlook reports and data from Enerji IQ magazine.

3.3 Technical Potential of Resources

The decarbonization of the energy system depends on both the technological advancements and the resource availability. The key concerns in installing new renewable energy power plant capacities mainly include the landscape availability as well as environmental concerns and regulatory constraints. In terms of renewable energy potential, Türkiye is one of the pioneering countries with high hydropower,

[8] Own assumptions based on EC RePowerEU Communication and EC Reference Scenario 2020 for the longer term

wind and solar energy potential. Considering the energy mix of Türkiye in 2020, hydropower stands as the main renewable energy resource which corresponds to 4.5% of the total energy consumption and 25% of gross electricity generation (MENR, 2022). In the study, the potential of hydropower capacity is assumed to be 35 GW, which is in line with SHURA's previous studies. In that regard, the potential for new hydropower plants is limited considering that the existing capacity reaches almost 31 GW in total.

As for the solar PV potential, currently installed capacity indicates that the resource is largely untapped in Türkiye. Considering the study conducted by the International Renewable Energy Agency (IRENA, 2022), with the current solar PV technology, approximately 35% of the land area in Türkiye corresponds to an average capacity factor of 19 to 20%, whereas another 45% indicates an average capacity factor of 16 to 17%. These figures render most of the Turkish territory suitable for solar power plant development. The study considers an average solar PV capacity factor of 19.5%, assuming that the land area is sufficient and feasible for implementing solar PV power plants to accomplish the net-zero carbon emission target. In that regard, it is assumed in the model that the potential of solar power is unrestricted.

Concerned with the wind power potential, the MENR estimates the economic potential is approximately 48 GW (MENR, 2022). According to the WB study that considered the offshore wind energy potential of Türkiye, the fixed-bottom offshore wind energy installation capacity is approximately 12 GW, whereas the floating offshore wind capacity is 63 GW (World Bank, 2020). Given the geographical features of Türkiye and considering similar studies for the EU Member States (European Commission, 2019), this study assumes that the onshore and offshore wind energy potentials are 120 GW and 20 GW respectively.

In the model, the nuclear energy potential is assumed as 14.4 GW. This assumption shows the total capacity in case 3 large nuclear power plants (Mersin, Sinop and Thrace) are built. In the model, it is assumed that the first reactor (1.2 GW) of Akkuyu Nuclear Power Plant will be operational by 2026 and the entire power plant (4.8 GW) will be operational by 2030.

Table 4: *Technical potential of installed power for RES and nuclear power plants*

Hydro Dam	GW	25
Run of river	GW	11
Pumped hydropower	GW	3.2
Solar PV	GW	Unlimited
Wind onshore	GW	120
Wind off-shore	GW	20
Geothermal	GW	4.5
Nuclear	GW	14.4

3.4 Policy Implications

Due to the decreasing capital costs and levelized cost of energy (LCOE) of renewable energy systems (RES), renewables have become one of the cheapest options for power generation. On the other hand, the installation of RES is rather slow due to the administrative and regulatory barriers, in addition to the financial and market related constraints. However, the net-zero goal for a would require policy changes to accelerate the deployment of renewables and accomplish a smooth transition from fossil fuels to the clean technologies in both demand and supply sides. In this context, various different policies can be adopted on a sectoral basis. Examples for these policies could range from subsidies to implement higher energy efficiency measures, installation of renewable energy technologies, CO_2 based emission performance standards, taxation on emissions or use of fossil fuels.

In that regard, the carbon pricing mechanism, which is an example to the market-based policy instruments, increases the cost of fossil fuels and hence reduces the competitiveness of these technologies. In secondary energy carriers, like electricity, the cost of emissions can be indirectly reflected to the end consumers. The revenues of the carbon price then can be used in order to finance the energy transition to meet the net-zero emission targets. Currently, Türkiye is planning to implement an emissions trading market, however it is yet not clear how the carbon pricing will be designed.

Considering these developments, this study utilises a similar driver that resembles with the carbon price, which is called the "carbon value". The carbon value resembles the carbon price in the sense that it covers an emissions cost that influences the decision of the power producers. However, within the carbon value mechanism, the electricity prices that are reflected to the end-consumers do not include the associated carbon costs. In terms of modelling practice, the carbon value is a parameter that would imply how much one tonne of CO_2 would cost to achieve a specific carbon emission target. In that perspective, the carbon value actually represents the marginal price of carbon.

4. Net Zero 2053 Scenario

Türkiye signed and ratified the Paris Agreement in October 2021 and subsequently pledged to accomplish net-zero GHG emissions in 2053 (TCCB, 2021).

After establishing the net-zero GHG emissions goal, Türkiye also convened the "Climate Summit" in February 2022, which was organised by the T.R. Ministry of Environment, Urbanisation and Climate Change. With these positive developments, it is expected that Türkiye would announce clear goals and establish climate-focused policies in the near future that would pave the way to accomplish the net-zero emissions target. In this direction, the Ministry of Energy and Natural Resources (MENR) published the National Energy Plan strategy document at the end of 2022[9]. In this document, the targets for 2035 are determined and some targets and predictions for 2053 are also shared.

The net-zero targets, which aim to reduce the greenhouse gas (GHG) emissions and remove any residual emissions either via carbon capture and storage (CCS) technologies or land-based sinks, intend to limit the global temperature rise at or below 1.5°C (IPCC, 2019). The main purpose of this study is to analyse a possible pathway that would result in achieving the power system with net-zero carbon emissions in Türkiye.

When the model is considered, there are various strategies that would be adopted to reduce the overall emissions, including:

1. High energy efficiency implementation including circular economy measures,
2. Maximum level of electrification in all sectors,
3. Using hydrogen as energy carrier,
4. The use of e-fuels (emission-free gas and liquid fuels) as energy carriers.

The implementation of these strategies depends upon a multitude of actors and stakeholders, both public and private. While a clear policy together with standards, obligations, incentives and disincentives is necessary for implementing all the strategies, the level of government involvement will likely differ for each strategy. For instance, actions from individual parties (i.e. residential or industrial) are essential for an energy efficiency-based strategy whereas a shift from the use of fossil fuel to emission-free fuel alternatives would require direct governmental and hence central policies and strategies. Nevertheless, no single strategy on its own will be sufficient to achieve the net-zero target; a strategic combination of all will be needed. The table below presents the pros and cons for each aforementioned strategy:

[9] https://enerji.gov.tr//Media/Dizin/EIGM/tr/Raporlar/TUEP/T%C3%BCrkiye_Ulusal_Enerji_Plan%C4%B1.pdf

Table 5: *Long-term strategies for the decarbonization of the energy sector*

Strategy	Advantage	Disadvantage
Maximum Efficiency and Circular Economy	• Less costly • No additional stress on the power-supply	• Dependent on individual investments • Level of implementation (potential) is uncertain • Appropriate policies need to be adopted • Low demand in implementing the energy efficiency measures in the supply side discourages investments
Maximum Electrification	• Efficient and convenient technology • Modest growth in the annual electricity demand	• Not fully applicable in industry and transport sectors • Lacks competition among different energy carriers • High daily and seasonal variability (i.e., EVs, heat pumps considering winter and summer) • High balancing costs
Use of Hydrogen as End-Use Energy Carrier	• Enables electricity to be stored chemically • Hydrogen can be utilised as a global energy carrier • Less electricity intensive than e-fuels	• Requires infrastructural development • Uncertainty in the future costs of hydrogen and fuel cells • Uncertainty in the acceptance of the technology considering public safety issues
E-fuels as Energy Carriers	• Applicable with the current infrastructure • Enables electricity to be stored chemically • Similar behaviour in the existing energy consumption understanding • Lacks competition among different energy carriers	• Requires carbon neutral feedstock (e.g., Direct Air Capture, biogenic) • Uncertainty in the future costs of e-fuels • Requires rapid increase in the total power generations

Regarding the policy practices, if it is required to model a more moderate reduction in the emissions, any of the aforementioned strategies could be adopted.

However, if the aim is to reduce the emissions to net-zero level, a combination of all strategies should be utilised to take full advantage of each strategy involved. Establishing a complex strategy which involves each individual strategy would in turn imply:

- Reducing the energy consumption when possible,
- Using electrification when feasible, and
- Utilising the potential of green hydrogen in addition to other e-fuels in sectors for which electrification is not sufficient considering the current technological limits.

To reduce emission reduction, electrification has proven to be one of the most efficient ways that can be applied in many of the sectors. This concerns road transportation (i.e., electric vehicles using batteries), residential and services sector (i.e., heating via heat pumps) and many other industrial applications and uses (i.e., electric arc furnaces, industrial heat pumps) and usage. In that regard, electrification is one of the preferred options for decarbonization, when possible. In other areas, where high-temperature heat (industrial processes), or long-haul cargo transportation (i.e., aviation or maritime), other energy carriers with higher energy density will be required, for which e-fuels and green hydrogen can be given as examples. These alternative clean energy carriers are produced via electricity using renewable energy systems (RES), and hence are an indirect way of electrification by nature.

Considering the pivotal role of electricity that is generated by the use of RES, the decarbonization of the electricity sector stands in the core of the "Net-Zero 2053 (NZ2053)" scenario conducted in this study. In that regard, the NZ2053 scenario considers timely and climate-focused actions and strategies adopted in the electricity sector. The scenario assumes that the decarbonization policies will be adopted as soon as 2020s and will speed up after 2030.

Energy transition of end-use sectors focuses on energy efficiency and electrification. E-fuels (such as emission-free liquids and gaseous energy carriers) are used mostly in hard-to-electrify sectors such as industry (requiring high temperature heat) and long-haul cargo transportation. In the scenario, both electricity and e-fuels are generated via the use of renewable energy power plants. In the model, both the current, mature and widely used (e.g., solar PV), and developing technologies (e.g., electrolysers) are applied in the electricity sector. The model assesses the potential for each technology and integrates them into the supply mix to simulate a net-zero pathway by analysing the technical and economic feasibility of the power system.

The NZ2053 scenario considers several enabling key conditions to achieve the net-zero target. In the scenario, it is assumed that both public and private sectors act according to the net-zero goals and have a positive market-anticipation. However, conditions that are assumed in the model are as follows:

- Carbon value is applicable to power, industry and air transportation sectors as a disincentive or restriction for the use of emitting technologies.
- Positive market anticipation is assumed, which considers lower non-market barriers to allow for a higher market penetration of the emission-free technologies.
- Market predictability, certainty in regulations and administrative facilitations are assumed to allow for a positive investment environment in the installation of new renewables capacities (distributed to utility scale projects).
- Applicable facilitations for the renovation of buildings in residential and services sectors are considered to be in place. This also concerns the incentives for installing heat pumps, solar water heaters (or the solar domestic hot water systems) and promoting energy efficient appliances.
- In transport sector, the carbon emission standards are assumed to be applied, which will imply a zero-emission constraint in the long-run. This would in turn speed up the transition to the electric or green hydrogen-using vehicles.
- It is assumed that the entire infrastructure will develop according to the needs, which includes the grid investments as well as recharging and alternative

refueling infrastructure developments. In the model, it is assumed that the lack of appropriate infrastructure could be a barrier in the market penetration of the alternative resources and emission-free technologies.

- In the model, it is assumed that the natural gas grid will also be using e-fuel mix in the future. In that regard, the pipeline gas will gradually be blended with low carbon alternatives (i.e. green hydrogen, synthetic gas and biogases). It is assumed in the model that this transition will commence by 2035, with low shares of e-fuels to the gas mix and the share of e-fuels will gradually increases in the future leading to net-zero pipeline gas mix by 2053.

As indicated in the previous chapters, a sensitivity analysis was conducted as part of this study to evaluate the consequences of delaying the decarbonization actions in the electricity sector. In that regard, the consequences of delaying the application of the carbon value approximately for a decade were analysed in the study. In this analysis, the net-zero emissions by 2053 target for the electricity sector was also achieved, while the energy demand was kept identical to the NZ2053 scenario. In that way, it was ensured that the results of the sensitivity analysis are comparable to the NZ2053 scenario. In this sensitivity analysis, it is assumed that there is no initiative to decarbonise the electricity sector until 2035, however a more rapid and sharp emissions reduction must be accomplished afterwards. It was aimed to analyse the impact of such a delay on the total costs, carbon budget and investment feasibility, as investments will need to be completed within even a shorter time period. The analysis further investigates the risk of higher cumulative emissions which exceed the carbon budget limits defined within the Paris Agreement.

5. Net-Zero 2053 Scenario Results

This section addresses the model results for the Net-Zero 2053 (NZ2053) Scenario in detail. The subsections present the model results for the demand and supply sides including the emissions and system costs and capital expenditures. In order to accomplish the net zero carbon emissions, all sectors must undergo significant transformation, while system efficiency must also increase significantly through direct energy efficiency improvements as well as utilising higher levels of renewable energy sources and electrification.

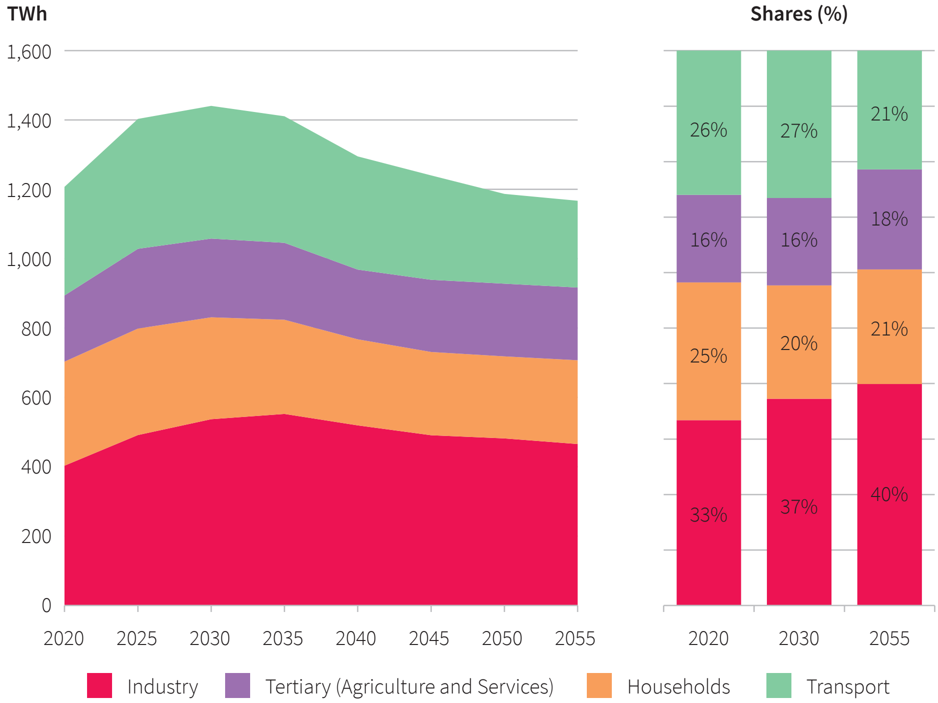
The below subsections present the energy demand projections by sector, followed by the developments in the energy supply, the modelled amount of investments and emissions.

5.1 Energy demand

Macro-economic trends foresee strong growth prospects for the Turkish economy, which are in line with the governmental targets for establishing high economic growth. Within this scope, Türkiye is projected to transition from an emerging to a high-income country with gross domestic product (GDP) rising annually with an average rate of 3.3% until 2053. Increasing economic growth and the objective of high levels of emission reductions require decoupling of physical activity and energy consumption from economic growth. The findings in this study demonstrate that sustained growth can be maintained together with reduced energy intensity and carbon-free energy supply.

Over the projection period, Türkiye is assumed to retain its manufacturing capacity; however, manufacturing will shift toward higher value-added and less energy intensive industries, mainly machinery, electrical equipment and vehicles, advanced sustainable products, renewable energy/energy efficiency equipment and basic chemicals. Construction is expected to grow in line with population growth and the decrease in the number of inhabitants per household. Manufacturing of construction materials, which are energy and carbon intensive, is assumed to grow in parallel to construction growth with low-value exports tapering off overtime. Transport activity is also projected to increase significantly in line with GDP per capita growth, triggering increased travel and trading. The growth in transport activity will stimulate a number of industries and services, especially automotive, machinery and travel services. Despite increasing activity in industry, construction and transport, primary energy use is expected to peak and decline overtime due to changing industrial and modal mix, electrification and increased efficiency.

Figure 17: Total final energy demand by sector



Achieving the net-zero carbon emissions goal by 2053 implies a significant reduction in the energy intensity of Türkiye's economy. The model results indicate that the final energy consumption peaks in 2030, reaching approximately 1,450 TWh and declines afterwards. This trend shows that although the economic growth is maintained, if the utilisation rate of energy efficiency and electrification in all sectors of the economy increase, the final energy consumption levels can be reduced to 1,200 TWh by 2053, which is close to the 2020 levels (Figure 17). Details on sectoral developments are provided in the relevant sections.

Energy intensity drops in all demand sectors, especially transport and households (also in per capita terms). Electric vehicles (EVs) are far more efficient[10] than conventional cars, allowing for a significant reduction in consumption per units.

On the other hand, investments in rail infrastructure are expected to trigger modal shifts. In the buildings sector, renovation, new low-energy buildings, the switch to electric equipment (e.g., heat pumps) and highly efficient electric appliances mitigate the demand for energy. Throughout the projection period, industry remains the most energy-intensive sector. This trend is moderate considering the strong economic growth prospects for the Turkish economy and also includes energy efficiency gains.

In 2020, fossil fuels (oil products, natural gas and solids) made 71% of final energy demand. This is projected to change drastically by 2053, when fossil fuels are projected to make up only 1.2%. The model results show that having achieved negative emissions by the electricity sector before 2053 compensates for the residual emissions from other sectors. Pipeline gas consumption is used only where electrification is not possible (mainly industry), while its composition changes over time from just natural gas to a mix of locally produced green hydrogen, biogas and synthetic gas (see Table

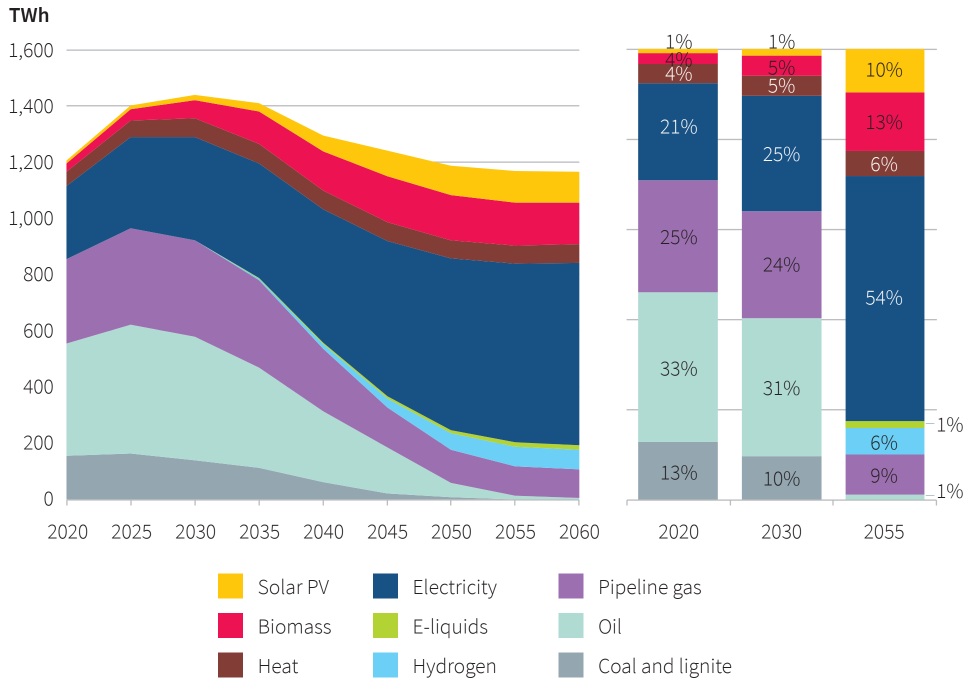
[10] Consumes approximately 30% energy compared to an equivalent internal combustion engine (ICE)

6). The introduction of e-fuels into gas grid begins in 2035 and by 2055 its carbon footprint is reduced to zero. The key to change the final energy demand is the shift towards electrification, which allows the sectors to reduce their emissions significantly (Figure 18).

Indeed, electricity demand grows vastly between 2020 and 2055 due to increased electrification in transport, residential and services sectors, as well as industry. From 21% in 2020 final electricity consumption increases moderately to 25% in 2030 and becomes the primary energy carrier in 2055 with a 54% share of total final energy demand.

The direct use of renewable energy sources (RES) includes biomass (including biofuel use in transport) and solar PV. Currently, direct consumption of RES represents only 4% of final energy consumption. This share reaches 23% by 2055, reflecting the increased levels of biomass use in the industry and solar heater use for water heating.

Figure 18: *Final energy consumption by fuel*



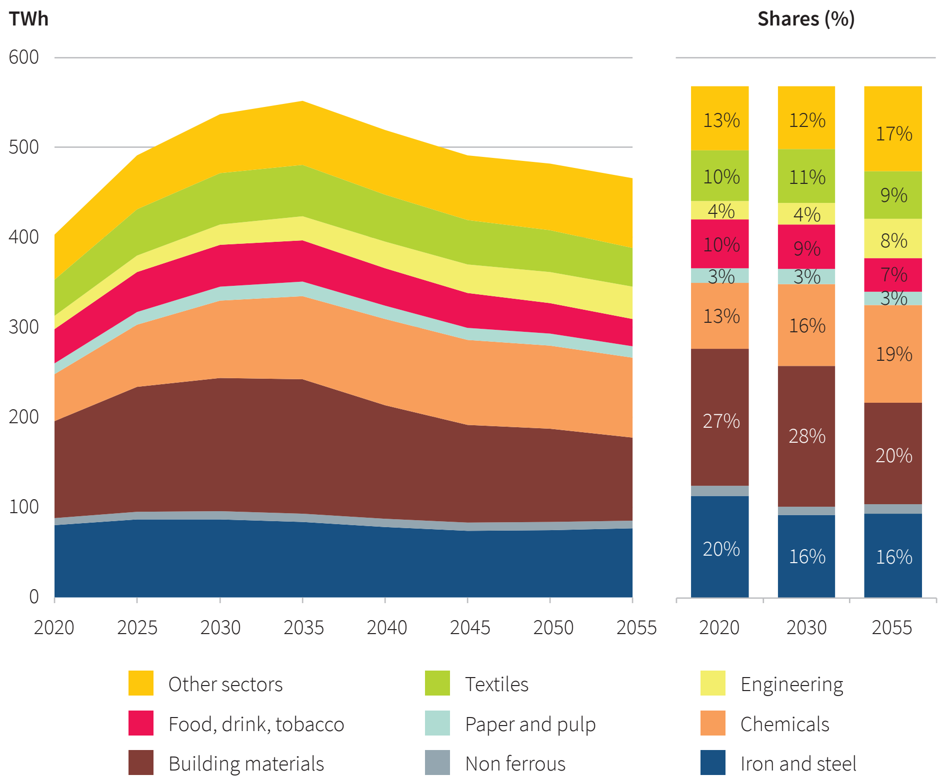
5.1.1 Industrial Sector

Industry is projected to decrease its energy and emission intensity significantly as a result of these two main trends:

- Activity increase in the less energy-intensive sectors, which is based on the assumed macro-economic developments, and
- Increase in total energy efficiency, including the effect of increased electrification.

Engineering, low energy chemicals and innovative green materials, which are more knowledge and less energy-intensive are projected to drive the growth in industrial value added in the three decades to come.

