January 2025

Integrated Policy Strategies and Regional Policy Coordination for Resilient, Green and Transformative Development: Supporting Selected Asian BRI Partner Countries to Achieve 2030 Sustainable Development Agenda

Project Paper No. 11

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Decarbonizing the Turkish power sector

Overview, challenges, opportunities, analysis and policy recommendations

Abstract

Turkish electricity sector, in line with those in many countries, has been experiencing a significant transformation process in the last two decades. In addition to the hydroelectric generation capacity, penetration of wind and solar power plants in the last decade provided a total share of renewables consistently more than 40% of the total generation in recent years. In 2024, even cases where renewable generation approached 80% on a daily basis were observed. Moreover, action plans shaped within the framework of the Paris Agreement and concomitant 2053 net-zero emission targets address that this transformation process will continue to gain momentum. This study provides an overview of the sector in terms of economic and environmental aspects, and discusses the policy landscape relevant to structurally transforming the sector including the key challenges and opportunities. Besides, a critical review and evaluation of the various pathways proposed in recent studies is presented comparatively with the recent national energy plan with an additional analysis that examines the impact of smoothing the load profiles. Finally, policy recommendations for decarbonizing the sector in line with the Paris Agreement goals are provided.

Contents

KEYWORDS: Green Transition, Turkish Power Sector, Decarbonization, Generation Expansion Planning

Acknowledgements

This paper has been prepared under the UNCTAD project "Integrated Policy Strategies and Regional Policy Coordination for Resilient, Green and Transformative Development: Supporting Selected Asian BRI Partner Countries to Achieve 2030 Sustainable Development Agenda", funded by the 2030 Agenda for Sustainable Development Sub-Fund of UN Peace and Development Trust Fund of DESA. The author would like to thank UNCTAD staff for comments on earlier drafts. This paper represents the personal views of the author only. The author accepts sole responsibility for any errors.

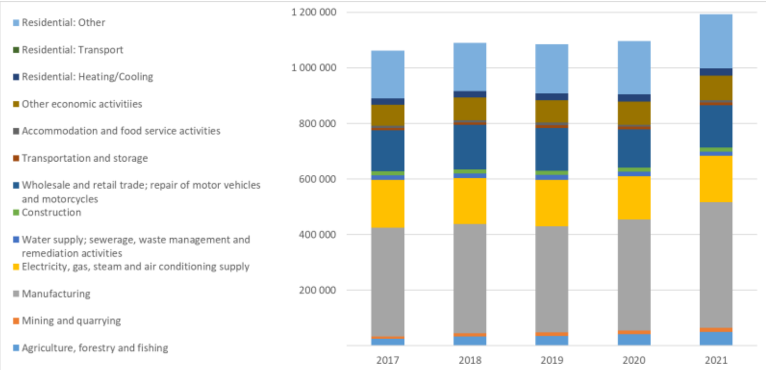
Introduction

With a population of more than 85 million, Türkiye is the fourth largest country among the OECD members and it is one of the G20 members where its GDP is 1.1 trillion USD as of 2023. Following a decade of continuing economic growth starting from 2007, Türkiye faced with three consecutive quarters of contraction, which was broken in the third quarter of 2019. Still at the end of the day, a relatively high rate of economic growth on the average i.e., 5.4%, was achieved after 2000 (World Bank, 2024). In line with this significant growth rate, the primary energy demand in Türkiye exceeded 150 Mtoe in recent years (MENR, 2024). The increasing trend in energy consumption has enabled the country to surpass world average in terms of energy consumption per capita but the indicator is still far behind the OECD or EU averages, i.e., less than half of the OECD average and less than two thirds of the EU average. It is more striking that current per capita energy consumption in Türkiye was experienced by most of the OECD or EU members before 1970s (The Energy Institute, 2024).