Figure 19: *Final energy consumption in industry*



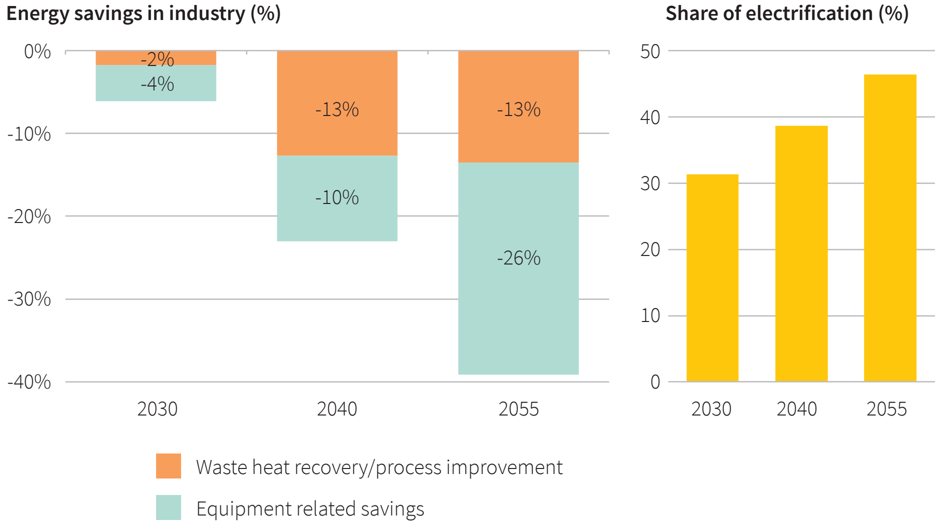
In industry, the energy consumption is projected to peak by 2035 in line with the growing industrial production. In the first decade of the projection, economic growth is more closely linked to rising energy consumption; afterwards the energy intensity is expected to decline due to both electrification and shift to less energy intensive processes and sectors. In the first decade industrial energy demand is set to increase further due to persisting trends, planned investments and system inertia, before hitting its peak. This is taken into account in the modelling and concerns both fuel choice and energy efficiency. Beyond 2030, the consumption of fossil fuels starts to drop due to changes in the activity and new investment patterns which lead to fuel switching. Fossil fuels are decreased gradually and almost entirely phased out by 2053. Currently, the production of iron and steel in blast furnaces ranks first in coal consumption, followed by the thermal processes of construction materials (primarily the production of cement). It is assumed that equipment replacement always leads to higher efficiencies in all sectors. These are the so-called market-based improvements which would occur independently of any policies, as a result of new equipment replacing old equipment at the end of lifetime[11].

A number of general or sector-specific options are included in the model to reduce energy consumption and emissions. Horizontal process improvements leading to waste heat recovery are assumed to take place in all relevant industries incentivized by the rising cost of energy and the need to decarbonise. This leads to process-wide energy efficiency. In specific industries additional process-wide improvements are

[11] A plant by plant analysis for Türkiye was not undertaken for the purposes of this study. However, some plants are considerably old and have been partially renovated at diverging moments in time. As most larger plants operate with more than one blast furnace per site it is expected that these are replaced one by one.

considered, such as the modification of clinker to cement ratios to reduce the energy and emission intensity of cement production. The assumptions regarding sectoral development (see Section 3.1.2) consider that recycling, i.e. secondary production, is maximized where possible for all industries, predominantly the production of metals (ferrous and non-ferrous) and glass. Secondary production is less energy intensive (e.g., aluminum) and can often be electrified (e.g., steel/glass) rather than using fossil fuels.

Figure 20: *Energy savings in industry[12] and share of electrification*



Besides energy efficiency and heat recovery, the most efficient way to reduce emissions in industry is to electrify industrial production wherever feasible. Based on the model results, between 2030 and 2055 the electrification of industry increases significantly. 46% of final energy consumption in industry comes from electricity by 2053, which is 29% in 2020. Majority of engineering, textiles, non-ferrous metals, and steel making will be almost entirely electrified by 2053. The electrification implies the use of heat pumps and electric furnaces where the technical conditions are met. While less energy intensive and low temperature sectors are easier to electrify, some processes (e.g., iron production, some glass manufacturing, cement production, etc.) cannot be thoroughly electrified based on technologies known today. The highest consumers of fossil fuels are, as would be expected, energy intensive industries. However, also in these fields, there is a trend to move from oil and coal to gaseous fuels and where possible to electricity and use biomass.

Iron and steel factories are expected to gradually transition from blast furnaces to direct reduction iron (DRI) processes using hydrogen as fuel. The shift is projected to begin after 2035 when the older factories will need to be replaced by new ones.[13] The use of green hydrogen in the production of iron is considered the most promising technology to reduce emissions originating from this process (IEA, 2022).

[12] Calculated based on the level of 2020 energy intensity
[13] For the purposes of the current analysis, a geolocation of these plants (same site or new site) has not been performed. However, most projects world wide are expected to take place on the same site.

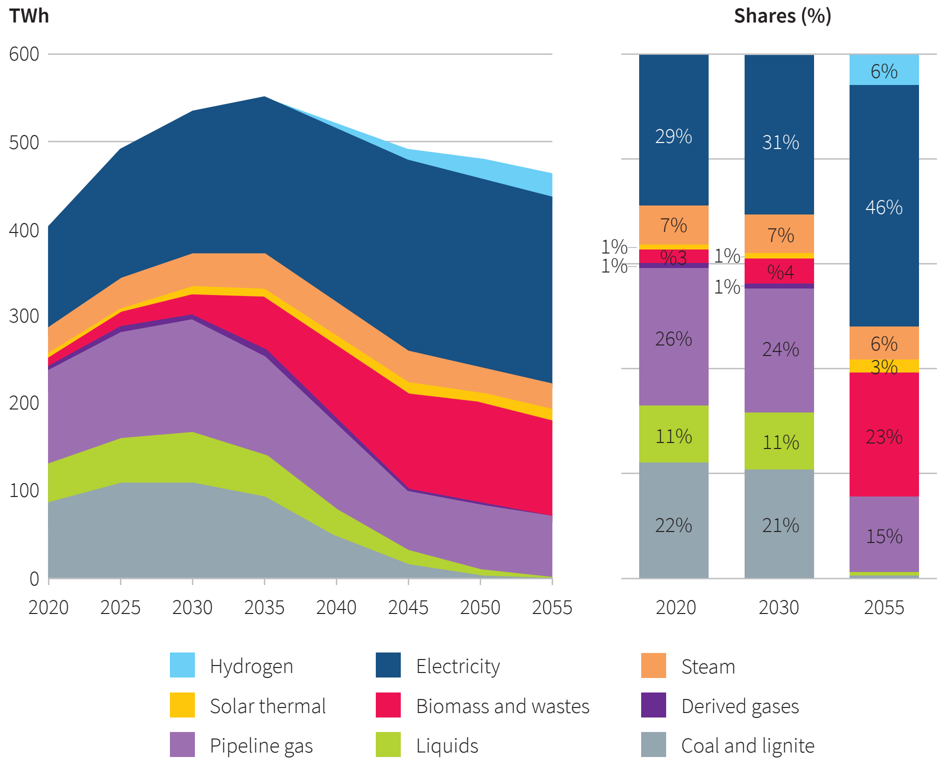
The industry of construction materials (primarily cement) needs to undergo significant changes to reduce both energy and process related emissions. The options that can be applied for the cement industry are as follows (IEA, 2022):

- reduction of clinker to cement ratios,
- higher use of biomass,
- use of green hydrogen or e-gas and,
- use of carbon capture and storage (CCS) for the remaining emissions in the long-term.

The strategy used in the projections adopt these different options. It is considered in the model that heat recovery and the change in clinker to cement ratio will result in energy savings, and the use of gaseous fuels and biomass as the preferred fuel types will allow for further emission reductions. CCS will be used to abate the remaining process emissions.

Finally, it is projected that by 2053, electricity accounts for almost half of final industrial energy consumption, while the share of biomass and waste shares (approximately 5% in 2020) reach 23%, while pipeline gas and direct hydrogen cover approximately 20% of industrial final energy consumption. Pipeline gas is expected to become net-zero to comply with the net zero target by moving away from natural gas to a mix of hydrogen, biogas and e-methane. Through energy efficiency, electrification, and greening of the gas grid as well as significant use of biomass, with limited use of CCS primarily to abate process emissions, the industrial sector is able to make a significant contribution towards reducing energy consumption and emissions, enabling the entire energy system to achieve net zero target.

Figure 21: *Final energy consumption by fuel in industry*

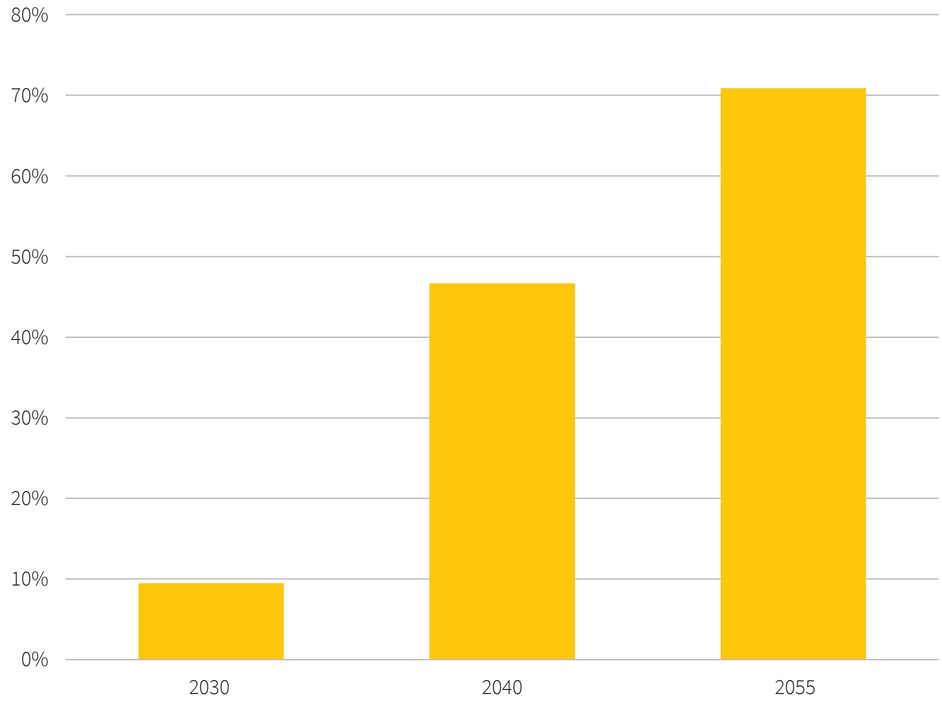


5.1.2 Residential and Tertiary (Agriculture and Services) Sectors

With rising household incomes, energy use in households and other buildings are expected to increase (i.e. spaces that are heated or cooled). The same applies to consumption of hot water. However, higher energy use is not projected to cause an increase In the total energy consumption, thanks to higher energy efficiency standards implemented through policies and measures. Examples for the policies and measures can be given as strict building codes for new and renovated buildings, as well as setting and enforcing minimum energy performance standards for equipment and appliances.

In the long run the main energy carrier in the residential and services sectors is electricity. This is primarily attributed to the commissioning of heat pumps, driven by the need to avoid rising energy prices and to reduce emissions (Figure 22). Strict standards for new buildings and renovations limit the need for heating and cooling, which can be covered, ideally, by heat pumps. It is projected that 20% of households use heat pumps as their main heating source by 2025; this share reaches 70% by 2053.

Figure 22: *Share of heat pumps in buildings*

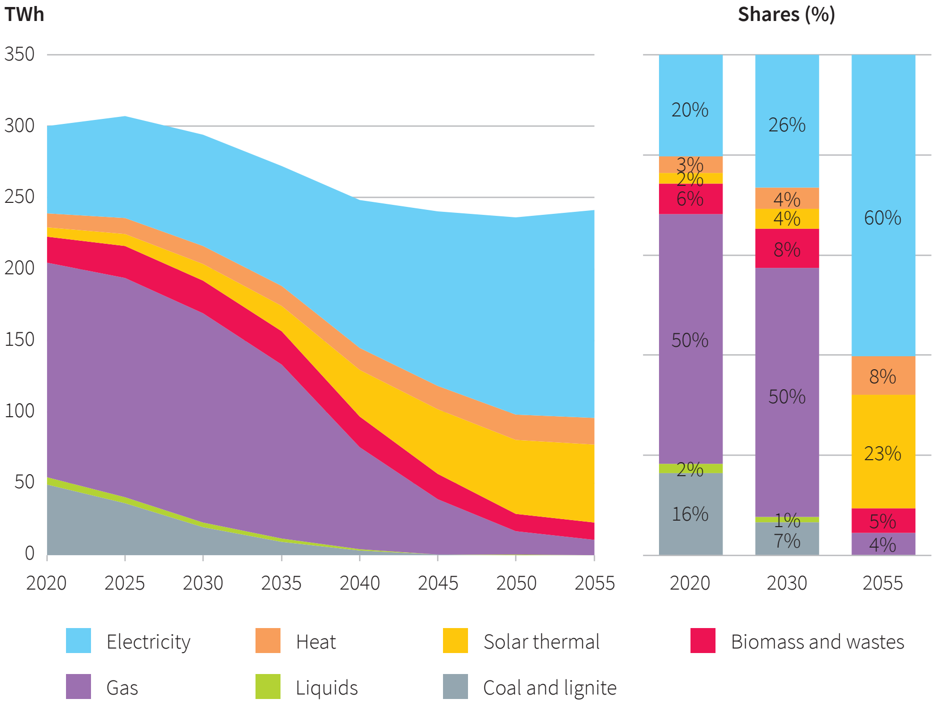


Solar thermal, which enable direct use of RES for water heating in the residential sector, is modelled to undergo an almost nine-fold increase from 2020 to 2055 (Figure 23). Thus, solar thermal goes from a small share of 2% in final energy consumption in 2020, to contributing almost 23% of the total final energy consumption in 2055. This increase is driven mainly by solar thermal water heaters penetrating into the market, which is an already known, widely available and easy to install technology. On the other hand, the share of geothermal heat doubles between 2030 and 2055 – from 4% to 8% – enabled by the market uptake of geothermal heat pump applications.

Additionally, with higher minimum energy performance standards, all appliances are expected to be highly efficient thanks to policies that favour energy efficiency and reduce market and non-market barriers.

The projection of energy demand in the tertiary sector[14] resembles that of the residential sector (Figure 24). Demand peaks in 2025 and drops sharply afterwards driven by high standards for new buildings, and renovations in both public and commercial buildings, the use of efficient equipment and the large deployment of heat pumps. In the long-term energy demand stabilizes at low levels in terms of energy intensity.

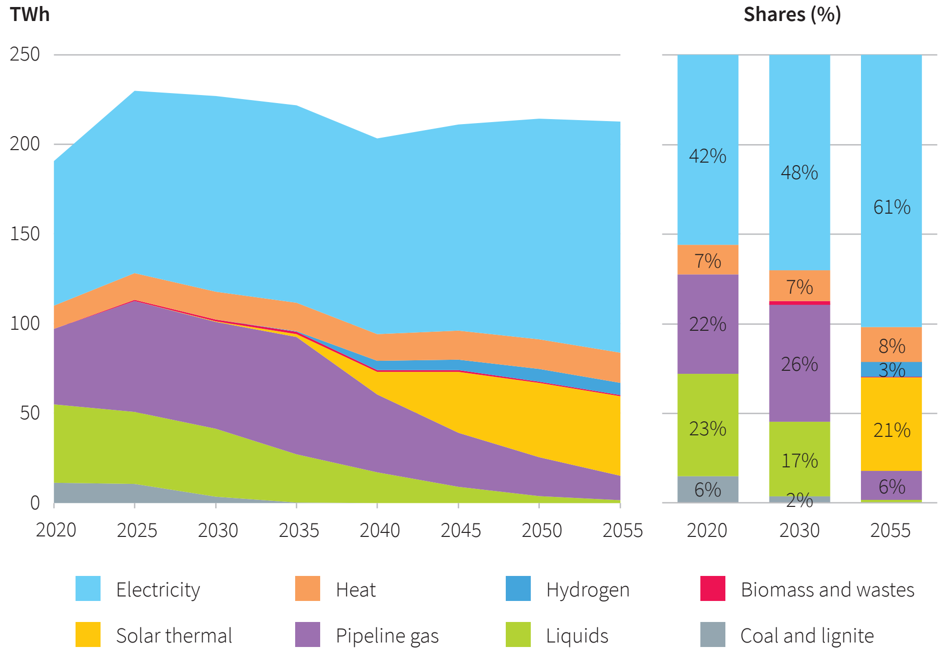
Figure 23: *Final energy consumption in residential buildings*



Growing electrification and uptake of solar thermal along with high levels of renovation are the main trends which lead to the reduction and then phase-out of fossil fuels. The remaining gas consumption is assumed to be zero-emission pipeline gas (see Section 5.1.5). By 2053 the electrification ratio in services and agriculture, which is referred as the tertiary sector in the study, is 61%, owing to the wide application of heat pumps and increased use of electric cookers and water heaters. Indicatively, 74% of space heating is met through heat pumps by 2053. In 2030, solar thermal is almost not utilised in the system at all whereas the share reaches 21% in 2055. Geothermal energy increases modestly, used mainly for heating greenhouses.

[14] Hizmetler ve tarım sektörlerinin toplamı

Figure 24: Final energy consumption in the tertiary (agriculture and services) sector



5.1.3 Transport Sector

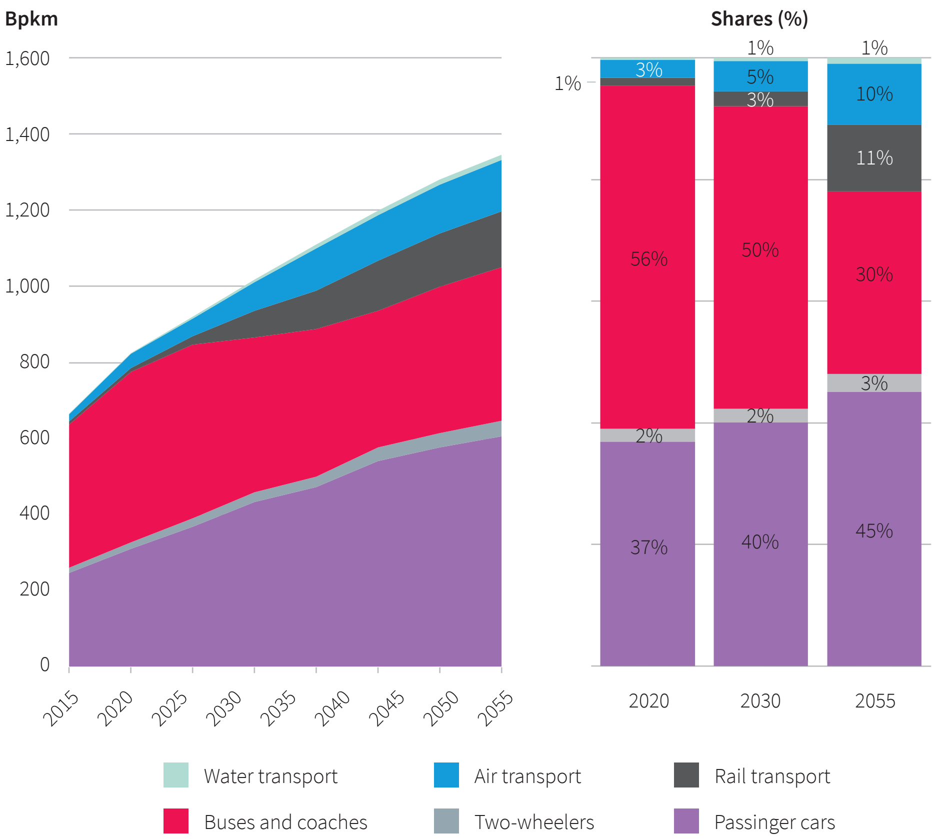
Currently, transport is the second most energy-consuming sector after industry and has the highest reliance on fossil fuels when compared to other sectors. In 2020, 98% of transport needs were met through oil products, mainly diesel oil, gasoline and liquefied petroleum gas (LPG).

Transport activity

Türkiye is currently characterized by its relatively low passenger mobility levels with an average of 7,890 km/person in 2020 (TÜİK, 2022). Whereas, the average European Union (EU) mobility was 13,498 km/person in 2019. With increasing income per capita, passenger transport is set to double in the projection period to 2053.

Public road transport, comprising busses and coaches, is currently the predominant mode of passenger transport with 56% share in passenger-km. Share of passenger cars, at 37%, is low in comparison to the EU average of 81.3% (EU Directorate General for Mobility and Transport, 2021). Share of rail transport, which has great potential for de-carbonizing passenger transport in both urban and long-distance travel is also currently quite low at 1%. Over the next thirty years, it is projected that passenger car ownership will increase with income growth and the share of passenger cars in total passenger-km will reach 45% by 2053. While passenger car-km will increase by a total of 121%, the increase in its share is expected to be limited due to the increased availability of low-carbon public and shared options and will remain well below current EU averages. The share of rail transport is set to increase 10-fold in line with the plans of government in transport sector to increase investment in high speed railways and urban rail transport (Ministry of Transport and Infrastructure, 2022). An increase in the share of air transport from 3% to 10% is projected driven by investments in domestic air travel infrastructure and geography which may limit further expansion of railways.

Figure 25: *Passenger transport activity projections*

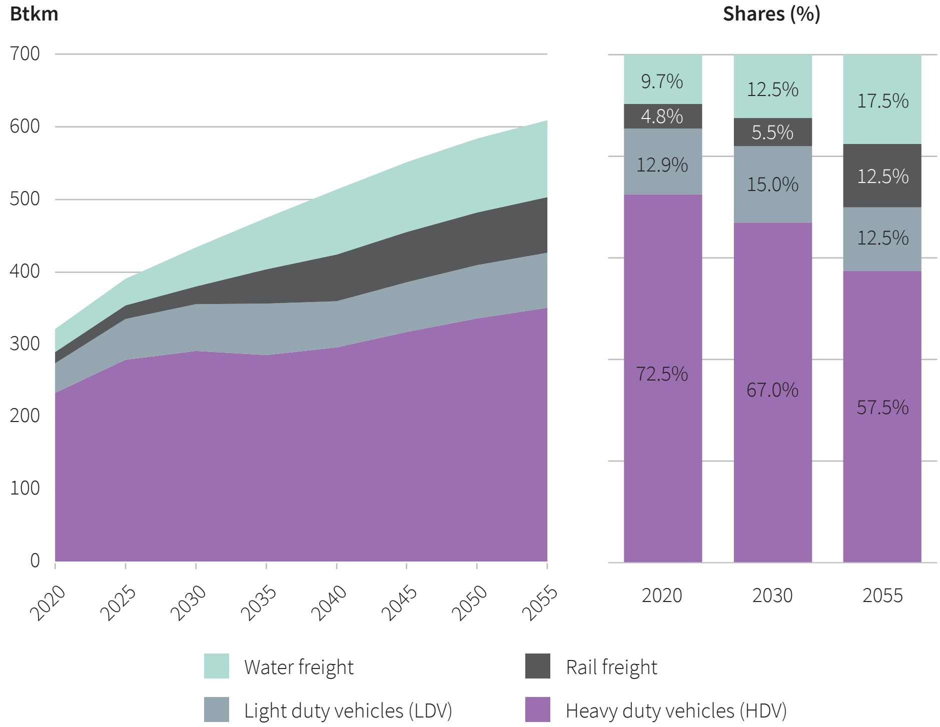


Freight transport activity in tonnes-km is assumed to increase at an average annual rate of 1.7%, lower than the growth rate in the economy overall and transport growth in previous years. While GDP and trade growth are the main drivers of freight transport activity, as the product mix becomes more sophisticated in terms of value added, the growth rate in tonnes of cargo is expected to decline in comparison to previous years. The majority of the cargo tonnage transported is comprised of fossil fuels, grains, construction materials, and similar bulk cargo whose production and trade growth are expected to slow down over the next thirty years.

Currently, heavy duty (HDV) and light duty (LDV) vehicles comprise over 85% of transport activity while water transport is 10% and rail transport is only 5%. In line with the plans of government in infrastructure, transport and de-carbonization, it is projected that the share of road vehicles in freight will decline to 70% by 2053 while the share of water is set to reach 18% and that of rail transport 13%.

The resulting modal mix in both passenger and freight transport will facilitate increased electrification of transport and allow for alternative e-fuels and green hydrogen where electrification is not feasible.

Figure 26: *Freight transport activity projections*



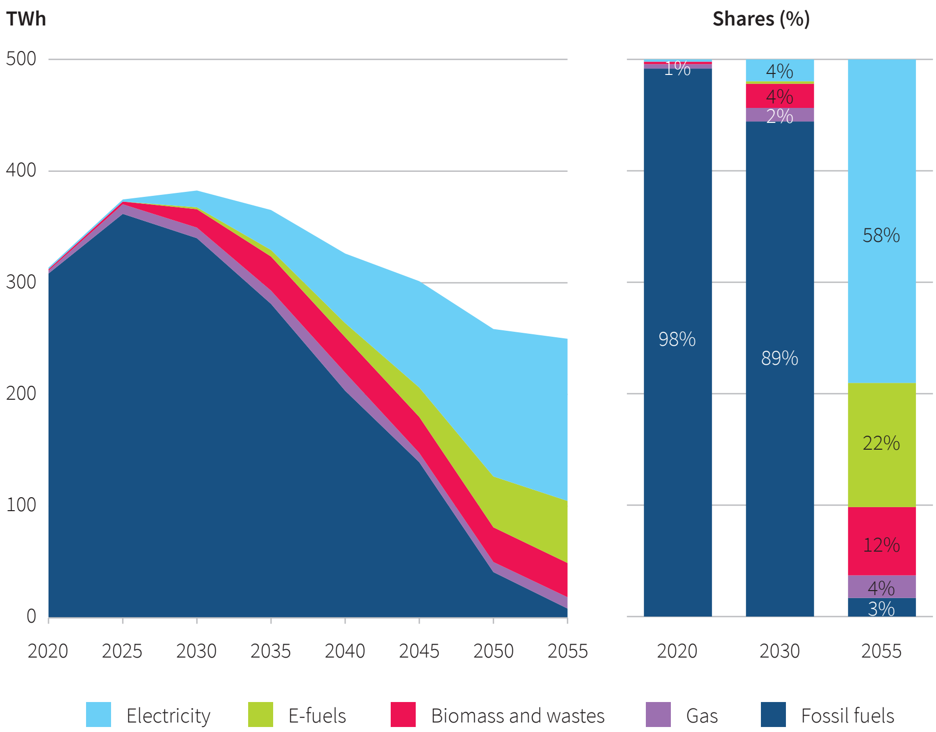
Final energy consumption in transport

Final energy demand in the transport sector peaks in 2030 and drops continuously thereafter until 2055, reaching consumption levels close to 2020. The use of fossil fuels, which is modelled to be 90% in 2030, is expected to decline to 3% by 2055. Fossil fuels are replaced mostly by electricity (58%) and to e-fuels (22%), which consist of green hydrogen and e-liquids. Advanced fully fungible biofuels, which are expected to replace conventional biofuels as of 2035, are projected to meet 12% of energy demand by 2055.

Electrification of transport serves the double aim of increasing energy efficiency and reducing emissions. Electric cars for instance use on average 70% less energy per vehicle-km compared to a conventional car and exhaust no emissions. Therefore, from an energy system perspective, and in light of a net-zero goal, direct electrification is the most efficient way to maintain transport activity while reducing emissions and saving energy. At the same time, using synthetic liquids produced through electrolysis requires significant more energy than direct electricity consumption in transport.

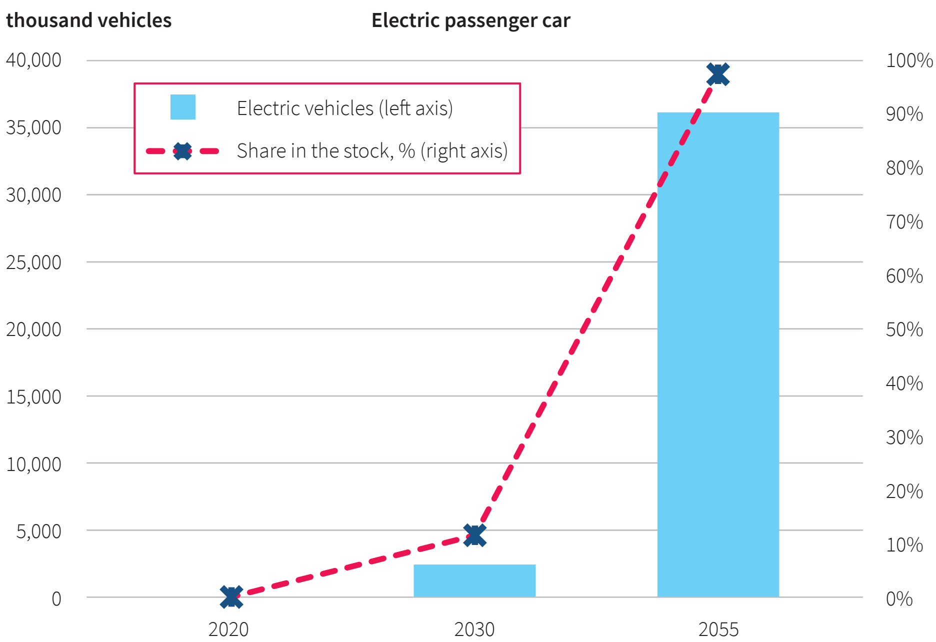
It is expected that other energy carriers will be used for specific modes/transportation routes where electrification is harder to implement based on currently available know-how. Accordingly, hydrogen is used in public road transport (10% of activity), in HDVs (30%) and LDVs (17%), whereas in air (synthetic kerosene) and naval (all e-liquids incl. ammonia) transport mainly electrolysis based e-liquids are used for long distances. In these sectors where electrification is challenging, policies that favour the blending of low-carbon and e-fuels will be critical. Total consumption of e-fuels in transport is projected to be at just above 55TWh by 2055.

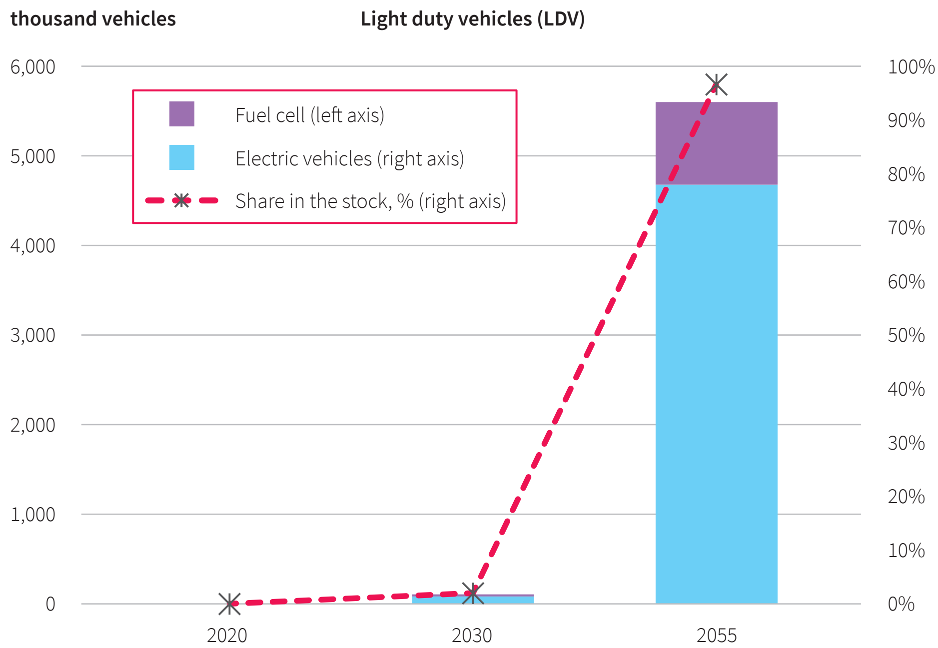
Figure 27: Final energy consumption in transport

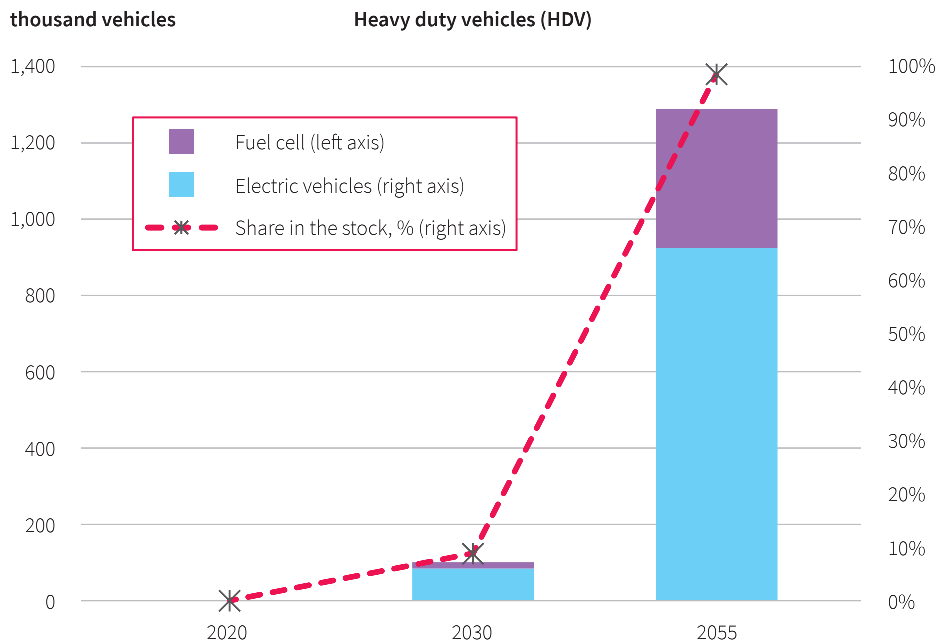


In this respect, the vehicle stock is expected to change radically. While currently the conventional internal combustion engine (ICE) vehicles are dominant for all road vehicle categories, this will change significantly by 2053 as electric vehicles or vehicles using fuels cells will become dominant. For passenger cars, electric vehicles will dominate the market. For LDVs and HDVs, the market will also be dominated by electric vehicles, however, fuel cell vehicles are also expected to enter the market, particularly for long-distance transportation.

Figure 28: Changes in vehicle stock according to alternative vehicle types by category







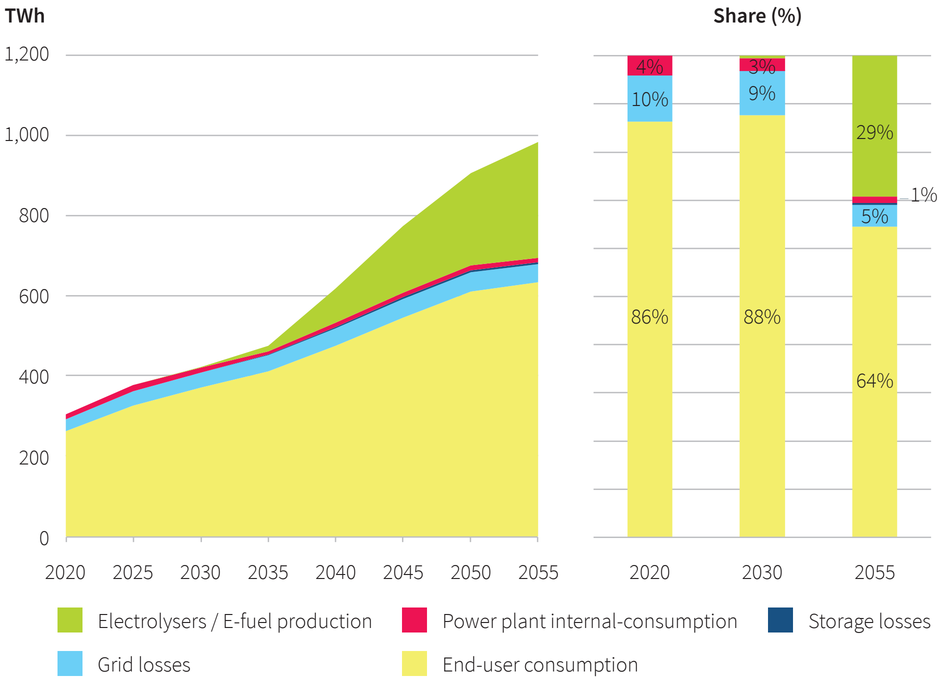
5.1.4 Electricity Demand

Electrification is the overarching trend that drives emission reduction and energy efficiency uptake in Türkiye, as in many other countries today (IEA, 2021). The growing adoption of electric technologies across end-use sectors and the production of e-fuels are the two factors that increase the demand for electricity (Figure 29). Especially from 2040 onwards, electricity demand grows at a higher rate as e-fuels start to blend with gas into the grid. Electricity consumption in end-use areas is becoming more efficient through the use of highly efficient equipment and appliances, limiting the increase in electricity demand in the residential and tertiary sectors (agriculture and services), as well as in industry.

The share of grid losses and internal consumption is projected to decrease in the long run. This is due to three main factors below:

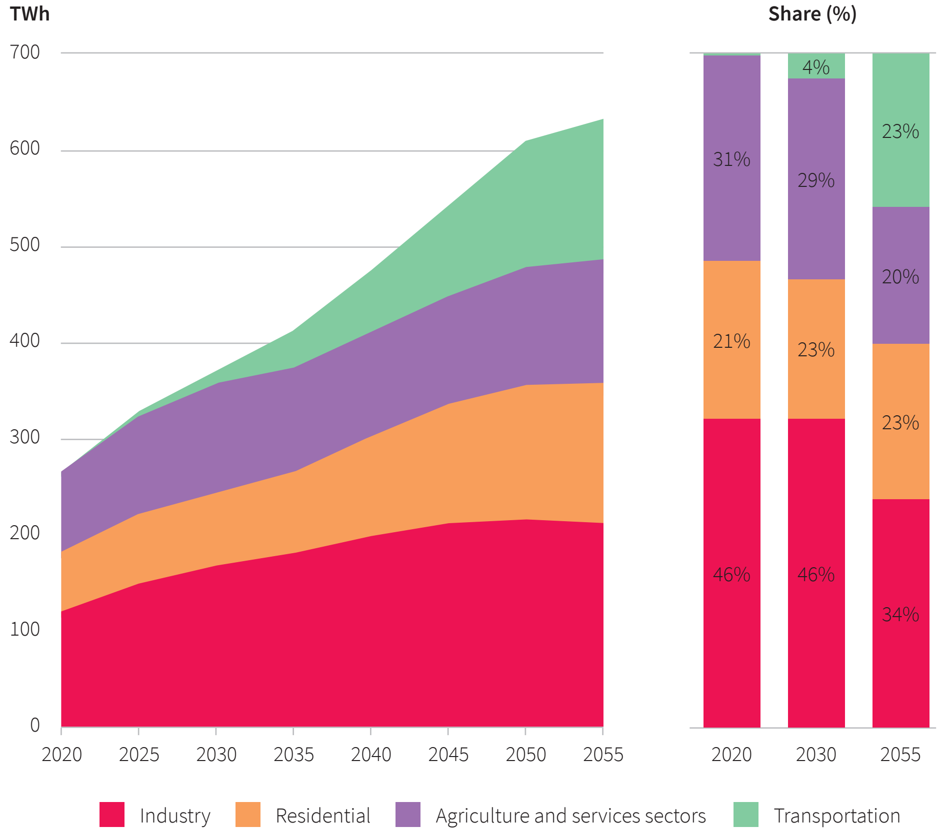
(i) Renewabel energy power plants need less electricity for internal-consumption compared to conventional plants,
(ii) Modernization and upgrading of electricity grids, and
(iii) Electrolyser (PtX) facilities, which are projected to consume almost 1/3 of gross electricity generation in 2055, will be connected to the transmission lines, and thus face lower grid losses in relative terms.

Figure 29: *Overall consumption of electricity*



In 2055 net electricity consumption is projected to be 2.4 times higher than in 2020. During the projection period, high levels of electrification occurs in all sectors. Transport sector starts with a low level of electrification, whereas the highest increase in electrification is observed in this sector in the future (Figure 30). Industry remains the highest consumer of electricity, although its share in total electricity consumption decreases due to the increase in electrification in the transport sector. The introduction of energy efficiency measures in industry and the shift towards higher value added and less energy intensive products mitigate demand for electricity.

Figure 30: *Consumption of electricity by end-users*



5.1.5 End-use Demand for Green Hydrogen and E-fuels

To meet the net zero emissions target in 2053, it is necessary to introduce green hydrogen and e-fuels in sectors where electrification is extremely difficult, based on technologies which are known today (Figure 31). These sectors that will require the introduction of alternative fuels are primarily:

- Transport: In aviation, maritime, long-distance heavy-duty road transportation,
- Industry: Particularly in primary steel production, cement and others.

Almost 80% of the demand for e-fuels is projected to rise from these sectors by 2053 (Figure 32). Aviation and maritime consume most of the of liquid e-fuels, whereas transport is responsible for consuming most of the green hydrogen. Industry is the second largest green hydrogen consumer. In transport, it is assumed that a dedicated infrastructure development for specific transport routes (heavy-duty road transportation - HDV) will take place. In industry, there will be direct consumption of green hydrogen for specific uses e.g., fertilizer production and iron ore reduction. At the same time, it is projected that a zero-emission gas mix that will be a blend of green hydrogen, synthetic gas and biogas will be used. The use of e-fuels is projected to be limited prior to 2035 but will increase rapidly afterwards as such technologies are assumed to become more available worldwide and in Türkiye.

As green hydrogen and e-fuels (PtX) are produced by the process of electrolysis, which is based on using electricity generated from renewables, their use is vital in the system and to reaching net zero goals, especially in sectors where high energy density levels are required (e.g., naval transport, aviation and various industries). In 2053, the share of green hydrogen and other e-fuels in total energy demand will be approximately 15%.

Figure 31: *Consumption of e-fuels by type*

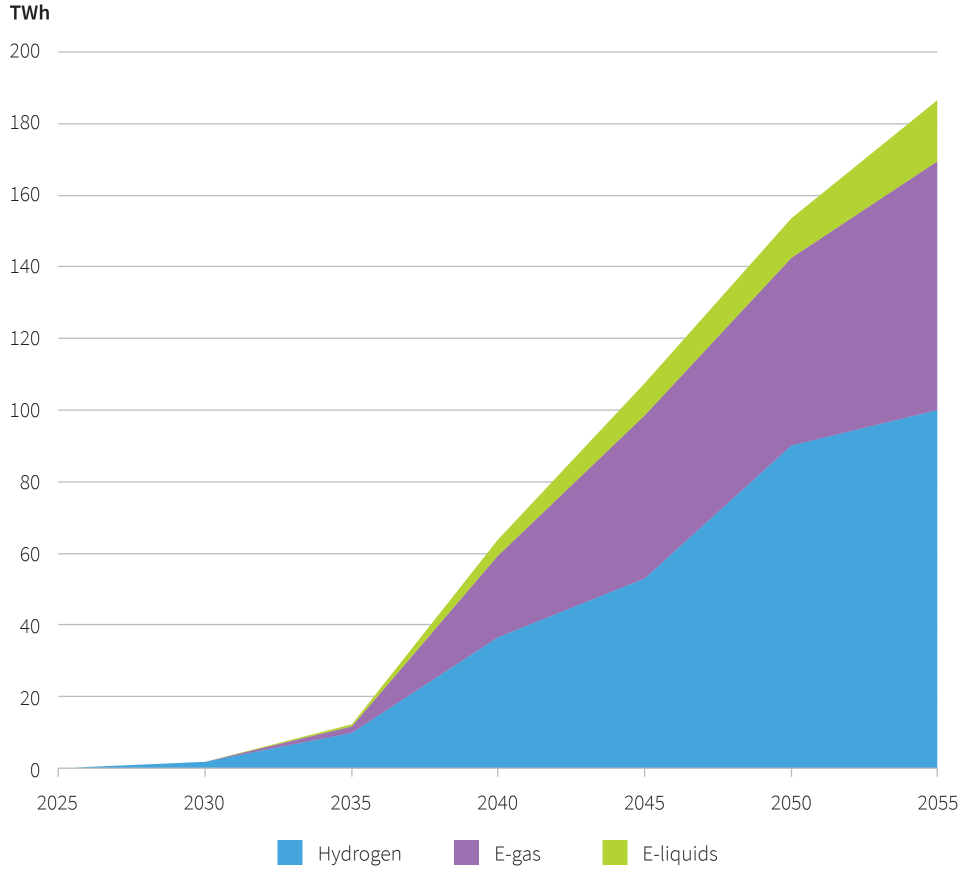
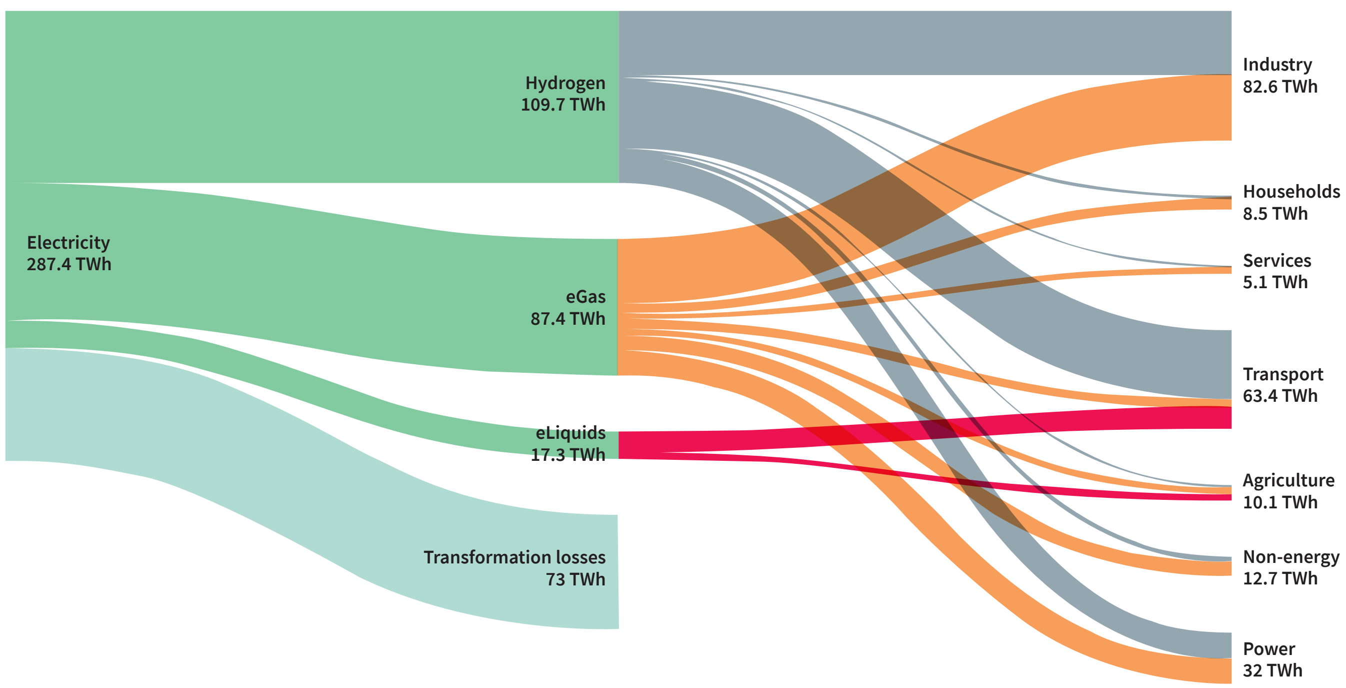


Figure 32: *Electricity demand to produce e-fuels in 2053 and the sectoral consumption of e-fuels by type*



Pipeline gas is expected to progressively become emission-free by 2053 through the use of green hydrogen, e-gas and biogas blend. By 2050, it is assumed that 20% of the gas blend in the natural gas grid will comprise of green hydrogen, which will start to be blended into the gas grid in 2030. The green hydrogen, e-gas and biogas mix will contain nearly the entire gas grid by 2053. The NZ2053 scenario assumes that all e-fuels are produced domestically.

Table 6: *Blending shares in the pipeline gas*

	2020	2025	2030	2035	2040	2045	2050	2055
Natural gas	100%	100%	100%	99%	79%	50%	21%	1%
Hydrogen	0%	0%	0%	1%	6%	10%	20%	20%
E-gas	0%	0%	0%	1%	9%	29%	40%	60%
Biogas	0%	0%	0%	0%	6%	10%	20%	20%

It is projected that the use of e-fuels (e-gas, green hydrogen, biogas) produced in Türkiye within the gas grid will also reduce energy dependence. Furthermore, as discussed in the Section 5.2, green hydrogen and e-fuels can serve as chemical storage and balance the variability of electricity production from wind and solar, enhancing grid flexibility.

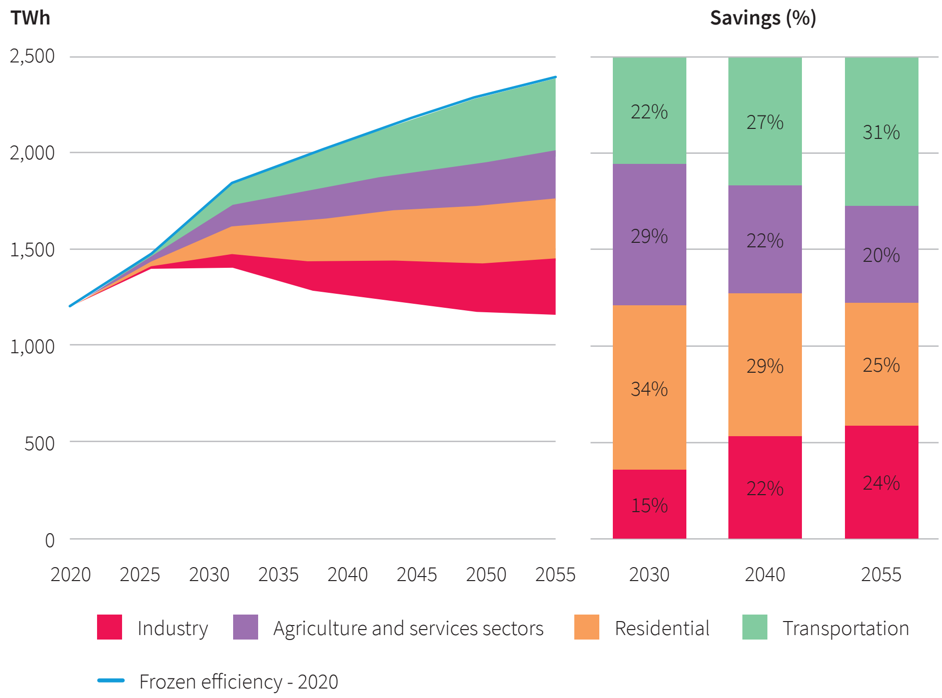
5.1.6 Energy Efficiency as Catalyst of Decarbonization

According to the model results, the total net electricity demand more than doubles over the course of the projection period, growing to 633 TWh in 2053 from 263 TWh in 2020. However, total final energy demand in 2053 reduces to similar levels as in 2020. The main reason behind this is the combination of energy efficiency improvements and the electrification of end-use sectors. Model results for 2053 show that the share of electricity in total energy consumption is 54% (Figure 18).