With urbanization, modernization and digitalization along with the other technological developments, the share of electricity over primary energy production has shown a significant increase in recent decades all over the world, i.e., the 12.75% in 1985 has been increased to 19.25% by 2023 (Our World in Data, 2024b). This situation occurred in the same way for Türkiye and the indicator has been doubled from 9.44% to 18.62% (Our World in Data, 2024b). After being stuck around 300 TWh in the 2017-2020 period due to political and economic turmoils followed by the COVID19 pandemic, electricity generation has risen to around 330 TWh in 2021. Similar generation amounts have been observed in 2022 and 2023 (TEIAS, 2024b) and is quite possible to hit 350 TWh by the end of 2024. The sector constitutes 1-2% of the overall GDP. As with energy consumption, electricity generation per capita has recently exceeded world average while it is also still well behind the OECD or EU averages (Our World in Data, 2024a). Total installed capacity has exceeded 100 GW, i.e., 106.7 GW by the end of 2023, where the structure shows a significant reliance on fossil fuels and hydropower for both installed capacity and actual generation, with increasing contributions from wind and solar energy sources (TEIAS, 2024b). The electricity generation is transitioning towards a more diversified mix, aiming to reduce reliance on fossil fuels and increase the share of renewable and nuclear energy sources in its energy portfolio. Total share of renewables consistently more than 40% of the total generation in recent years. In 2024, even cases where renewable generation approached 80% on a daily basis were observed (TEIAS, 2024b). The transition to renewable technologies has begun to bear fruit and the emission intensity has shown significant decrease after 2010s, i.e., 16% decrease during 2010-2020 period, by continuing the decrease due to the substitution from coal to natural gas in the decade before. Another important evolution in the power sector is the liberalization of the market in a way that state-owned facilities have largely been replaced by private producers. The share of state-owned installed capacity has decreased from ~55% to ~20% in the last fifteen years while a decrease from ~50% to ~14% has been occurred in the generation amounts for the same period (TEIAS, 2024a). The last remaining capacity that belong to the government-controlled Electricity Generation Corp. (EÜAŞ) consist of coal power plants in addition to large hydroelectric power plants. However, these capacity and generation amounts are still higher than any individual power company (TEIAS, 2024a).

Nearly one fifth of electricity is consumed by households as residential demand i.e., space heating, space cooling, water heating, cooking, lighting and electrical appliances, where all population has access to the electricity in the country. Manufacturing sector is the leading one with over 35% consumption for the remaining demand. Figure 1 illustrates the break-down of electricity consumption by sectors as well as households. It is seen from this figure that there has not been a significant change in share of the end-use categories recent years. Note that the share of residential transportation is almost zero for the given period. However, high spikes are expected to happen in the near future even for the year 2023 due to the sudden penetration of electric vehicles and future projections (EMRA, 2024).

a) Terajoule



b) % of total

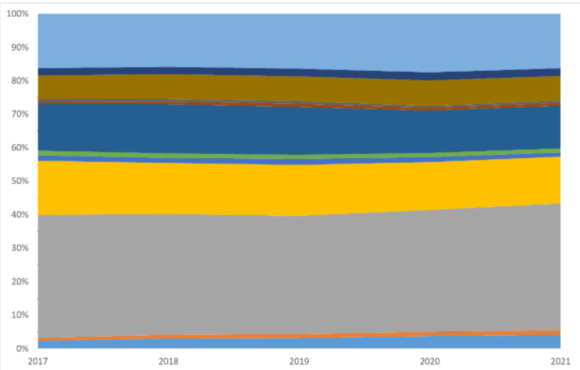


Figure 1. Electricity consumption by sectors, 2017-2021.

Sources: TURKSTAT, 2023

Ultimately, Türkiye relies heavily on imported energy sources, with natural gas and oil being primary contributors to its energy mix while the country has been actively diversifying its energy sources to include renewable energy such as wind, and solar power. Government initiatives aim to reduce dependence on imports, enhance energy efficiency, and promote renewable energy investments to meet growing demand. However, challenges such as energy security, infrastructure development, and environmental concerns remain key considerations for Turkey's energy strategy moving forward.