Figure 33 shows the energy savings achieved within the NZ2053 scenario by sector, while keeping the energy intensity level in 2020 constant and adhering to the same sectoral activity.

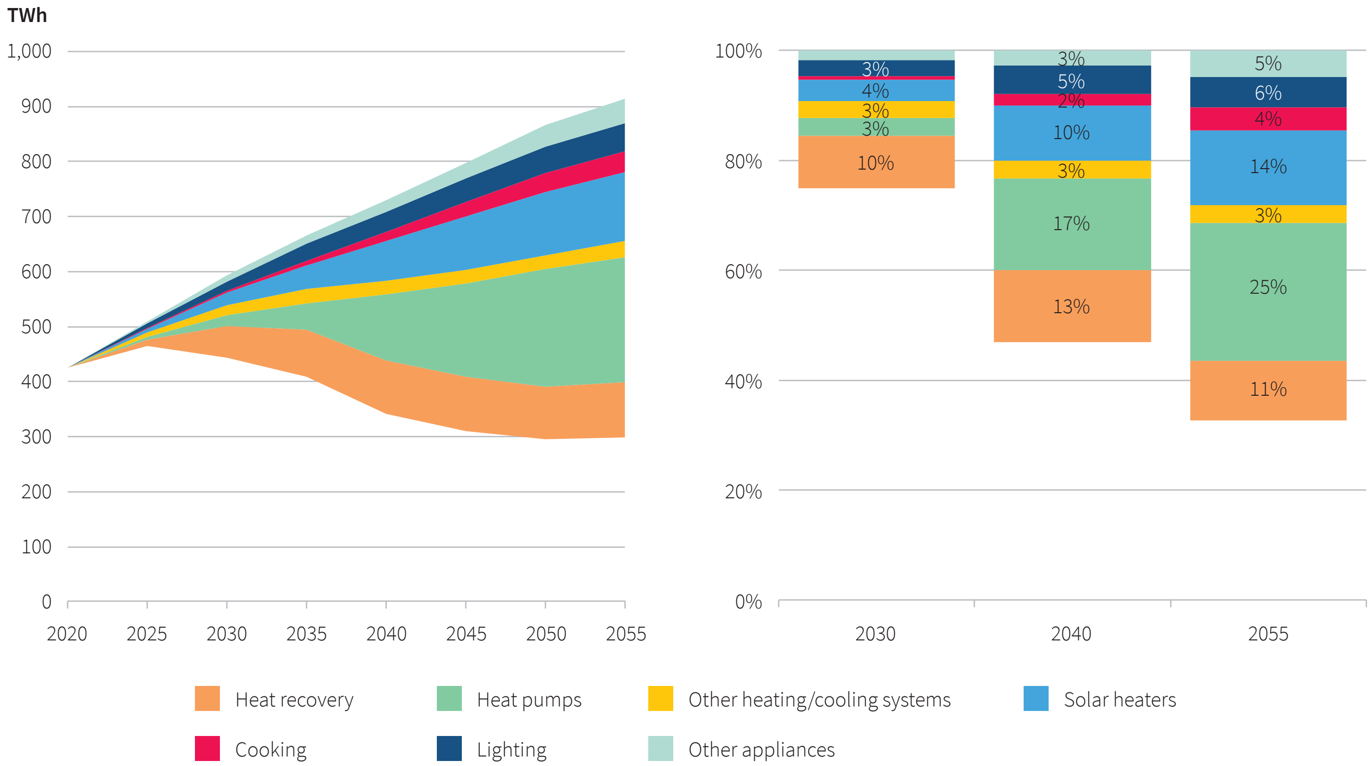
The NZ2053 scenario uncovers the high energy efficiency potential with a total saving of 53% in energy consumption. Figure 33 shows the importance of energy efficiency to achieve net-zero target, stressing its potential to all sectors. Most of energy savings in 2053, with a total share of 31%, comes from the transport reflecting the high efficiency rates of electric vehicles. The participation of households in energy savings is also significant, which is 25% of the total. The residential sector contributes higher energy savings already early in the emission reduction process; through building renovations and the use of heat pumps, both of which lower the energy intensity of space heating despite increased activity. The same is true for services, however a lower contribution is projected from agriculture, where efficiency potential is assumed limited. While the industry sector provides less energy savings compared to buildings and transport; in absolute terms though, industry has a savings contribution equal to that of households, given its high share in final energy consumption.

Figure 33: *Sectoral energy savings computed within the NZ2053 scenario*



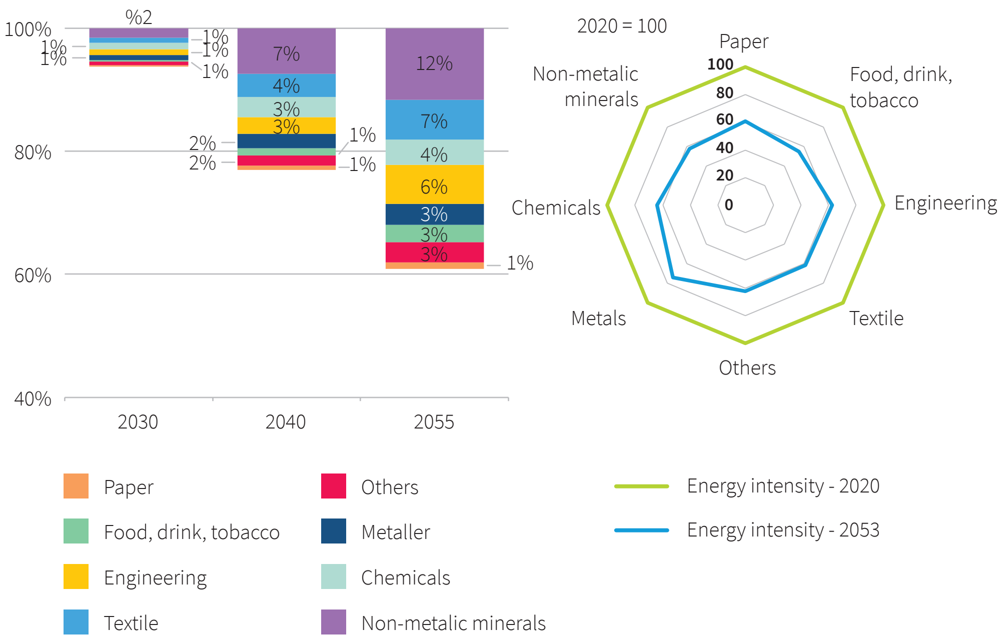
In buildings, it is essential to imporve the exterior of the buildings to ensure energy efficiency. It is essential that all buildings are progressively renovated or replaced to meet higher energy efficiency standards. In Türkiye, however, the increase in the total heated space both in the renovated old buildings and planned new buildings limit the potential savings in this sector. Over time the highest savings are provided by the use of heat pumps in new and existing buildings with shift from boilers. However, significant savings are achieved when shifting to solar heating from other heat sources to meet the hot water demand. In addition to their impact on savings, these solar systems provide a relatively inexpensive option. Moreover, the transition to more efficient appliances and lighting maximise the key efficiency potential in buildings. (Figure 34).

Figure 34: *Energy savings in buildings compared to a frozen efficiency (based on 2020 energy intensity) case*



In industry, efficiency savings are due to improvements in waste heat recovery, overall horizontal process improvements, and a shif to advanced electrical equipment (see Section 5.1.1). This leads to a reduction in the energy intensity of all industry sectors, ranging from 25% to 45% (Figure 35).

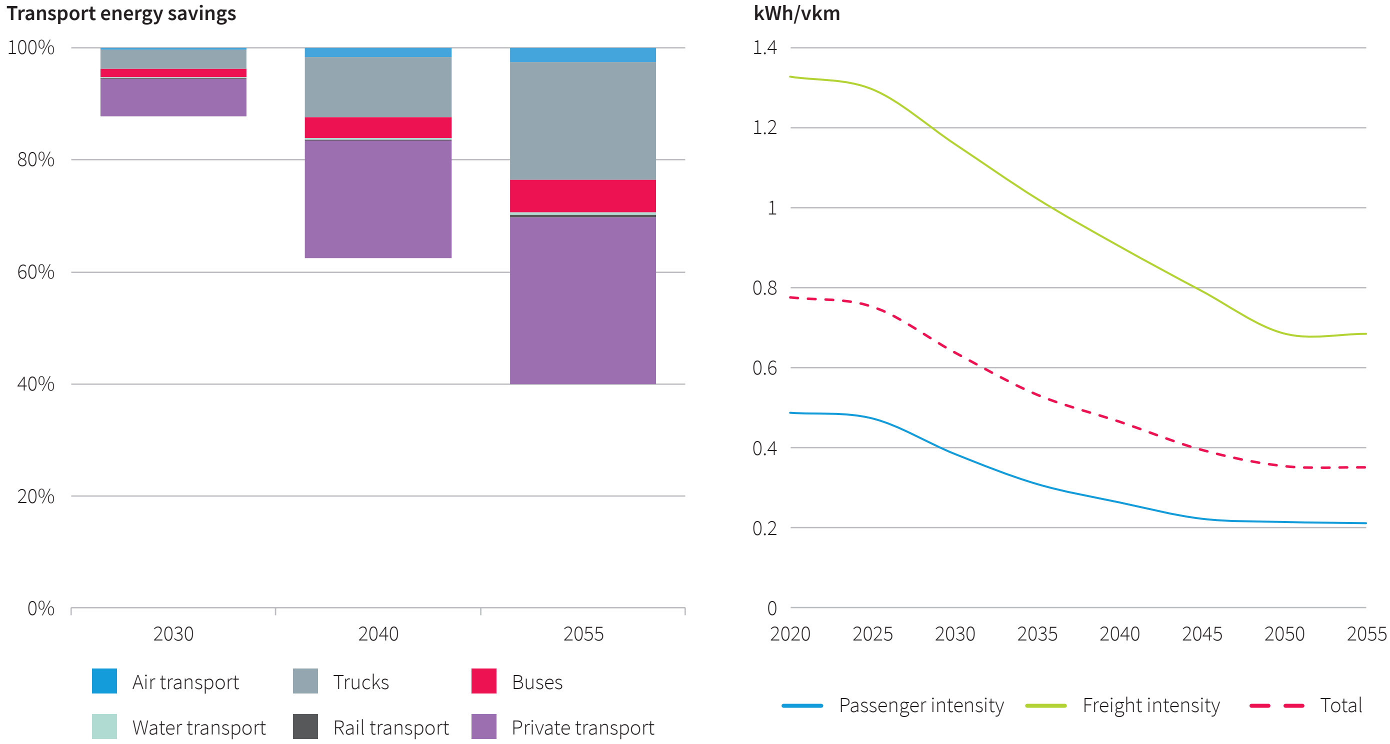
Figure 35: *Energy savings in industry compared to a frozen efficiency (based on 2020 energy intensity) case*



The savings in the metals industry lie on the lower bound due the high energy intensity of DRI furnaces introduced by 2040. One third of energy savings come from non-metallic minerals, mainly from the cement industry. Cement is currently the most energy intensive industry of Türkiye and its activity is projected to expand in the next two decades. In the cement industry, electrification plays a minor role. In this sector, the energy intensity is mainly reduced by the recovery of waste heat and through the optimization of production process[15].

In the transport sector, the sectors shifting to electric vehicles (Evs) achieve the highest energy savings. EVs both for passenger cars, as well as HDVs lead to significant savings due to the inherent efficiency of these vehicles. Transport modes that are already largely electrified (e.g. rail) carry less efficiency gain potential. Although aviation and water transportation also have efficiency gains, due to their small share in overall transportation, their share in total savings is smaller.

Figure 36: *Energy savings in the transport sector (in comparison to 2020 energy intensity)*



[15] For instance, energy savings are achieved by reducing clinker requirements.

5.2 Energy supply

5.2.1 Gross electricity generation

The electrification of end-use sectors and the production of e-fuels within Türkiye requires a strong increase in gross electricity generation. Electricity generation increases from 305 TWh in 2020 to 618 TWh in 2040 and 984 TWh in 2055. With end use sectors transforming from fossil fuels to electricity-based systems, it is critical to ensure that the consumed electricity is supplied particularly by zero emission RES.

The power system in 2053 is assumed to be radically different from the current power system with two major trends:

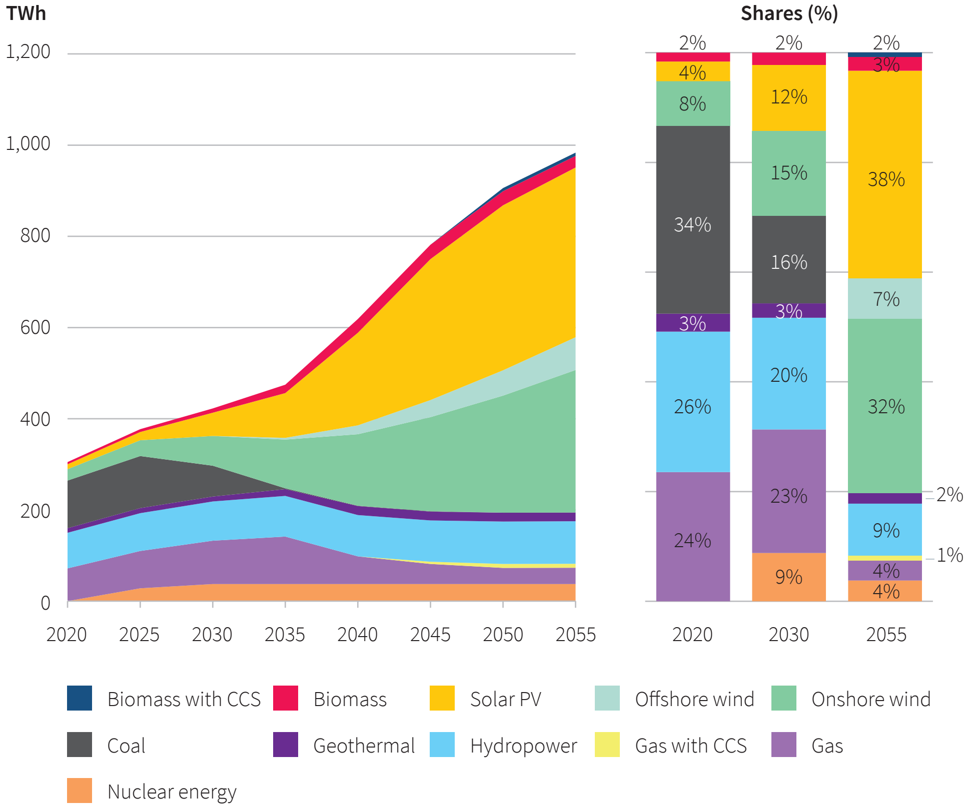
- considerable increase in total electricity generation, and
- increasing share of variable RES in electricity generation.

While currently RES represents almost 40% of electricity generation, this comes mainly from dispatchable hydropower, which has limited capacity for expansion in the future. By 2053, solar and wind become the dominant sources of electricity generation. These resources represent only 12% of electricity generation in 2020, whereas their share increases to 27% in 2030 and 77% in 2053. Together with hydro, biomass and geothermal, renewable energy sources cover over 90% of the total electricity generation in 2053. Together with the gas-fired power plants, which run mostly with green hydrogen and biogas, batteries and pumped hydro used for storage purposes, ensure the system with flexibility.

Generation by wind and solar triples from 2020 to 2030 and continues its growth throughout the projection period. By 2040, electricity production by variable RES is 379 TWh, accounting for 61% of total electricity generation. Considering that this value is higher than the total electricity production in 2020, which is 305 TWh, shows that the scale of investment required for production capacities and grid enhancement in the medium-term are significant. As of 2030, as e-fuel production commences, it is projected that the future electricity demand increases at a high pace. In 2053, this increase is covered mainly by solar and wind, producing 77% (757 TWh) of the total gross electricity generation.

Solar and wind have an equal contribution to electricity generation in the long run. In the medium run though, solar outweighs wind, due to decreasing capital costs and higher potential. As the power system increasingly depends on variable RES, the shares of solar and wind in electricity production converge in the coming decade. This is driven mainly by the smoother load profile of wind plants during the day (even seasonally), resulting in lower generation peaks and storage requirements. To a lesser extent, it is related to the increasing efficiency and decreasing costs of wind-offshore technologies.

Figure 37: Electricity production projection by technology



However, with the "carbon value" strategy applied in the model, coal and lignite plants see increased marginal costs and therefore gradually phase out. By 2030, total power generation by coal and lignite decreases by 35%, as the operating hours of the least efficient coal and lignite power plants are reduced. The phase-out process speeds up afterwards, as all coal and lignite-fired plants stop generating electricity between 2030 and 2035, due to the rising costs of emission. In the model, some of the power plants stay in place as "cold reserve capacity", between 2030 and 2035 before being decommissioned completely later.

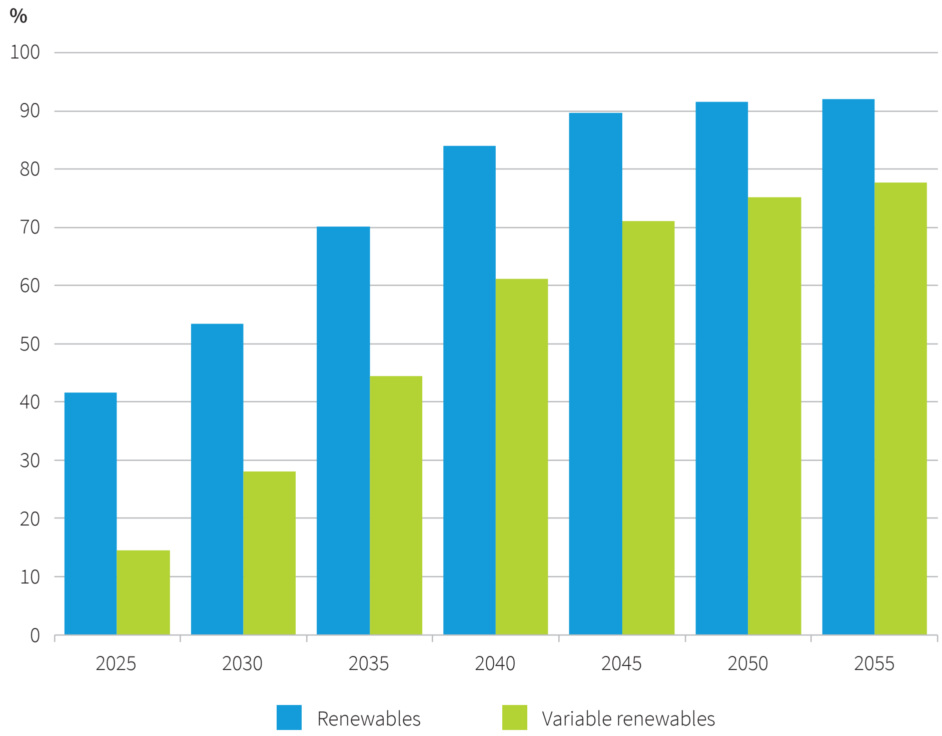
Natural gas power plants produce approximately 97 TWh by 2035. Following the emission reduction pathway, the share of combined cycle gas turbine power plants (CCGT) in power generation falls to 5% in the long run. However, CCGT plants remain in the system as reserve capacity, providing system flexibility. Most of these plants consume e-gas from renewable energy (green hydrogen and biogas), whereas small quantities of natural gas are consumed in plants equipped with CCS infrastructure.

With Akkuyu Nuclear Power Plant fully operational by 2030, nuclear power plays an important role, representing 9% (37.2TWh) of power generation. Throughout the modelling period, the nuclear power plants stay in the system.

Biomass and geothermal power plants play an essential, albeit small role, in providing the system with dispatchable renewable energy complementary to the variable power from wind and solar. These power plants provide approximately 7% of total electricity generation in 2053. There is also an indirect biomass capacity in the system considering that the CCGT plants also use biogas in the projection period and the total share of biomass use in the system is higher.

Biomass plants using CCS are also included in this category; their share in total power generation is small but plays a key role towards achieving the net zero target due to offsetting remaining emissions from end-use sectors. It should also be noted that biomass with CCS entails high capital costs and requires support schemes that reward emissions removal.

Figure 38: *Shares of variable RES[16] in total renewable energy production*



5.2.2 Development of Installed Power Capacity

By 2020 total installed power capacity in Türkiye reached 96 GW. Increasing electricity demand and rapid deployment of renewable power plants – with lower capacity factors compared to conventional plants– drive capacities up. The total installed capacity reaches 267 GW by 2040 and 453 GW by 2053. The rate of capacity expansion is higher between 2040 and 2050, as demand for e-fuels increases in the end-use sectors. As demand stabilizes over time, capacity increase in the electricity sector slows down.

Although the share of solar is similar to that of wind in electricity generation, the required solar capacity is much higher due to lower capacity factors. Solar capacity rises to 119 GW by 2040 and stabilize at 220 GW by 2053. With most investments concentrated in 2035-2045, the average rate of capacity additions for the projection period is approximately 6 GW per year. These investments are feasible from an economic point of view, given the growth prospects of the Turkish economy (see Section 3.1.1). The increase in RES is accompanied by investments in grid and battery energy storage.

[16] Wind and Solar PV

The wind onshore capacity is approximately 9 GW in 2020, whereas its capacity reaches 58 GW by 2040 and 120 GW by 2053. The comissioning rate of new capacities stabilises after 2030, with an average of 4GW on annual basis. Another significant result is that due to the higher capital costs, the offshore wind power plants enter the system not earlier than 2035. Decreasing costs due to economies of scale and improved efficiency allow for offshore wind power plant investments, with total offshore wind capacity reaching 20 GW by 2053. For both onshore and offshore wind power plants, the technical potentials are assumed to be exhausted over the projection period in the study.

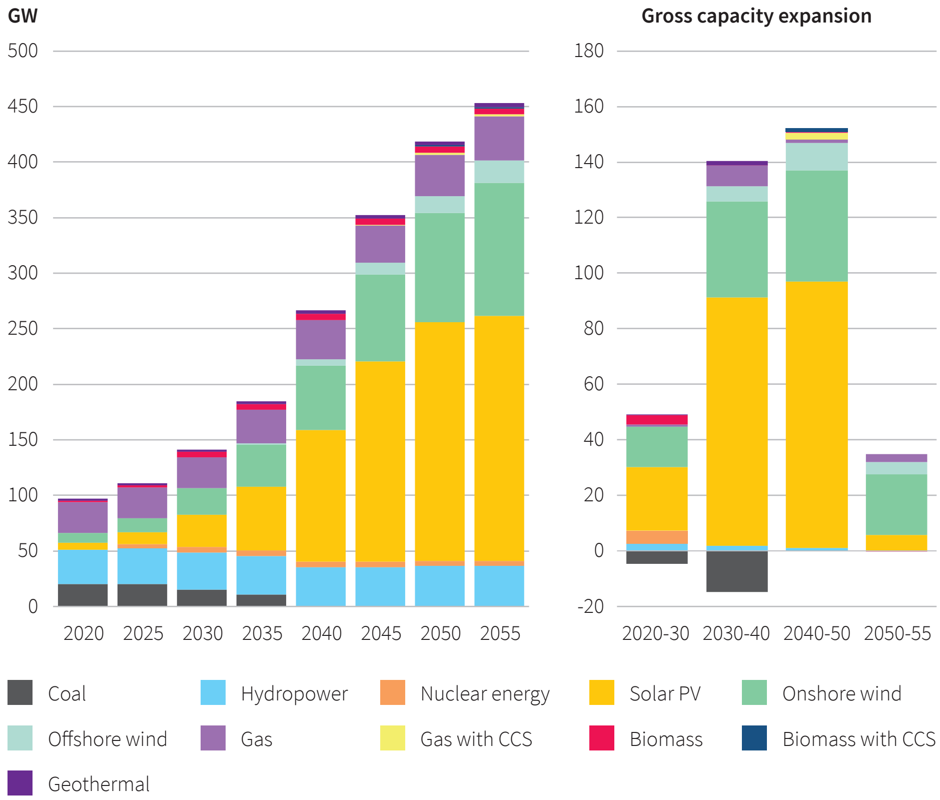
Until 2030, only old coal and lignite power plants are decommissioned. According to the model results, relatively new coal power plants operate with lower capacity factors until this period. Between 2030-2035, approximately 11 GW of coal and lignite power plants are decommissioned prior to their project lifetime. Apart from Akkuyu Nuclear Power Plant, the model does not project any further investments in the nuclear power. After fully commissioning og this power plant, the total nuclear energy capacity remains at 4.8 GW throughout the projection period.

In the model, the capacity of all types of gas plants increases, however these plants produce less. Gas capacity is exploited when electricity production from renewables is less than required to secure the energy supply. System balancing and reserve-capacity requirements are satisfied mainly by CCGT, gas turbine (GT) or gas with CCS power plants in the model. By 2053, overall capacity of plants fired with gaseous fuels reaches 40GW, 2.2GW of which is using CCS. The CCS capacity consists of 4 CCGT units, to be invested between 2045 and 2050. Compared to the supply mix in 2020, the model projects approximately 12 GW of additional gas capacity. In 2030, e-fuels are gradually added to the pipeline network. It is modelled that the gas-blend used by 2053 will be composed primarily of green hydrogen and biogas.

9 GW geothermal and biomass power plant capacity is added to the power system in the long run. These plants have high capacity factors, providing stable electricity to the grid. Two biomass power plants with CCS are commissioned by 2050, whose total capacity is 1.3 GW.

CCS is used to capture carbon emissions from the power generation sector and process emissions. The latter being the primary motivation for the construction of carbon storage facilities. The biomass with CCS provides an option for negative net emissions which are needed to compensate for the residual emissions from other sectors.

Figure 39: Installed power capacities and capacity expansion over the years

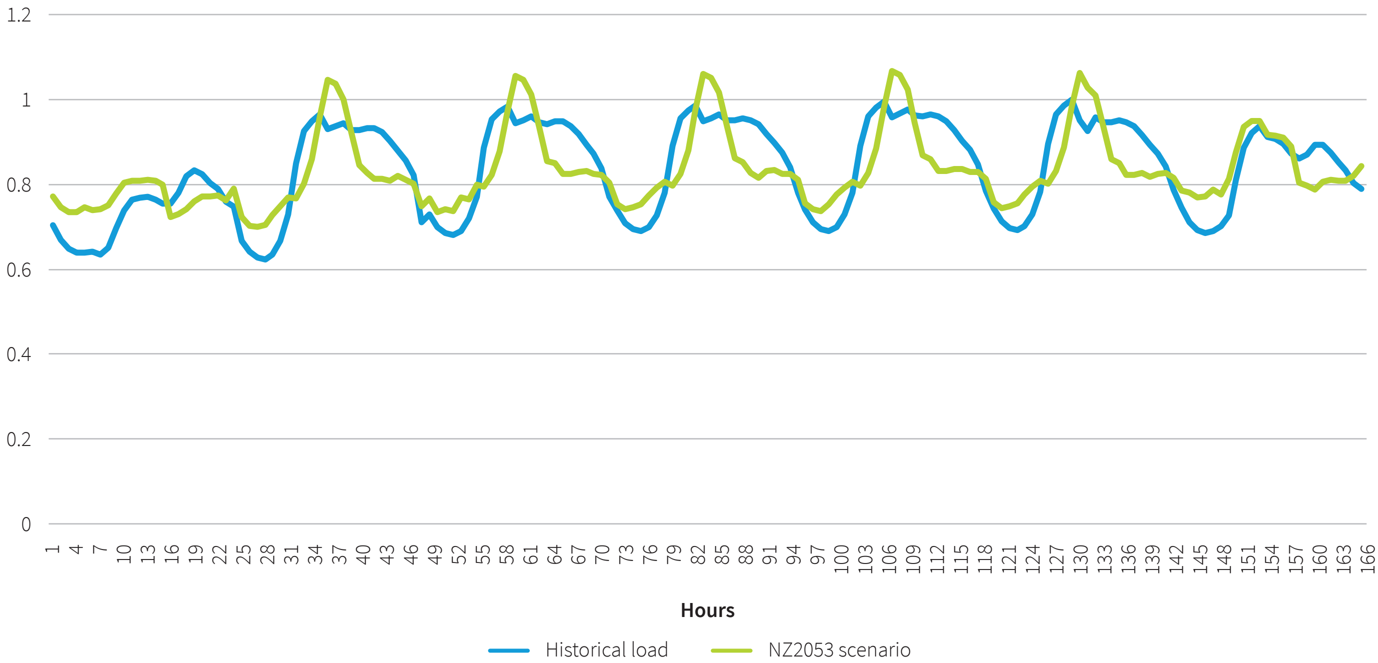


5.2.3 System Flexibility and Energy Storage

The high-level integration of renewable energy sources into the power system will increase the grid flexibility requirements. The flexibility of the system needs to be accomplished both within the supply side, as well as on the demand side to ensure system security. Demand flexibility of end-use sectors is critical in a power system with high shares of variable RES. In the NZ2053 scenario, demand-side participation is mostly achieved by transport sector, mostly through smart charging of electric vehicles at times when electricity supply is high in the system. In other words, the model uses a significant demand flexibility potential with smart charging of electric vehicles. The residential sector also holds significant potential for system flexibility through demand-side participation.

In Figure, the weekly load profile (red line) for end-use sectors, excluding the electricity consumption to be used for production of green hydrogen in 2053, is compared against the actual load profile (blue line), based on historical load curve data. Both curves correspond to the same daily demand. In the NZ2053 scenario, demand response is exogenous modelled using predefined shifted load curves. In this way, the development of a framework is presupposed which allows for fast reactions from the demand and supply sides to the flexibility signals (e.g. through price signals).

Figure 40: *Comparison of NZ2053 load profile and actual load profile of end-use sectors*



In both load profile series, the peak load of electricity is normalized by referencing with 1. The load in NZ2053 scenario results in higher peaks, concentrated at noon hours, in line with the profile of solar power generation. On the other hand, actual load presents a relatively stable profile during daytime, with higher load reduction during night hours.

This shift in the load profile is explained by the sectoral electricity demand and the load shifting performed by end-use sectors in 2053. Transport sector, whose share in electricity demand is currently negligible, represents 23% of electricity demand by 2053 and modifies the shape of the load curve by providing utmost flexibility to the system. Through smart charging, EVs play a significant role in balancing power supply, especially during high solar generation periods. Part of the charging is expected to be at noon hours, taking advantage of high solar energy production. Demand for charging is minimized during the peak hours of transport activity. As a result, the electricity load decreases in the afternoon. Since charging is performed also partly at night, load stays at higher levels compared to the actual profile. In households, demand-side participation is enabled, particularly through load shifting (e.g. by changing the operating hours of electrical appliances such as dishwashers and washing machines). However, there is no contribution to grid flexibility via space heating in the residential sector.

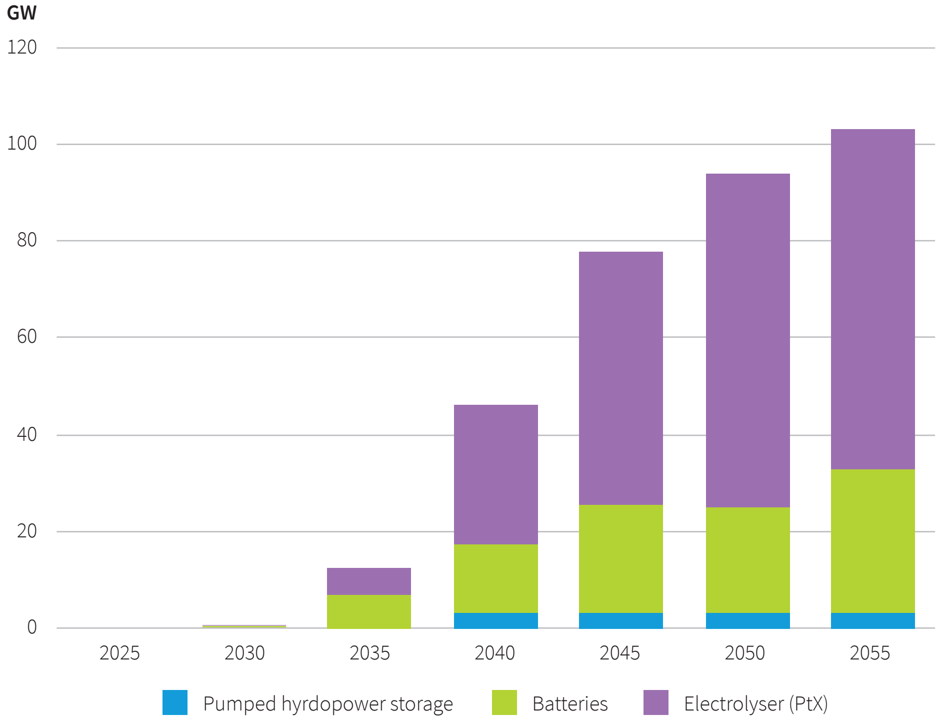
Grid-scale energy storage systems have a complementary role to demand side flexibility. Model results show that adequate storage capacity is required when a high level of solar PV capacity is installed. Besides, solar PV has largely predictable production and expected daily profiles. Energy storage capacity is thus required primarily for daily balancing and to a lesser extent for long-term storage. The possibility for vehicle-to-grid (V2G) use of mobile batteries is not considered in the study. This could potentially reduce the need for grid-scale batteries.

Pumped hydro storage, batteries and PtX systems provide the grid flexibility and energy storage requirement of the system to a great extent. Approximately 33 GW of energy storage capacity is projected by 2053. 30GW/120 GWh of this capacity corresponds to the battery energy storage systems, and the rest to pumped hydro storage. Batteries are the preferred option for daily storage, due to capital cost, which is expected to decrease by 62% until 2040. Batteries are charged at noon, absorbing excess electricity from solar PV (Section 5.2.4). Although pumped hydro storage has a much higher capital cost, it can be used for daily and long-term storage. Pumped hydro storage capacity is limited to the estimated technical potential in the study. Higher potential assumption would result in higher capacity use, but it will not be easy for pumped hydro storage to replace batteries, which remain to be the main energy storage option.

From 2035 onwards, electrolysers produce green hydrogen and other e-fuels for the end-use demand sectors. Electricity requirements for e-fuel production increases throughout the projection period and reaches approximately 29% (287 TWh) of gross electricity demand. This renders electrolyzers a major consumer of electricity, providing huge opportunities for system flexibility. E-fuels and especially green hydrogen, can be further used internally in the electricity sector, as an input to gas plants. As the production and later conversion to electricity of e-fuels involve significant conversion losses (approximately 50%), e-fuels are preferred for weekly or seasonal storage rather than daily storage purposes.

Electrolyser capacities reach 29 GW in 2040 and increase further to 70 GW in 2053. Most of these capacities cover the clean fuel requirements from end-use sectors, whereas a small share (~7%) is used for long term storage in the electricity sector. In the model, production of e-fuels is assumed to be flexible, not subject to hourly or seasonal constraints. In this context, electrolysers operate mainly during peak solar energy production hours, therefore limiting the need for battery storage capacity while ensuring highly predictable generation periods for e-fuels. This is detailed in Section 5.2.4. Technically, electrolysers are expected to be located close to large hydrogen consumers, as it is more efficient and less cost intensive than developing additional large-scale green hydrogen infrastructure. On the other hand, electrolysers are assumed to be connected to high voltage lines reducing the need for additional line investments on the distribution level.

Figure 41: *Energy storage and electrolyser capacities*



5.2.4 Hourly Electricity Generation

To assess the feasibility of the decarbonized electricity sector, 672 hours were simulated, representing four weeks of the year. For this purpose, the model simulates two "typical" weeks and two "extreme" weeks.

- Typical weeks for 2053:
    - Autumn – Winter week (Figure 43)
    - Spring – Summer week (Figure 44)
- Extreme weeks for 2053:
    - Low-capacity factor of variable RES (Figure 45)
    - High net load week (Figure 46)

In the power system, supply and demand must meet one another. In the present power system, coal and lignite power plants provide base load electricity generation, while hourly variations are covered by gas and hydropower plants. Demand sectors determine the periods for generation peaks, while flexibility requirements are limited and the need for electricity storage is little. However, in a power system based on renewable energy sources, especially one with high PV capacity, daily peaks occur when the electricity supply exceeds the demand. In a system with such high shares of solar PV, the daily peaks are supply-driven rather than demand-driven. While the high electricity generation is driven by the electricity demand and e-fuel production; the timing of the peak supply is driven by the high share of solar PV in the system. By 2053, these peaks occur at noon in the spring-summer period, where the total production exceeds 200 GWh for several hours (Figure 44).

Firstly, the grid needs to be improved to absorb excess electricity generation from renewables and avoid renewable energy curtailment. Additional investments in grid improvement is reflected in the growing shares of transmission and distribution costs (see Figure 48). Moreover, pumped hydro storage systems, which has more limited installed capacities due to its potential, and batteries provide long-term storage that affects the operation of the system in a positive way. These systems store the surpluse of electricity supply at daytime and use this stored energy to balance the system during times of low electricity generation from RES. On some days of the week, the discharge is directed to the electrolyzers, which produce e-fuels at off-peak hours.

Even more important is the role of electrolysers acting as flexibility options. It is calculated that 75% of e-fuels is produced between 08:00 and 17:00, which reduces the need for energy storage capacity. The generation profiles of nuclear, geothermal and biomass power plants are relatively stable. On the other hand, generation from gas and hydropower plants is flexible thanks to fast ramping rates, which provides system flexibility when electricity generation from RES is not sufficient.

Figure 42: *Hourly electricity generation and consumption (winter - autumn typical week)*

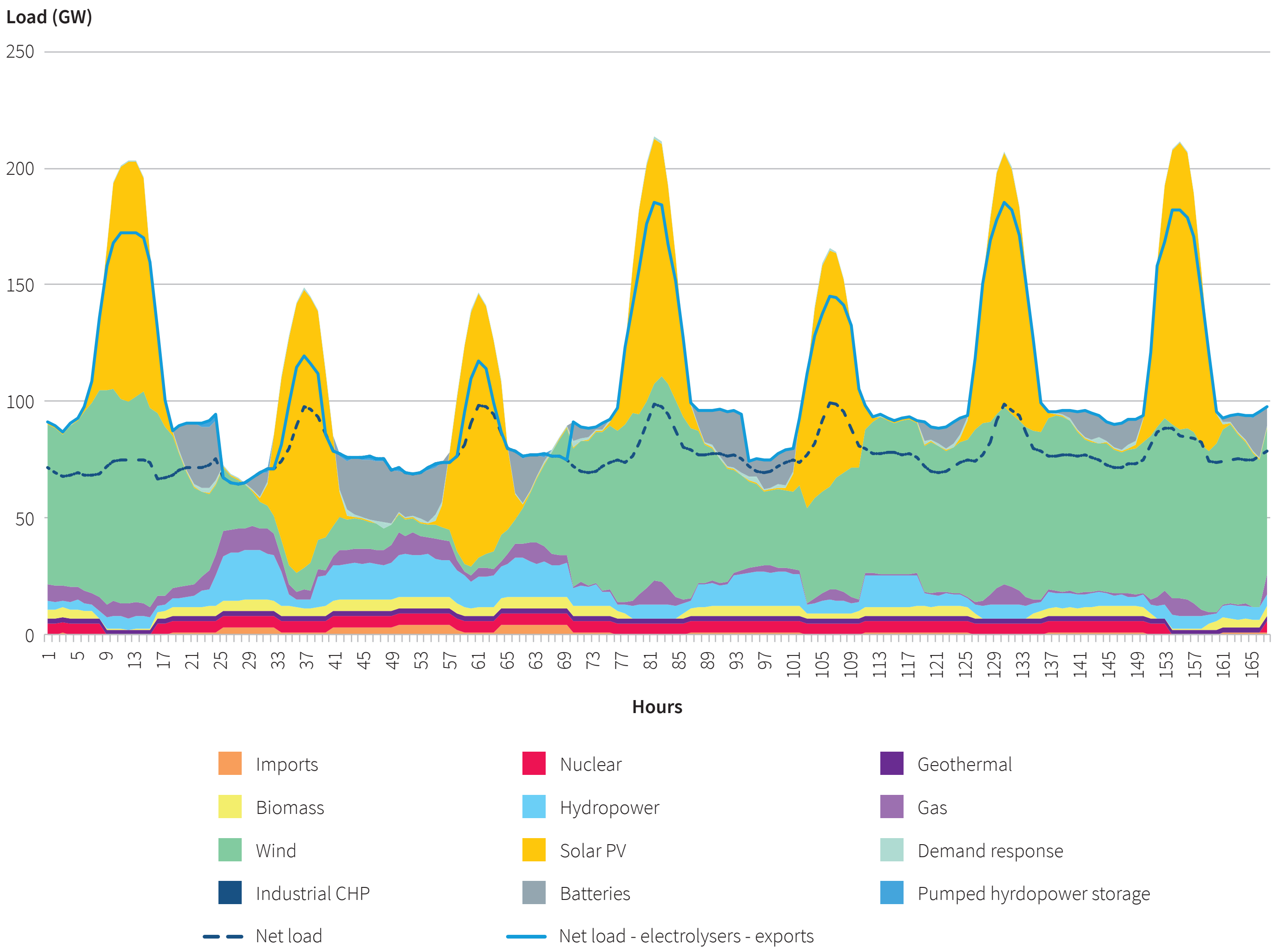
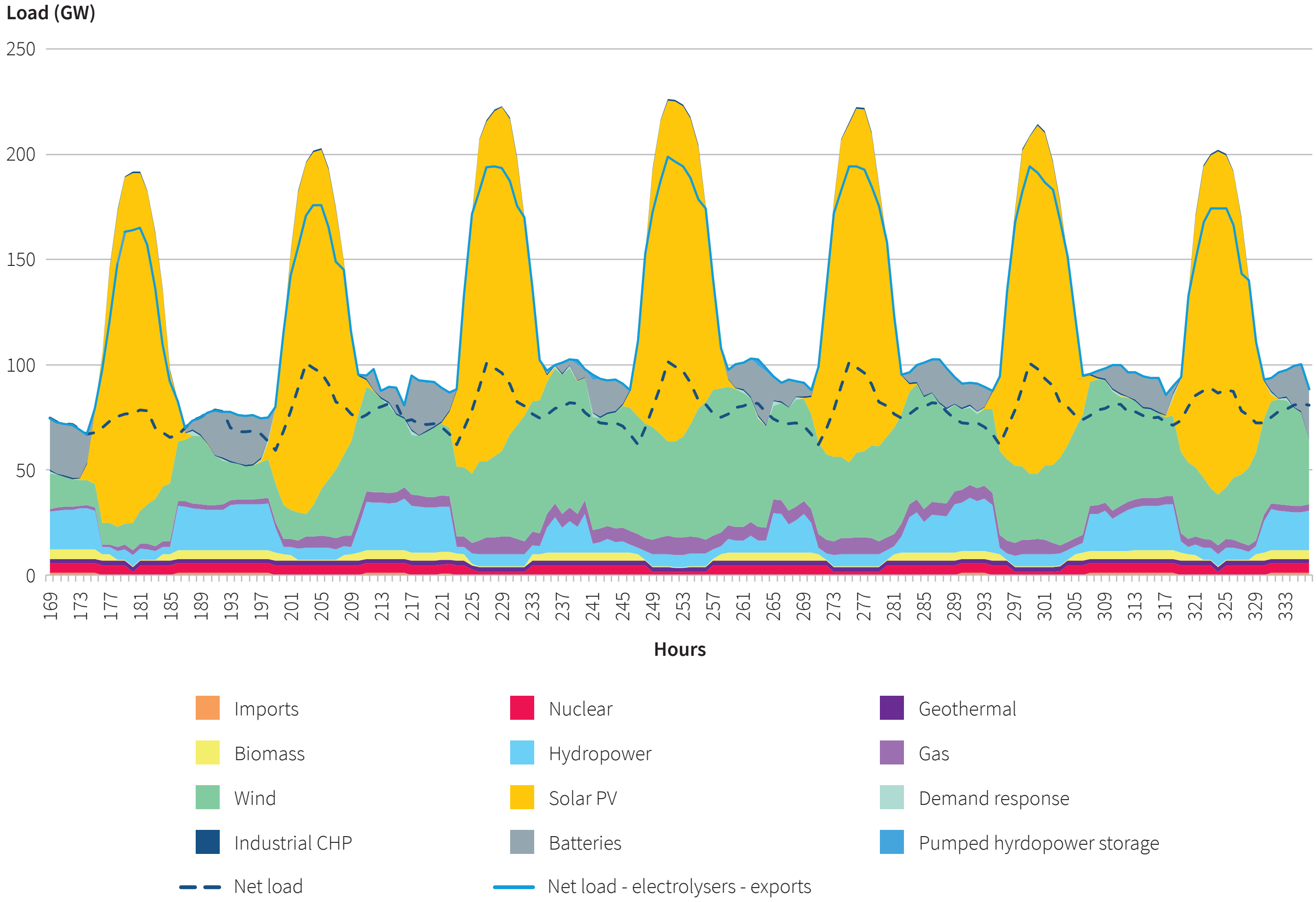


Figure 43: *Hourly electricity generation and consumption (spring - summer typical week)*



Considering variable renewable energy sources (VRES), the week with low capacity factor (Figure 45) represents a one-week period with low levels of electricity and e-fuel production. Even under these conditions, the contribution of the electricity generated by RES is significant, thanks to the high installed capacity of RES. In the hours when generation from RES is low, electricity is supplied by other energy technologies – nuclear plants, gas plants that run on biogas or hydrogen, geothermal, hydro and batteries. The power system is designed with adequate reserve capacity that allows meeting the electricity consumption by end-consumers (excluding electrolysers). An example of a week with high net load is a spring-summer week (Figure 46). During this week, there is lower electricity generation from variable RES compared to an average spring/summer week, while there is higher electricity demand by end-consumers. To cope with these constraints, the system reduces the production of e-fuels without curtailing electricity load of end-consumers.

__Figure 44:__ Hourly electricity generation and consumption: Low-capacity factor of variable RES (VRES)

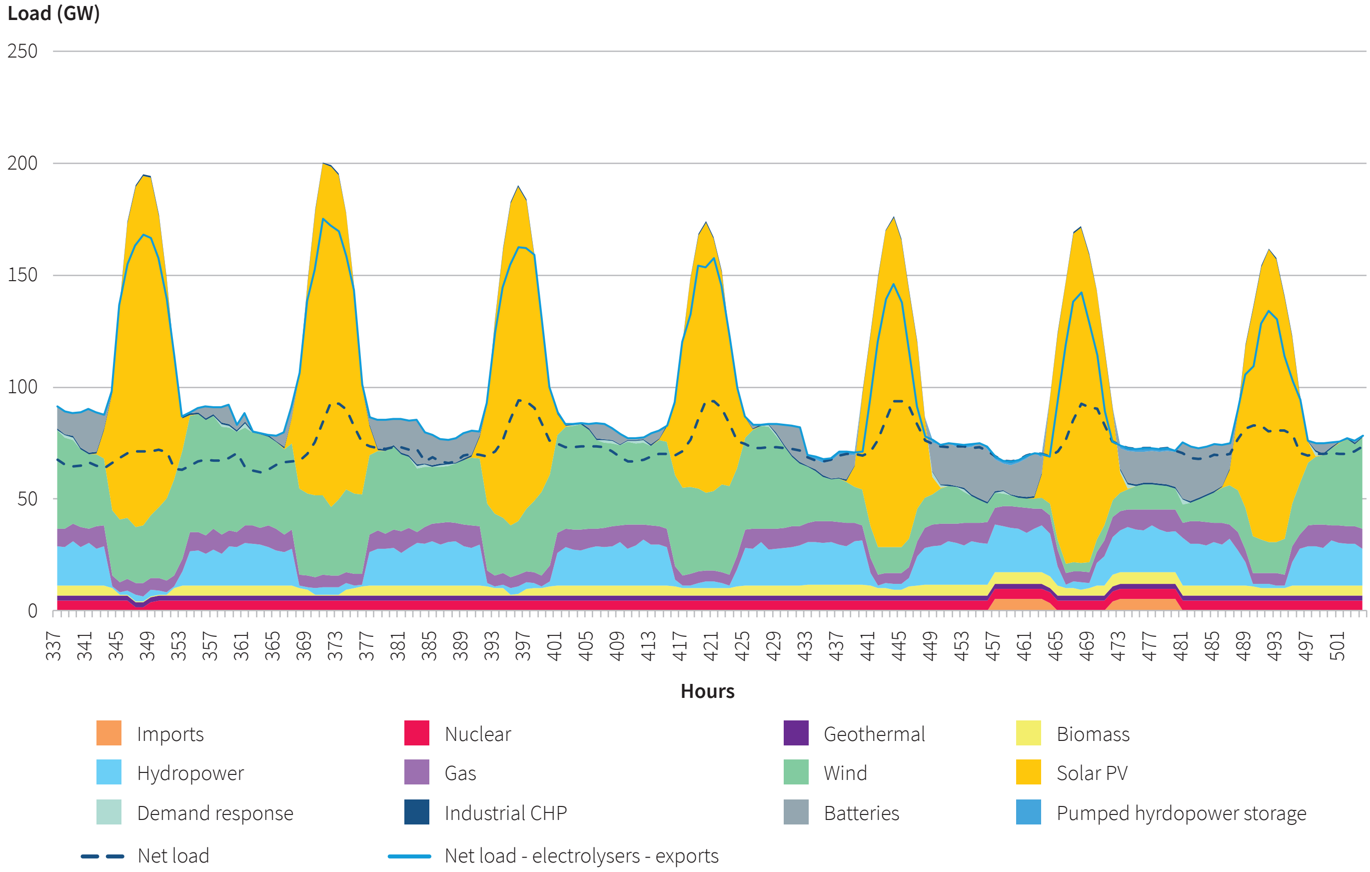
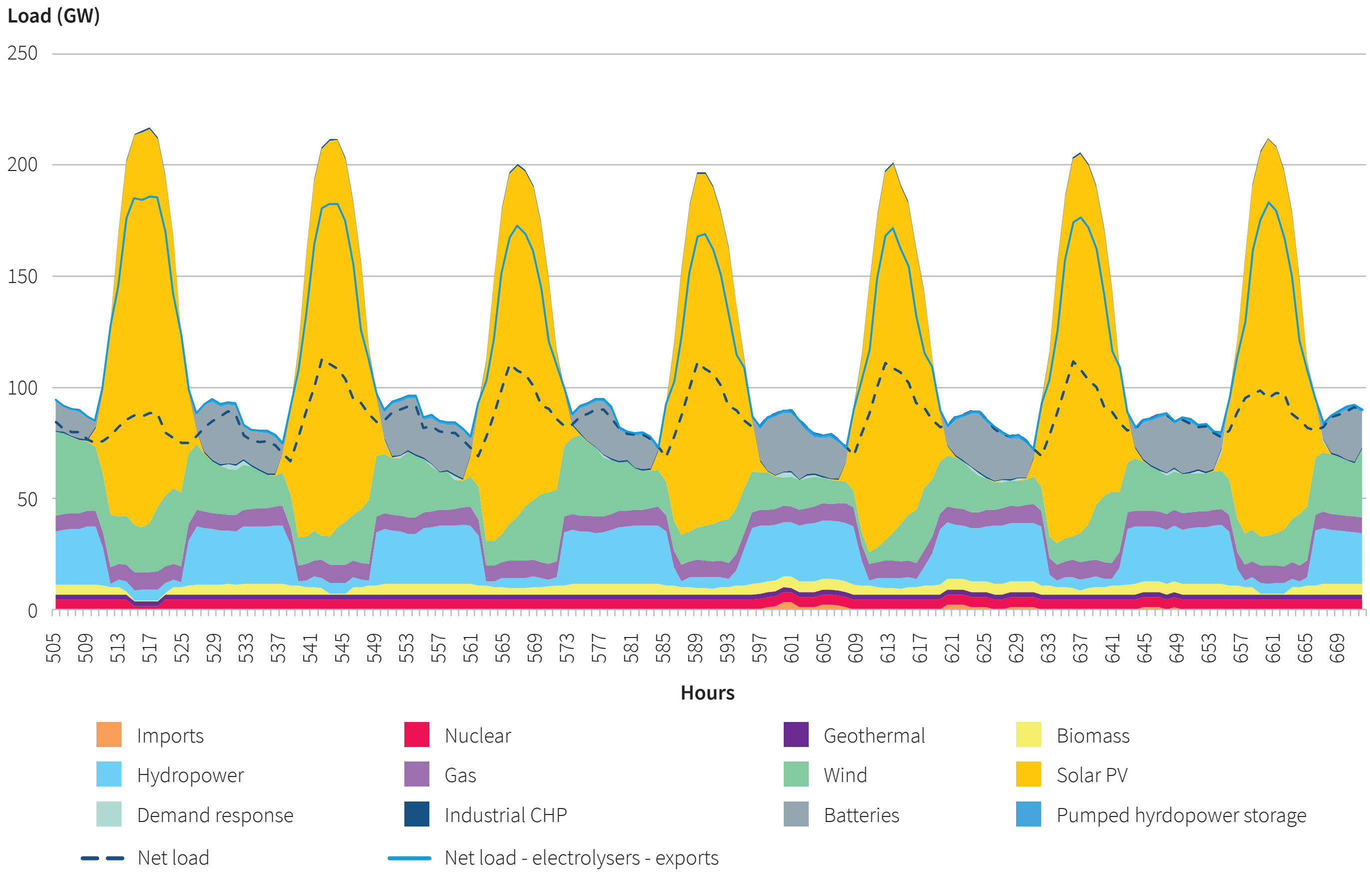


__Figure 45:__ Hourly electricity generation and consumption: High net load week



Detailed hourly simulation results show that the projected capacity of the power generation system meets the demand even under stress load conditions, which demonstrates that the system is functional.

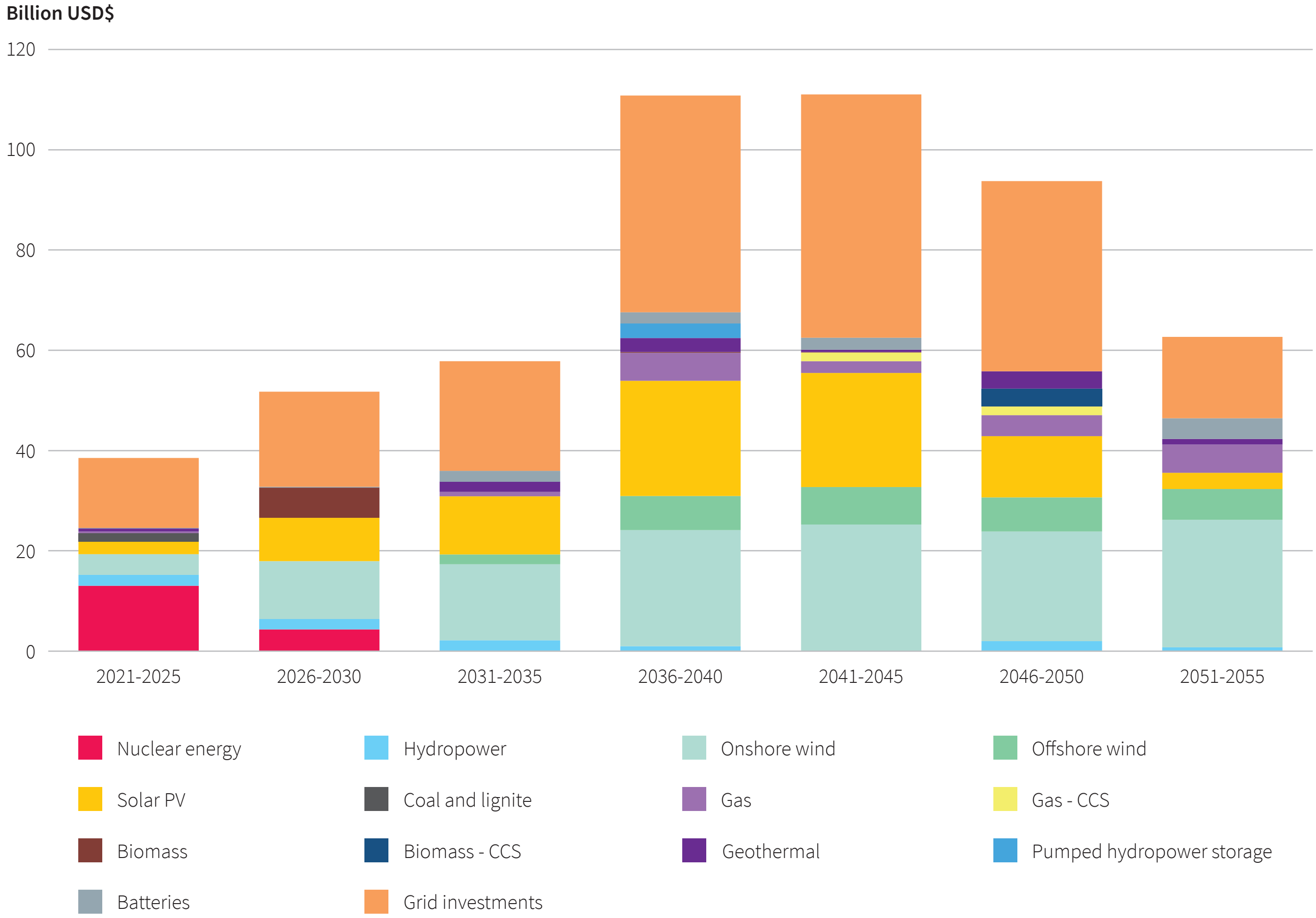
5.2.5 Power System Investments and Costs

The NZ2053 scenario requires significant amount of investments to achieve the net-zero goals. The scale of investments is in line with the projected growth in the electricity supply capacity, energy storage and electricity demand. During the period 2021-2055, approximately 526 billion USD in total, or 15 billion USD annually, is required to finance the transition in the electricity sector. 62% of this amount is directed to power plants and energy storage systems, and the rest to grid development.

Investments peak between 2035 and 2040. In this period, approximately US$ 62.5 billion will be required to install 86.5 GW of power plant capacity, mainly solar and wind, to meet the rapidly growing electricity demand and support clean fuel production. It is estimated that US$ 45 billlion worth of grid investment is required for the system to accommodate these capacities. Most of the grid investments will be conducted in response to the rapid increase in electricity demand and hence are partially independent of the renewable capacity growth.

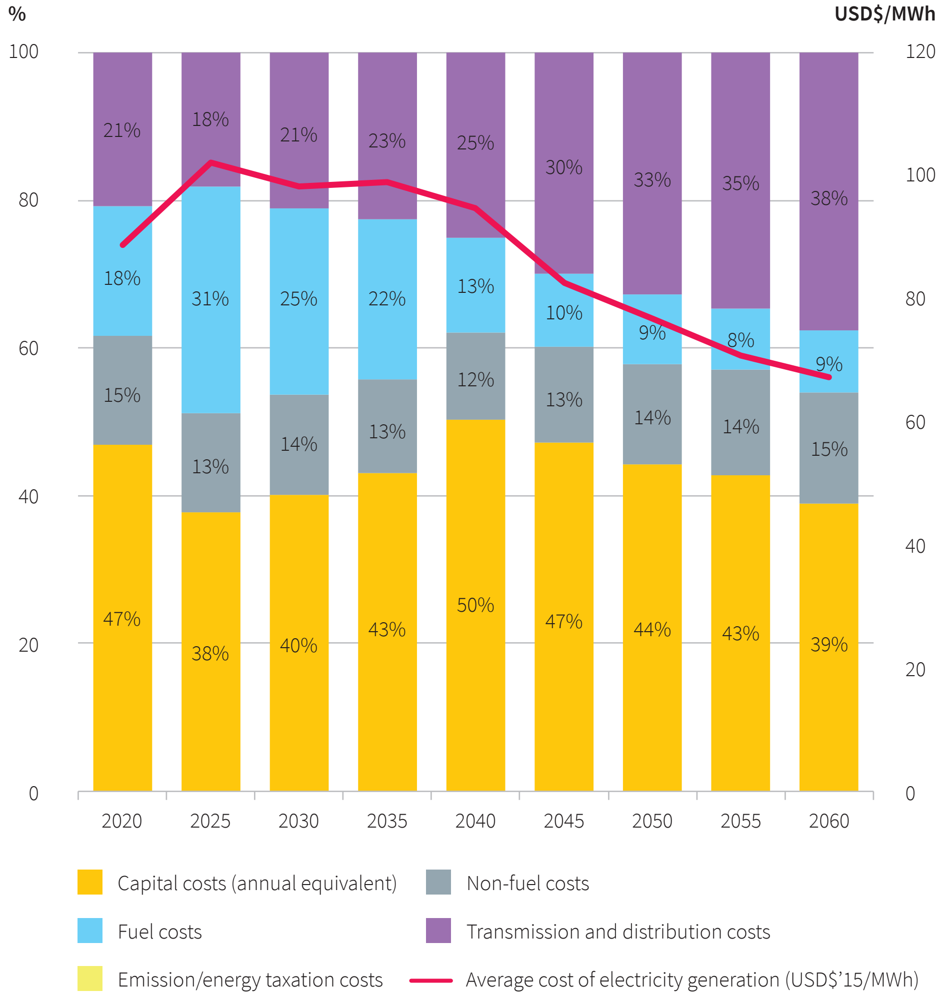
Moreover, investments will be needed for developing energy storage infrastructure to support variable RES capacity expansion. The investment rate is projected to be high until 2050 and drop afterwards, when the energy transition is completed (Figure 47). Moreover, as costs for renewable energy technologies decrease, investment savings increase over time. Between 2020 and 2030, onshore wind and solar PV will be a less expensive source of electricity compared to the fossil fuels. Grid costs are expected to rise considerably, due to the increase in electricity demand and the transition to a power system with more distributed power generation.

Figure 46: *The total amount of investments in the electricity sector*



The average cost of electricity generation is projected to peak in 2025. The main reason for this is the expected rise in the fossil-fuel prices. While prices are projected to remain at similar levels as of today until 2040, due to the effect of energy transition the cost of electricity generation will be cheaper in 2040 than in 2025. Capital costs constitute an increasing share of total generation costs until 2040 to support the establishment of new power generation infrastructure. While fuel costs are decreasing as fossil fuels are less and less used, transmission and distribution costs are increasing. This trend is projected to continue as utilities invest in grid modernization and overall transmission infrastructure to accommodate new wind and solar power plants (Figure 48). The significant reduction in fossil fuel use and therefore costs implies that the system is more resilient to price shocks and helps maintain price stability.

***Figure 47:** Breakdown of electricity generation costs*



5.2.6 Energy Import Dependence

Since 2020, Türkiye is highly dependent on imported fossil fuels to meet its growing energy demand. Despite a 40% increase in domestic energy production over the past ten years, the share of domestic resources in energy supply has remained at around 30%[18]. Depending on fossil fuel prices, Türkiye spends in the range of 26 to 50 billion USD on imported fossil fuels per year, averaging 38 billion USD per year between 2016-2021. Foreign trade deficit arising from energy imports constitutes over 60% of the overall foreign trade deficit and is an important underlying factor in Türkiye's persistent current account deficit. Rising fossil fuel prices in 2022 have had a major impact on energy imports which has gone up to 80 billion USD at the end of October 2022 (TÜİK, 2022; TCMB, 2022). Under the NZ2053 scenario this is projected to change radically (Figure 48). From being close to 69% in 2020, energy imports drop to 64% in 2030, 39% in 2040 and 9% by 2053[19]. Under the modelled new energy system, renewable energy sources dominate and e- fuels, including green hydrogen, are produced domestically.

[18] MENR, Türkiye National Energy Balance Sheets.
[19] The figure of import dependency for 2053 includes non-energy uses in the industry, where most imported fuels are used.

Figure 48: *Energy import dependence*

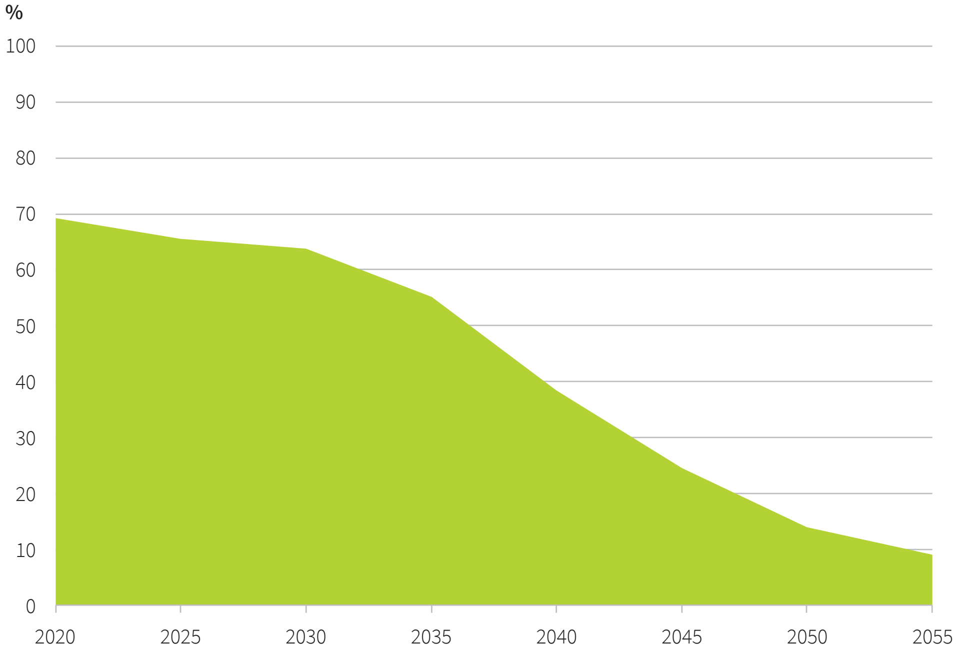
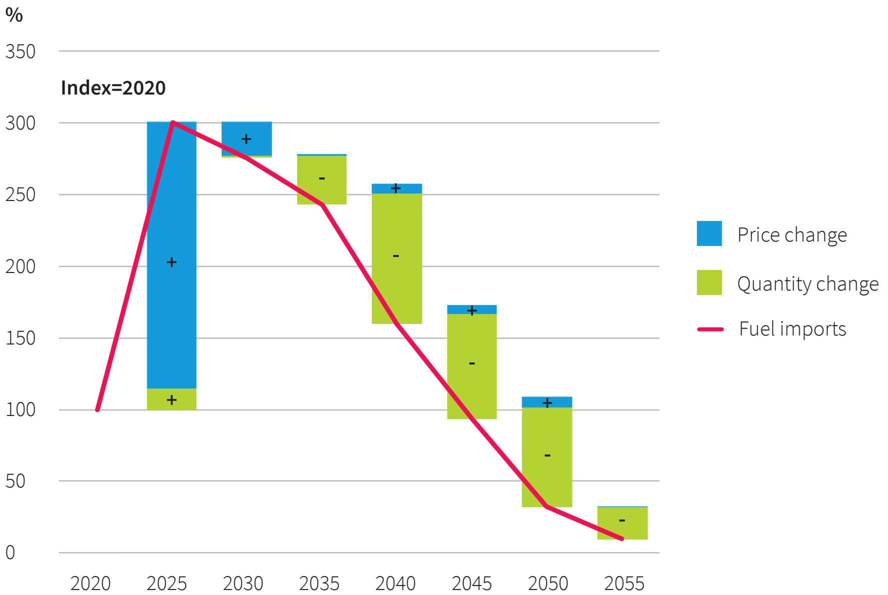


Figure 49 shows the evolution of expenditures for imported fuels in the energy system, excluding oil and gas for non-energy uses. It further splits the year over year expenditure difference in two components to exemplify the effect of the energy price increase and the effect of the import quantities on import expenditure. In 2020, expenditures for energy imports are extremely low, due to the low international fuel prices, following the outbreak of the Covid-19 pandemic. On the contrary, during 2021-2025 expenditures show a sharp increase due to the high energy prices following the global energy crisis and the war between Russia and Ukraine. While prices are gradually envisaged to return to previous long-term trajectories, they are expected to be slightly higher than historical averages; therefore, natural gas prices are also foreseen to stabilise at higher levels.

Figure 49: *Evolution of fuel import expenditures (excluding non-energy uses in the industry); contribution of prices and quantities to the annual change of import expenditures*



Until 2030, import expenditures remain high due to the combination of economic growth leading to higher quantities and higher prices. Decreasing consumption of fossil fuels is the primary reason for the drop of import expenditures afterwards. Nevertheless, the reduction in expenditures is limited due to the average unit cost of imports which increases over time. By 2045, although the prices are significantly higher than the 2020 levels, the steady decline in the import quantities over time cause a drop in the total energy expenditures as well. Energy import expenditures in 2053 are projected to be significantly lower than the expenditures in 2020.

5.2.7 Emissions

The NZ2053 scenario is in line with Türkiye's net zero target. The model results show that energy and process carbondioxide (CO_2) emissions drop to net-zero level by 2053.

Emissions in the electricity sector are projected to peak in 2025 and then decline sharply. In 2035, there will be a 65% decrease compared to the 2020 emission levels. This decrease is anticipated to occur due to the gradual shut down of coal and lignite power plants (Figure 50).

Figure 50: *Comparison of CO_2 emissions in 2020 and CO_2 emissions in the electricity sector over the years*

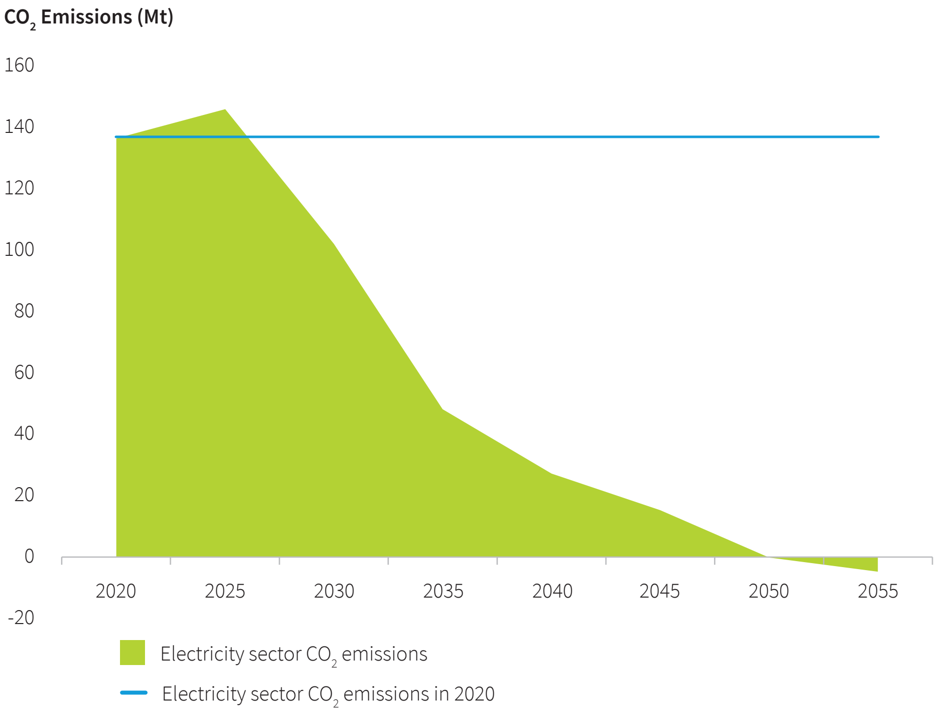
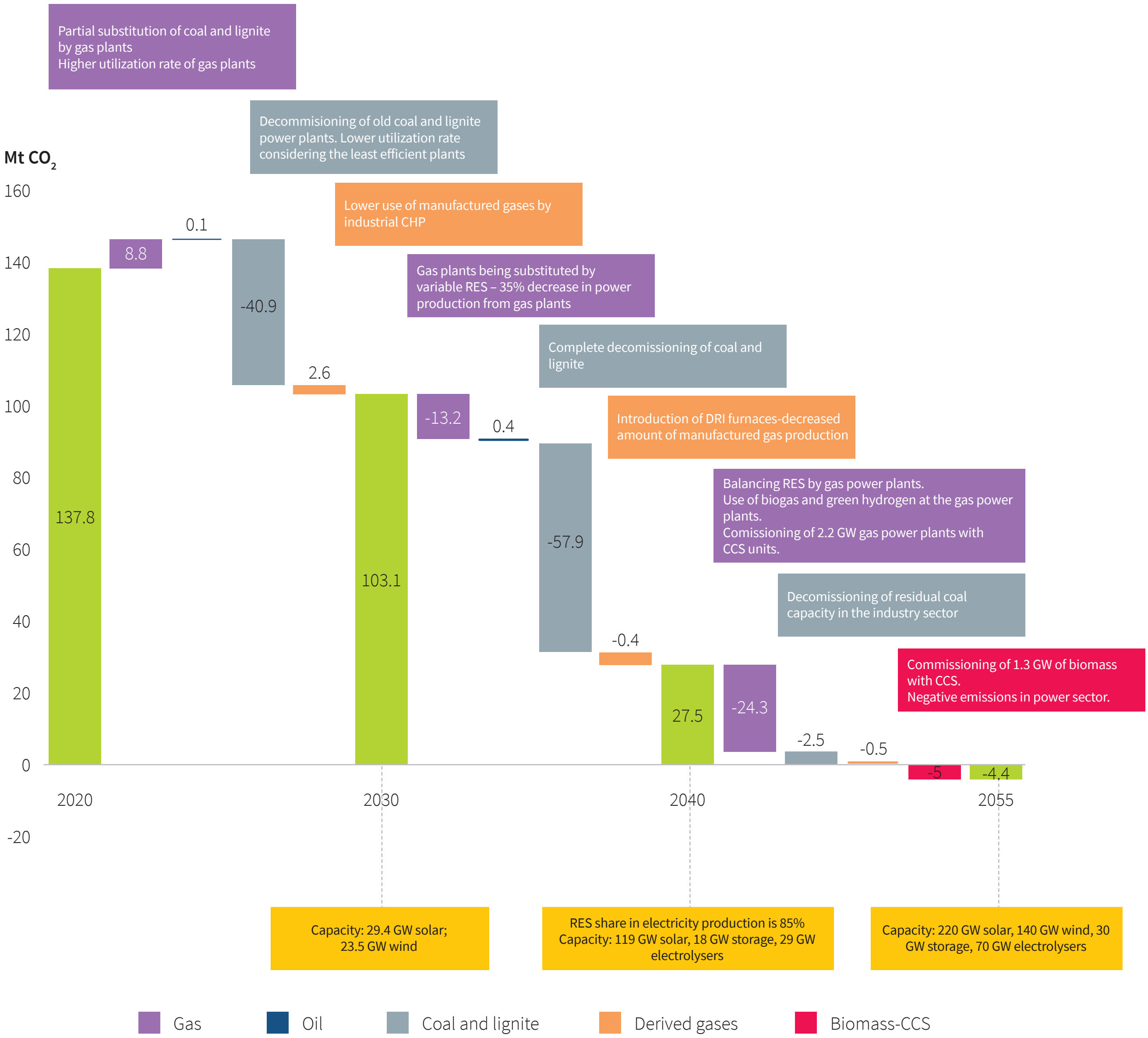


Figure 51: *Overview of the projection for CO_2 emission reduction driven by the electricity sector*



Due to the rising electricity demand until 2040, emissions continue to decrease after 2035, albeit at a slower pace, due to the use of gas power plants that operate mostly with natural gas. Gas plants have significantly lower emissions than coal/lignite plants, and in the long run the natural gas is substituted by green hydrogen and other e-fuels.

Power generation achieves zero emissions in 2050 and negative emissions in 2053, owing to the installation of 1.3GW of biomass with carbon capture and storage (BECCS) plants. The negative emissions in the electricity sector is necessary to compensate for the remaining emissions in demand sectors (transport and industry) and allow for the entire economy become net-zero between 2050 and 2053.

Figure 54 provides an overview of emission reduction projections by sector compared to 2020 levels. All sectors, especially power generation and industry, which cause the most emissions in absolute terms, need to undergo a significant transition. In the model, emission reduction is computed with an energy balance approach, based on the sector where energy is consumed.

Overall, in the period until 2030, although the emissions increase in the industry and transport sectors; the emissions reductions due to the building renovations and shift to heat pumps offset the emissions increase in other sectors, leading to an overall emission reduction compared to 2020 levels. A high degree of emission reductions occurs between 2030 and 2040 primarily due to the coal phase-out, which provides the majority of emission reductions. This is followed by industry via the reduction of the emission factor of the pipeline gas, and increased levels of energy savings via the use of biomass. Other savings in the model are due building refurbishments, the shift to heat-pumps, and the penetration of electric vehicles (EVs) in the transportation sector. Beyond 2040, the remaining emissions from road transport and industry are reduced. In the transport sector, nearly the entire vehicle are electrified (via batteries and fuel cells). It is assumed that gradually e-fuel blends will be used in the industrial pipelines in the industry. Heat pumps and solar water heating will entirely be used in the buildings to reduce all remaining emissions. In 2053, electricity is generated almost entirely by renewable energy power plants.

Figure 52: *Overall CO_2 emissions in all sectors*

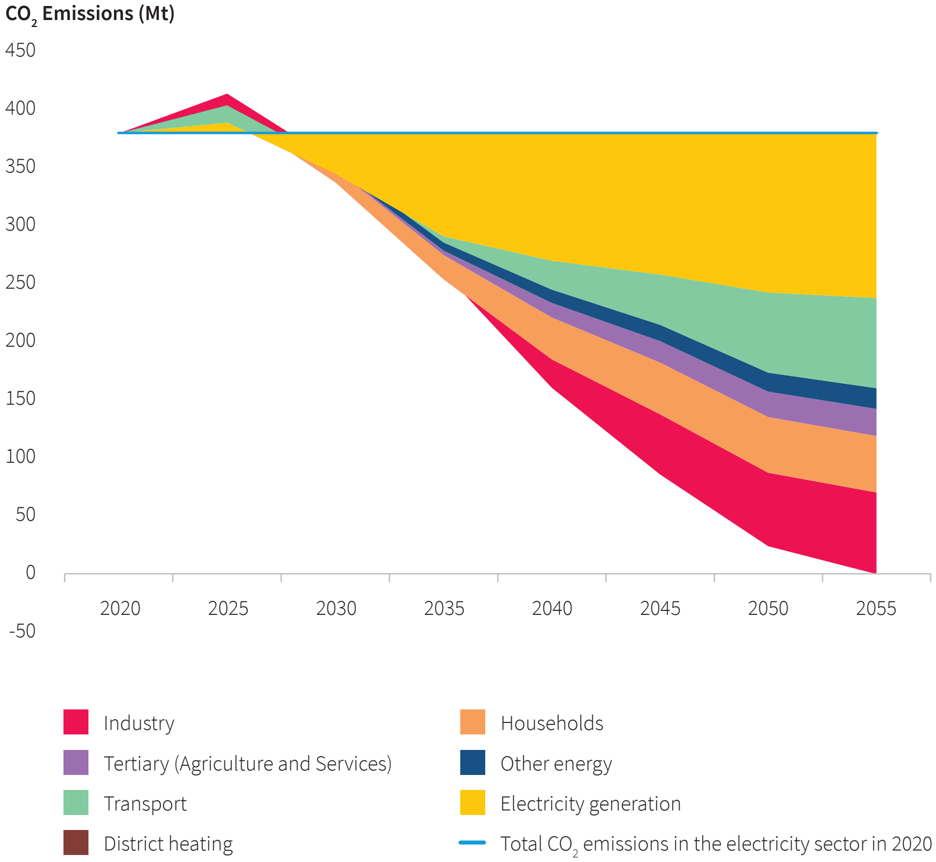
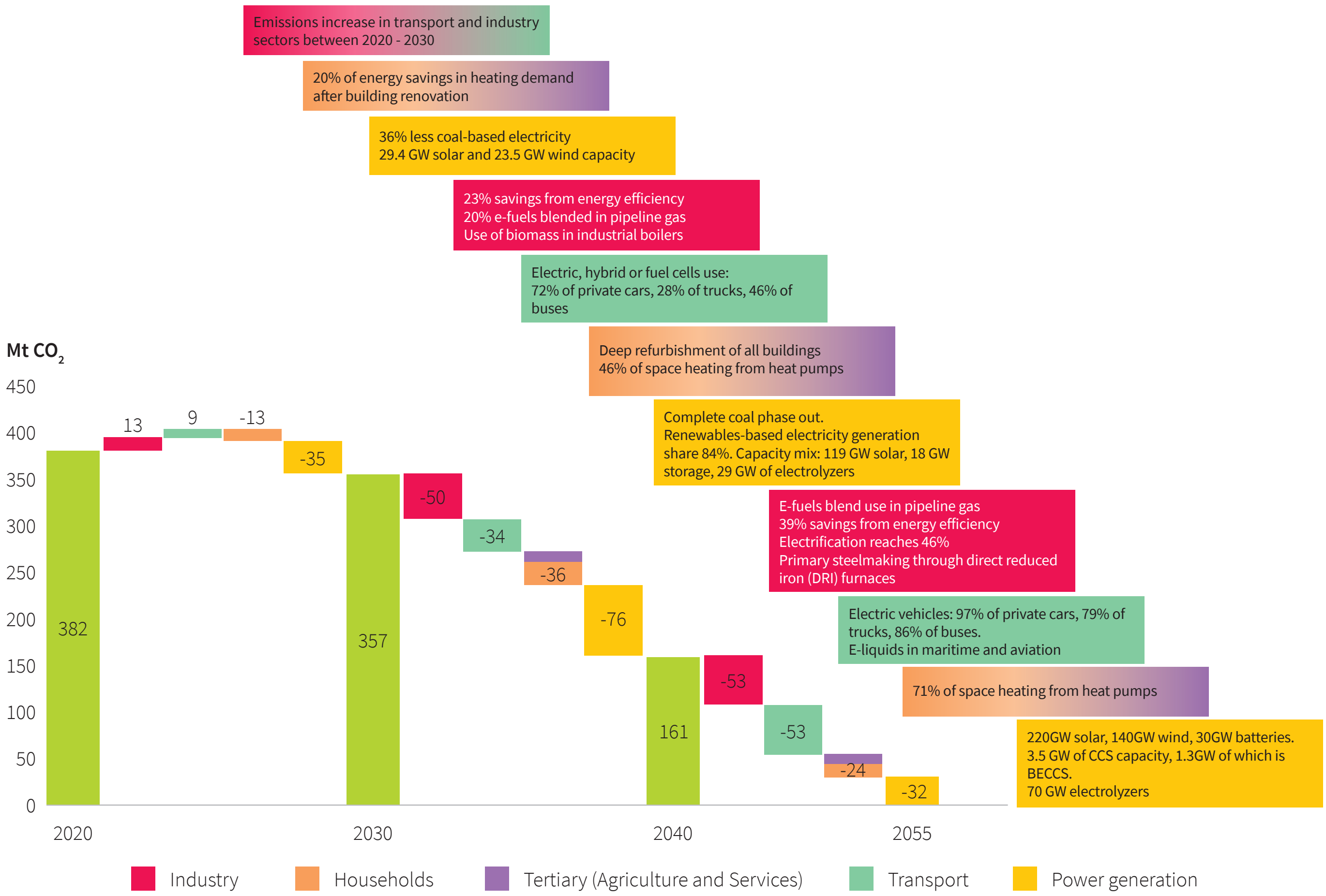


Figure 53: *Total CO_2 emission reduction and milestones by sector*



6. Sensitivity Analysis: Consequences of delayed action

The following section assesses the impact of delaying climate actions and energy transition on the development of the electricity sector. Within this context, a sensitivity analysis was undertaken that delays the energy transition and climate actions by ten years, implying that significant emission reductions begin in 2040 instead of 2030. In the sensitivity analysis, net-zero carbon dioxide (CO_2) emissions are still attainable by 2053, but the pathway to achieve this goal is significantly different. In order to maintain comparability between the Net Zero 2053 (NZ2053) scenario and the sensitivity analysis in the focus of the electricity sector, it is assumed that electricity and hydrogen demand growth will remain unchanged, although some minor differences occur due to the price effects.

Factors hindering the energy transition or delaying climate action within the scope of this study are:

- absence or delayed implementation of effective policies (carbon value),
- legal and administrative barriers, and
- lack of infrastructure development such as grid expansion.

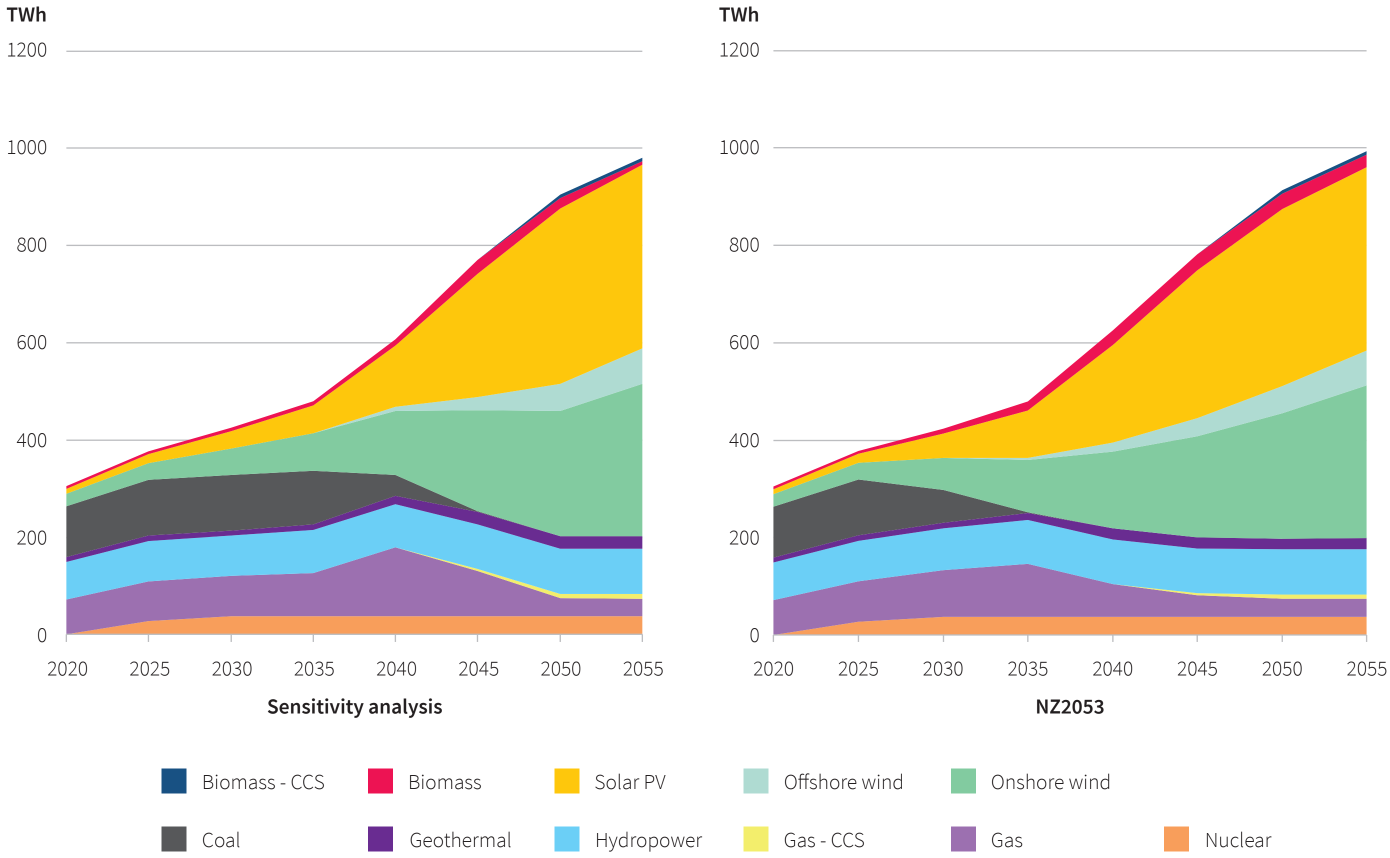
Therefore, the development of renewable energy power plants in the power generation sector is limited in the current sensitivity analysis.

6.1 Sensitivity Analysis: Gross Electricity Generation

Delayed energy transition and climate action, which is represented by a ten-year delay in the introduction of a carbon value (2035 instead of 2025), means that coal and lignite plants remain economically viable in the system until 2045. The continued presence of these power plants, combined with administrative barriers for renewables and poor grid development, limits the capacity increase in the renewable energy sources. As such, coal and lignite power plants continue to generate more than 100 TWh per year until 2035, after which the introduction of a carbon value instigates a switch from coal to gas (Figure 54). Power generation in coal and lignite power plants declines to half its current level by 2040 and is completely phased-out by 2045. This contrasts with the NZ2053 scenario, where effective energy transition and proactive climate measures succeed in ending power generation from coal by 2035.

Due to the delayed energy transition and climate actions, as the coal and lignite power plants remain in the system, the power generation from gas-fired power plants does not increase as quickly as observed in the NZ2053 scenario. Yet as energy transition action begins, gas power plants begin to replace coal and lignite power plants from 2035 onwards and power generation from gas power plants peak in 2040 at around 135 TWh, after when decreases rapidly as lower-cost renewable energy sources begin to enter the system en masse. By 2050, power generation from gas power plants stabilises at around 40 TWh per year.

Figure 54: *Evolution of electricity production in the sensitivity analysis and NZ2053 decarbonization scenario*

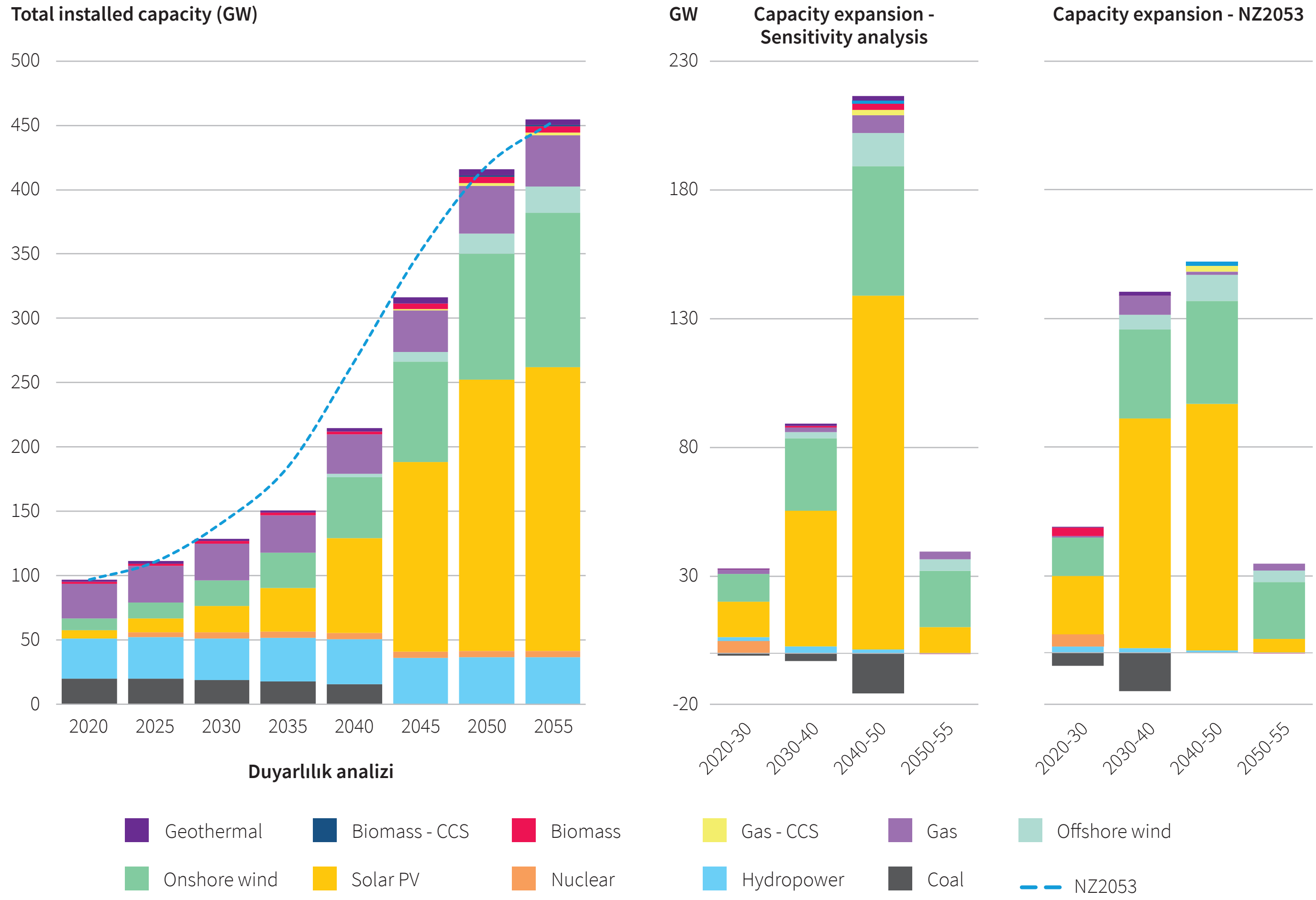


6.2 Sensitivity Analysis: Outlook of Installed Power Capacities

The achievement of a net-zero power system in Türkiye by 2053, solar and wind installed capacities reach 221gigawatts (GW) and 140 GW, respectively, in both the NZ2053 scenario and the sensitivity analysis. However, the slower integration of renewable energy sources into the system due to the effect of delayed energy transition action, means that the power system takes a considerably different pathway to reach net-zero. In this regard, the consequences of delayed energy transition and climate actions delays the development of solar PV and wind to the final decade of the transition.

Timely and effective action taken in the NZ2053 scenario results in the deployment of greater volumes of wind and solar PV into the system between 2020 and 2040. In these two decades, approximately 167 GW of new wind and solar PV capacity is commissioned (Figure 55). However, within the delayed energy transition and climate action analysis, only around 108 GW new capacity is installed over the same time period. This deficit in the capacity expansion is shifted to the last 13 years of the transition in the sensitivity analysis, in which 240 GW is deployed between 2040 and 2053, whereas in the NZ2053 scenario this value is 178 GW. This high concentration of investments in the sensitivity analysis comprises significant implementation risks, including the availability of finance, material, and workforce.

Figure 55: *Installed power capacity development in the NZ2053 scenario and the sensitivity analysis*



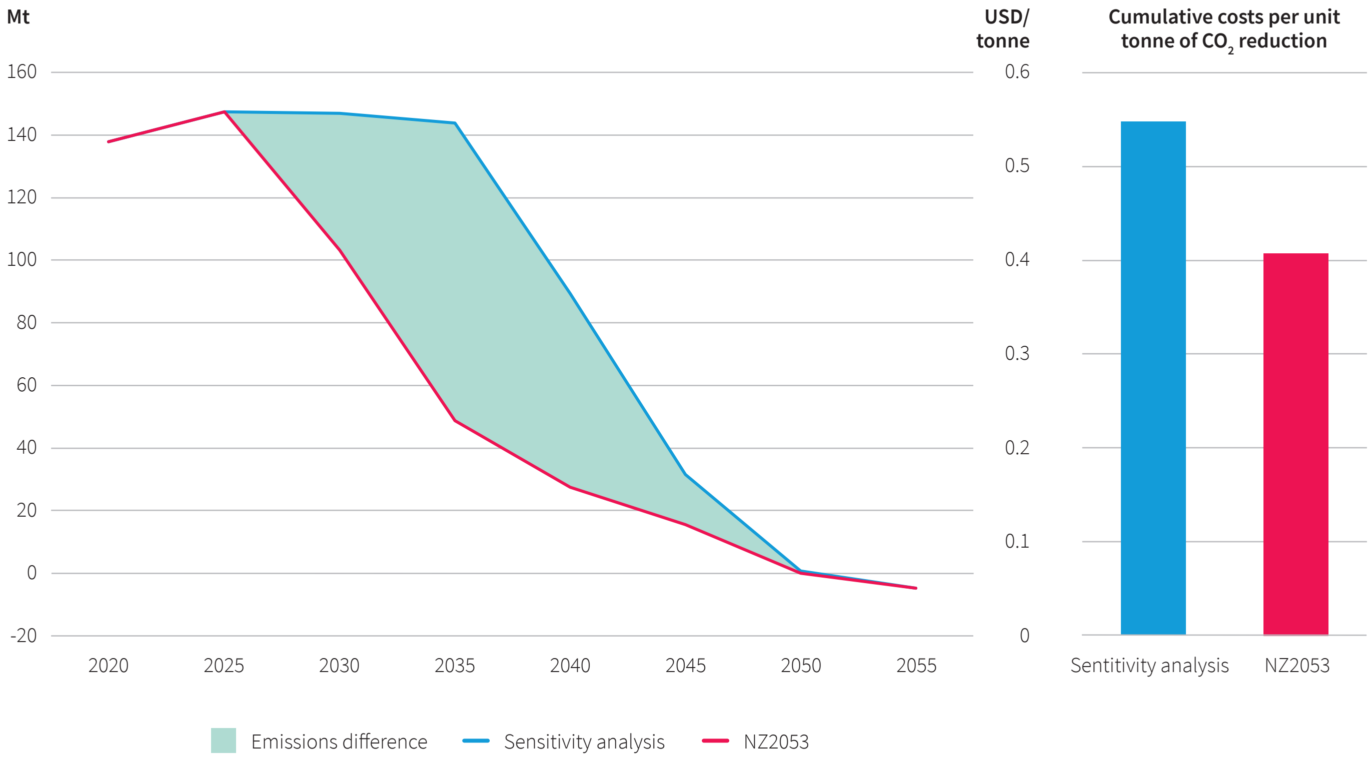
6.3 Emissions and costs

Türkiye's cumulative GHG emissions toward 2053. In case of delayed action, annual CO_2 emissions remain constant at around 146 Mt between 2025 and 2035 as lignite and coal plants continue to operate and investments in RES remain limited. Although there is a decrease in emissions between 2035 and 2040, as of 2040 CO_2 emissions will need to reach net-zero rapidly in only 13 years. Therefore, in the case of delayed action, the cumulative emissions are approximately 46% higher than in the NZ2053 scenario, resulting in an additional 1,086 Mt CO_2 emissions between 2021-2053 (Figure 56).

In absolute terms, the cumulative costs of the energy transition are quite similar even with delayed action. Delaying climate action avoids the premature decommissioning of fossil fuel power plants, but will require higher investments in the renewables in much shorter timeframes. On the other hand, the cost of reducing emissions will be much higher when the implementation of climate action is delayed. The cumulative costs per reduced emissions are approximately 34% higher than in the NZ2053 scenario.

However, delaying energy transition and climate action also has additional and far-reaching economic implications. For instance, continuing to rely on coal and lignite power plants until 2040 and then exercising a coal to gas transition leads to an increase in energy import expenditures. In the sensitivity analysis, the cumulative expenditures between 2031-2055 for energy imports are 20% higher than in the NZ2053 scenario. Given the potential volatility of fossil fuel prices in the future, impeding renewables expansion would weaken Türkiye's energy security and independence. Delayed energy transition and climate action could also have a significant negative impact on Turkish exports, especially to the European Union (EU) as the Carbon Border Adjustment Mechanism (CBAM) is expected to be implemented in 2026.

Figure 56: *Cumulated CO_2 emissions and cumulative carbon abatement costs computed in NZ2053 and in the sensitivity analysis*



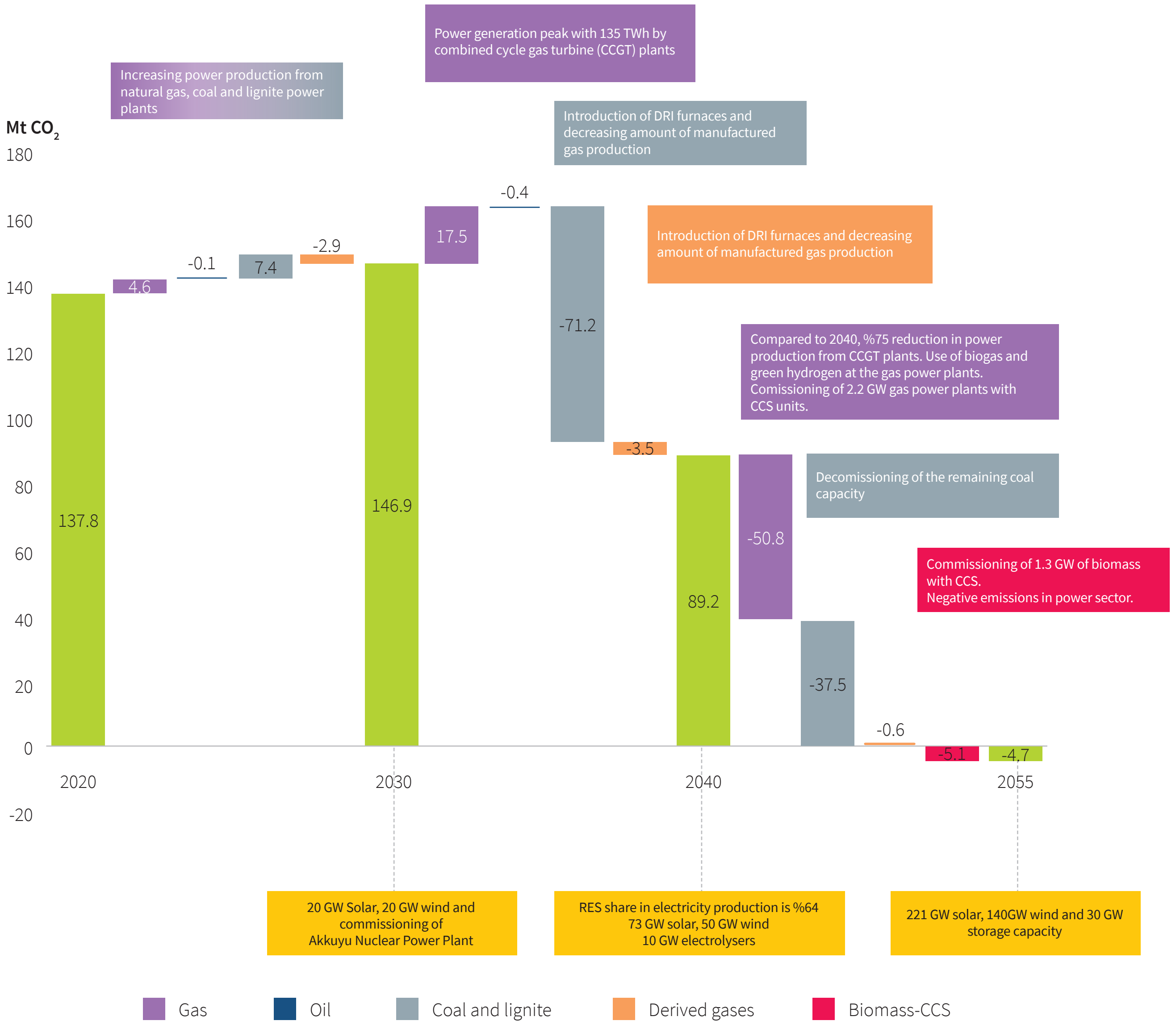
Even though Türkiye's net-zero ambitions could theoretically still be attained even despite a delay in energy transition and climate action, delaying action incurs a significantly higher carbon budget and much higher implementation risks. The additional 1.1 billion tonnes of carbon dioxide ($GtCO_2$) emissions due to the delayed climate action represent more than 0.25% of the remaining carbon budget to keep global warming to below 1.5°C[20]. Additionally, it remains unclear whether the roadmao in the sensitivity analysis is feasible as there is a risk of further increasing emissions due to the delayed climate action and moving the renewables investments toward to the end of the projection period carries significant implementation risk, it is questionable whether the roadmap in the sensitivity analysis is feasible and risks increasing emissions even further. The cumulative costs of the NZ2053 scenario and the sensitivity analysis are very similar. However, the feasibility and achievability of the NZ2053 scenario in terms of speed of investment requirements provides a more realistic and implementable transition pathway than the sensitivity analysis.

[20] United Nations (UN) Environment Program Emissions Gap Report, 2022

This analysis assumes that delayed action occurs mainly on the supply side, while the energy end-use sectors continue to electrify and reduce direct emissions with only a slight delay compared to the NZ2053 scenario.

However, this underestimates the effect of delayed action, which if it occurred in all sectors, emissions reductions would then be delayed further and the net-zero target would be less likely to be reached on time.

Figure 57: *CO_2 emissions in the electricity sector within the sensitivity analysis*



7. Key Conclusions

Türkiye's ratification of the Paris Climate Agreement in October 2021 and subsequent pledge to achieve net-zero greenhouse gas (GHG) emissions by 2053 are paving the way for an accelerated energy transition and more ambitious climate action.

In order to achieve net-zero emissions by 2053, Türkiye requires long-term policy visions, a clear strategy and a roadmap that outlines how each sector of the economy can achieve significant emissions reductions. In this context, it is critical to determine the interim targets in climate and energy policies to be reached until 2053 while establishing the action plans and priority policy mechanisms necessary to achieve these targets. The net-zero target is also an opportunity for Türkiye to fully transform its energy sector via the utilisation of its renewable energy, energy efficiency and electrification potentials, which are the key pillars of the energy transition. The electricity sector plays a crucial role in this transition, since decarbonization in many sectors will most effectively be attained through electrification, be it in the heating and cooling processes in residential and industrial sectors or in the transport sector through electric mobility. On the other hand, where the direct use of electrification is insufficient, use of green hydrogen and its derivatives (PtX technologies) through indirect electrification (electrolyzers) play a critical role in decarbonizing hard to abate sectors.

In that regard, the study provides the results of a comprehensive quantitative model that analyses the energy transition, which will allow Türkiye's energy system to reach net zero emissions by 2053, with a focus on the electricity sector. The key findings of this analysis are as follows:

- **Considering that energy systems are key drivers for economic development and climate action, Türkiye requires a sound energy transition roadmap that is vital for both economic and climate resilience, as well as for the environmental and human health.** Türkiye needs a long-term energy and climate strategy to achieve a net zero carbon economy by 2053. Türkiye has made important progress in setting up new institutional frameworks to combat climate change. That needs to be followed by economy-wide transition across all sectors and policy areas, focusing on the net-zero emission commitment. While analysing the impact of energy transition on all related sectors, the entire energy ecosystem that affects Türkiye's account deficit, energy independence and climate goals should be evaluated. In the Net-Zero 2053 (NZ2053) scenario, energy imports are projected to change significantly. From being close to 69% in 2020, energy dependence drops to 64% in 2030, 39% in 2040 and 9% by 2053. The new energy system, which is based on renewable energy, the potentials in energy efficiency and e-fuels, which includes green hydrogen and are produced domestically, are the most important reasons for this decline.

- **The net-zero emission goal by 2053 is achievable through the replacement of fossil fuels by renewable energy sources in the electricity sector.** As Türkiye moves towards the net-zero target of 2053, its power system undergoes a radical transformation when compared to current power system. One of the most significant trends in this transformation is the increasing share of variable renewables. While currently renewable energy sources represent almost 40% of the power generation, the majority of this comes from dispatchable hydropower, which has limited capacity for expansion in the future. By 2053, solar PV and wind are the dominant sources of electricity generation. Their total share in electricity generation is around 12% in 2020, which increases to 27% in 2030 and 77% (757 TWh) in 2053. Renewable power plants together with hydroelectric, biomass and geothermal provide 90% of the total electricity production in 2053 (899TWh). Gas fired power plants running on hydrogen and biogas, batteries (30 GW/120 GWh), pumped hydropower (3.2 GW), demand-side participation (predominantly via the use of electric vehicles), and electrolyzers (70 GW) for seasonal storage (PtX systems) as well as the electricity grid investments are the main options that provide flexibility to the power system.

- **The results show that the total energy demand of Türkiye increases until 2030 (1.441 TWh) due to increased economic activity and then the energy demand starts to decline despite economic growth due to the effect of electrification and energy efficiency back to its 2020 level (1.167 TWh) by 2053.** The macro-economic assumptions adopted in this analysis consider substantial economic growth of Türkiye. In the model, Türkiye is assumed to retain its sectoral manufacturing capacity, while manufacturing will shift towards producing higher value added and less energy intensive products. **Energy efficiency across all sectors is one of the key drivers for the decarbonization of the Turkish economy.** The residential sector contributes high energy savings through building renovations and the use of heat pumps, lowering the energy intensity from increased space heating activity. In industry, the final energy consumption is projected to peak by 2035 in line with the growing industrial production. Afterwards it is expected to decline due to electrification and shift to less energy intensive processes and sectors. One of the main drivers in reducing energy demand in industry is the process improvements for waste heat recovery, leading to process-wide energy efficiency. On the other hand, **electrification, which will help replace the use of fossil fuels, will play a crucial role in the decarbonization of the system while providing significant energy efficiency.** For example, in the transport sector, the model results indicate that increasing the share of electric vehicles is the main driver for energy efficiency in this sector. While approximately 80% of energy is lost in traditional internal combustion engines, electric vehicles are significantly more efficient, losing only about 10% of the electricity supplied.

- **In terms of total cumulative emissions, there is a slow decrease of 6.4% between 2020 and 2030; and in 2035, with no coal-based electricity generation in the system, the reduction in emissions is increasing.** The model results show that the most efficient way to meet the increasing electricity demand (considering costs and carbon emissions) is to increase renewable energy capacities. During the coal phase out period, the investments in the variable renewable energy technologies will increase and the solar PV installed capacities will reach 119 GW in 2040 and 220 GW in 2053 respectively. The model projects that the offshore wind potential of Türkiye will also be utilised, whose development will take place between 2035 and 2055. The delay in the deployment of the offshore wind is mostly due to the current technology costs which affects the levelized cost of electricity generation (LCOE). The onshore wind capacity, on the other hand, reaches 38 GW by 2035 and thereafter approximately 20 GW per each 5-year period is added to that amount. Energy storage systems (pumped hydropower and batteries) reaches an installed capacity of 33 GW by 2053, ensuring system stability and security. The battery capacity used in the model reaches 30 GW/120 GWh, which corresponds to a 4-hour discharge at maximum efficiency. Additionally, in order to meet the electricity demand to produce green hydrogen, electrolysers will need to be installed as of 2030 and the total electrolyser capacity will reach 5.5 GW in 2035. To meet the growing demand for e-fuels, the electrolyzer capacity grows rapidly to reach a total of 70 GW by 2053.

- **Considering the sectors such as transport and industry that are heavily dependent on the use of fossil-fuels today, indirect electrification through the use green hydrogen and other e-fuels (PtX) will play a major role in the decarbonization of these sectors.** The PtX technology will be used especially in sectors where high heat processes take place or high energy intensity is required. The shares of e-fuels and green hydrogen in industry and transport are limited before 2030 but increase rapidly afterwards due to the expected technological advancements, the drop in the technology costs and acceptance of the PtX technologies both in Türkiye and worldwide. Accordingly, it is projected that the Turkish natural gas pipeline will also undergo a gradual transition to the use of e-fuels. **Approximately, 70 GW of electrolyzer capacity is required by 2053 to meet the need for indirect electrification (to produce green hydrogen and e-fuels). In 2053, the share of green hydrogen and other e-fuels in total energy demand corresponds to approximately 15%.**

- **Achieving Türkiye's net zero target would bring net economic benefits but would require extensive public and private sector investments across the economy.** The pathway towards an energy system with net-zero emissions in Türkiye does not rely on reduced consumption or slow economic growth. On the contrary, it is assumed that the Turkish economy grows by an average of 3.3% per year until 2053. This growth relies on a comprehensive set of public and private sector investments that redesign Türkiye's electricity and transport sectors in addition to renovations in buildings, while also modernizing the construction sector and industrial processes. In addition to reducing GHG emissions, these measures contribute to the improvement of human and environmental health and welfare throughout theTurkish society and drive the shift in moving Türkiye from a developing to a high-income economy. **The results indicate that between 2020 and 2055, a total of 526 billion USD worth of investments, which includes the projected capacity expansions in the energy mix and grid as well as installing new energy storage systems in the power system is needed.** Managing the new variable renewable energy capacities connected to the grid will depend on grid infrastructure investments. The average annual investment for the electricity sector is US$15 billion between 2020 and 2055. However, the investment rates start to decline after 2050 as growth in energy demand slows down and the system gets closer to achieving the net-zero target.

- **Unless rapid steps are taken to decarbonize the power system, reaching the target of net-zero emissions in Türkiye by 2053 will become significantly more challenging with considerably higher implementation risks. Within this study, a sensitivity analysis, which considers delayed climate actions but the system reaches net-zero emissions by 2053, was also carried out. This analysis shows that keeping coal and lignite power plants in the system beyond 2035 not only increases the cumulative GHG emissions, but their presence also makes the transition more difficult in the later steps, as the continued presence of fossil fuels delays the deployment of renewable energy sources.**

In case of delayed climate actions, an additional 59 GW of installed wind and solar power plant capacity that is otherwise deployed between 2020 and 2040 in the NZ2053 scenario, is commissioned in the last 13 years of the energy transition within the sensitivity analysis. However, continuing to rely on coal and lignite until 2045 and then switching to gas and imported coal leads to an increase in expenditures for energy imports. In the case of delayed climate actions, the cumulative energy import costs between 2031 and 2055 are approximately 20% higher than in the NZ2053 scenario. This carries the risk of being more vulnerable to fossil price fluctuations due to the dependency on imported energy. Additionally, the delay in the integration of renewable energy sources into the power system due to the remaining fossil fuel power plants in the system increases the total power system cost. On the other hand, due to the delay in energy transition in the sensitivity analysis, the availability of finance, equipment, and workforce to deploy more than 200 GW of new capacity (primarily solar and wind) in the period between 2040 and 2055, is almost impossible.

Between 2050 and 2053, the negative emissions achieved by the electricity sector offset the residual emissions from transport and industry sectors. With the electricity sector leading the transition, the entire economy can become net-zero in 2053. In that regard, it is of importance that electricity sector achieves the net-zero emissions earlier than later to counter-balance the other sectors that are more difficult, timely and costly to decarbonize.

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Annex 1. Discount Rates

To determine the discount rates, the model in the study uses the same methodology as in the PRIMES model. Information on the discount rate method used in the model can be found in the European Union (EU) Reference Scenario 2020[21].

For convenience, the method to compute the discount rates in the electricity generation is summarised below:

Calculation of discount rates for investments in the electricity sector
To determine realistic discount rates, it is necessary to start from a risk-free (or low risk) discount rate. According to the literature, the common practice in industry is to take a value of 4%-5%.

Literature indicate that equity risk premium, which is added on top of the risk-free discount rate, is usually defined at 6-9% plus a country- or project-specific risk which can vary between -1% up to 6%. Assuming a capitalization structure consisting of 65% borrowed funds at 5.5% interest rate and 35% equity capital valued at 9% cost of equity rate (large, capital intensive business), the minimum level of WACC would be calculated as below:

WACC:

= 65% x 5.5% (debt)
+35% x (4%+2.5%+2.5%+2%) (equity)
= 7.5%

In the above calculation, 4% is the risk-free rate, 2.5% the equity risk premium, 2.5% the industry risk premium and 2% the company-specific risk premium.
+
In the model, the minimum WACC is used as a proxy of the rate of return, a regulator would agree to award to regulated natural monopoly infrastructures. This value corresponds to common practice of regulators in Europe and in the USA. In practice, regulated rates of return on capital have been confirmed to vary between 7% and 8%. In the model it is applied to the infrastructure for calculating the service tariffs.

Large energy utilities operating in competitive markets would add 1-2 percentage points as a company-specific risk premium, and small or medium size companies would add 1-3 percentage points as a size-related risk premium. Therefore, WACC for electricity generation and trade companies operating in competitive markets ranges between 8% and 12%. Adding country- or project- specific risk premiums would make the WACC vary between 8 and 18%. Among the studies on this subject, AFP (2011) and Fernandez et al. (2011) can be found for more information.

[21] Reference scenario 2020: https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

The basic discount rate in competitive power, gas, coal, and gas markets used in the model is 8.5%, based on the WACC calculation shown below:

WACC:

= 65% x 5.5% (debt)
+35%x (4%+3.5%+3.5%+3%) (equity)
= 8.5%

In the calculation, 4% is the risk-free rate, 3.5% the equity risk premium, 3.5% the industry risk premium and 3% the company-specific risk premium. The cost of equity rate is assumed 14% for companies exposed to competition and 11% for companies serving as regulated monopolies.

Annex 2. Calculation of Carbon Emissions in the Model

In the model (compactPRIMES), emissions are calculated based on the energy balance methodology. In this method, energy balance quantities are multiplied with standard emission factors (e.g. factors specified in the Intergovernmental Panel on Climate Change (IPCC) Guidelines). This may lead to discrepancies compared to the United Nations Framework Convention on Climate Change (UNFCCC) reporting in the common reporting format CRF tables[22] which may use different activity data[23] or different emission factors. For Türkiye, the power generation and iron and steel sectors, which are cause the largest divergence in emissions, have been analysed in detail. The assessment is based on the publicly available data and expert opinions inferring data gaps.

- **Iron and Steel Industry**
  - The quantities of coal and lignite referenced in the CRF tables are very small. It is inferred that coke used for the blast furnaces is not accounted for in the activity data of Category 1. In the model, this is considered in the final energy consumption of iron and steel, as per the energy balance.
  - The emission factor used for gaseous fuel in the CRF tables is very close to the factor of natural gas. In the model, based on data presented in the National Energy Balance Tables published by the Ministry of Energy and Natural Resources (MENR), gaseous fuels are split between natural gas and derived gas from blast furnaces, which has a much higher emission factor based on the IPCC guidelines.
  - The following check was performed:
    - The emission factor of the gaseous fuels in the model was modified to that of natural gas only and including the emissions from Category 2 (process related CO_2 emissions). The emissions are almost identical between the two approaches.

[22] Türkiye (2021) Common Reporting Format (CRF) Table: https://unfccc.int/documents/271541
[23] Energy quantities or other basic unit of activity

- **Power generation**
  - The energy balances include both main activity (grid-scale) producers and autoproducers (according to the terminology of the balances).
  - In the CRF tables, Category 1.A.1.a refers to "public electricity and heat production".
  - There are some divergences between the energy balances and the activity data used in the CRF tables.
  - Considering the checks conducted, it is concluded that there is a difference due to the basic activity used which leads to the discrapencies in the amount of emissions.

The National Energy Balance Tables published by the MENR are used as basis for emission calculations in the model.

The model uses the below emission factors as inputs:

Table 7: *Technology-based emission factors*

Supply technologies	tn/MWh fuel
Hard Coal	0.3536
Coke	0.3853
Lignite	0.364
Liquid petroleum gas (LPG)	0.2268
Gasoline	0.2492
Kerosene	0.2585
Naphta	0.2639
Diesel Oil	0.2664
Residual fuel oil	0.2783
Petroleum Coke	0.351
Natural gas	0.202
Manufactured gases	0.5861

Annex 3. Changes in Capital Cost of Technologies Used in the Model Over the Years

Table 8: *Power generation technologies and associated capital costs*

Power generation					
Technologies and their costs		2020	2030	2040	2050
Lignite power plant	USD'15/kW	1,150	1,150	1,150	1,150
Lignite power plant with carbon capture and storage (CCS)	USD'15/kW	3,270	3,070	2,880	2,830
Hard coal power plant	USD'15/kW	1,350	1,350	1,350	1,350
Hard coal power plant with CCS	USD'15/kW	3,270	3,070	2,880	2,830
Onshore wind power plant	USD'15/kW	1,100	1,060	1,010	980
Offshore wind power plant	USD'15/kW	3,600	2,020	1,510	1,420
Solar PV power plant	USD'15/kW	790	460	375	340
Hydropower Plant with Dam	USD'15/kW	2,000	2,000	2,000	2,000
Run of river hydropower plant	USD'15/kW	1,600	1,570	1,570	1,550
Biomass power plant	USD'15/kW	2,200	2,110	1,890	1,890
Biomass power plant with CCS	USD'15/kW	4,500	4,100	3,700	3,600
Geothermal	USD'15/kW	3,750	3,750	3,750	3,750
Combined cycle gas turbine power plant (CCGT)	USD'15/kW	680	640	640	630
CCGT with CCS	USD'15/kW	2,250	2,020	1,830	1,810
Open cycle gas turbine power plant	USD'15/kW	425	425	425	425
Nuclear	USD'15/kW	6,600	6,600	6,600	6,600

Table 9: *Associated costs for green hydrogen and energy storage technologies*

Storage technologies and costs		2020	2030	2040	2050
Green hydrogen	USD'15/kW	1,300	575	360	340
E-gas	USD'15/kW	2,700	1,600	1,220	850
E-liquid	USD'15/kW	3,150	1,925	1,265	1,020
Battery energy storage	USD '15/kWh	200	100	75	70
Pumped hydropower	USD'15/kW	920	920	920	920

About Istanbul Policy Center at the Sabancı University

Istanbul Policy Center (IPC) is a global policy research institution that specializes in key social and political issues ranging from democratization to climate change, transatlantic relations to conflict resolution and mediation. IPC organizes and conducts its research under three main clusters: The Istanbul Policy Center–Sabancı University–Stiftung Mercator Initiative, Democratization and Institutional Reform, and Conflict Resolution and Mediation. Since 2001, IPC has provided decision makers, opinion leaders, and other major stakeholders with objective analyses and innovative policy recommendations.

About European Climate Foundation

The European Climate Foundation (ECF) was established as a major philanthropic initiative to help Europe foster the development of a low-carbon society and play an even stronger international leadership role to mitigate climate change. The ECF seeks to address the "how" of the low-carbon transition in a non-ideological manner. In collaboration with its partners, the ECF contributes to the debate by highlighting key path dependencies and the implications of different options in this transition.

About Agora Energiewende

Agora Energiewende develops evidence-based and politically viable strategies for ensuring the success of the clean energy transition in Germany, Europe and the rest of the world. As a think tank and policy laboratory, Agora aims to share knowledge with stakeholders in the worlds of politics, business and academia while enabling a productive exchange of ideas. As a non-profit foundation primarily financed through philanthropic donations, Agora is not beholden to narrow corporate or political interests, but rather to its commitment to confronting climate change.

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European Climate Foundation

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