Türkiye announced its net-zero emission targets pointing to the year 2053 at the United Nations General Assembly in New York City in 2021. Considering that over 400 Mton CO2 equivalent (CO2e) emissions of the total GHG emissions around 550 Mton CO2 equivalent (CO2e) originate from the energy sector (TURKSTAT, 2024a); thus, the mitigation pathways in the energy sector will play a crucial role in achieving net-zero target. However, the asymmetries in technical and economical feasibility of prospective clean technologies in different sectors and end-use consumptions result in different decarbonization pathways. In other words, technological constraints in eliminating process emissions in industries and high transition costs of decarbonization in buildings and transportation sectors make the power sector (which constitutes nearly one quarter of total emissions and nearly one third of energy related emissions) low-hanging fruits for achieving short-term and interim targets and commitments for emission mitigation.

This study provides a detailed overview of the sector in terms of economic and environmental aspects on top of the key indicators given in the previous paragraphs, and discusses the policy landscape relevant to structurally transforming the sector including the key challenges and opportunities. Besides, a critical review and evaluation of the various pathways proposed in recent studies is presented comparatively with the recent national energy plan. Finally, policy recommendations for decarbonizing the sector in line with the Paris Agreement goals are provided. The report is organized into five sections. Next section provides the historical background and the detailed overview of the Turkish power sector. Section 3 examines and summarizes the feasibility of the net-zero target in a comparative manner with its links to the studies in the literature. This section also presents a discussion on the expected impacts of the transformation by taking EU as reference and provides an analysis that demonstrates the role of an efficient demand side management (DSM) policy. Challenges and opportunities are discussed in Section 4. The paper ends by providing concluding remarks and policy recommendations.

2. Historical Background and General Overview

The Turkish power sector has gone through a remarkable journey of evolution and transformation, reflecting the country's determination to meet the challenges of modernization, economic growth and sustainability. The development of the Turkish power sector dates back to 1910s just before the foundation of the Republic of Türkiye and small-scale local plants were observed until 1950s. The generation fleet expanded mainly with hydroelectric power plants in the 1950-1980 period. Although privileges were given to some companies for generation distribution and trade in their own regions and built-operate-transfer (BOT) or build-operate (BO) schemes during 1980s and 1990s, it was early 2000s that Türkiye took the path of liberalization and introduced a series of market reforms (i.e., establishment of the independent regulatory body -Energy Market Regulatory Authority, EMRA-; separate bodies for generation, transmission, distribution and trade operations; the privatization of state-owned assets; introduction of market-based mechanisms; opening up of the sector to private domestic and foreign investors, etc.) in the power sector aiming to create competitiveness in the market.

In the first period after liberalization of electricity sector, the market was dominated by natural gas power plants with the continuing effect of the pre-liberalization build-operate practices. During this period, natural gas based production constituted up to half of the total production in some of the years (TEIAS, 2024a). The increase in dependency to the imported natural gas, not only for the power sector but also for the whole energy system, was also significantly reflected in the macro-economic balances of the country that revealed and brought about the supply security concerns. Natural gas demand over 2000-2010 period jumped from 12.4 M Sm3 to 38.1 M Sm3 where more than half of these amounts are used in the power plants (MENR, 2024). Then, after 2010s, these concerns were replaced by new and completely different problems when the dominance of natural gas plants was weakened by the two groups of technologies that are contradictory to each other, i.e., coal plants and intermittent renewable technologies such as solar and wind. In this era, the environmental advantages of renewable technologies have been significantly eliminated by the increases in coal power plants, and even increased emission values have been encountered in total. Moreover, the decrease in the flexibility of the system due to the increasing shares of intermittent technologies and the replacement of natural gas plants by relatively less flexible coal plants reveal potential problems in case of further penetration of solar and wind technologies.

While all these developments are taking place, Türkiye signed the Paris Agreement in 2016 and the Agreement has been ratified in 2021. The main outcome of this agreement is the commitment given by the countries to reduce their emissions starting from 2020 and to limit the global temperature increase in this century well below 2°C, preferably to 1.5°C. In line with this objective, Türkiye has announced 2053 as the target year to decarbonize her economy. Then, for the power sector, as a key sector in the decarbonization of the economy; the main challenge to overcome is to find the optimal pathway that supports intermittent technologies with various flexibility options under a plausible investment plan.

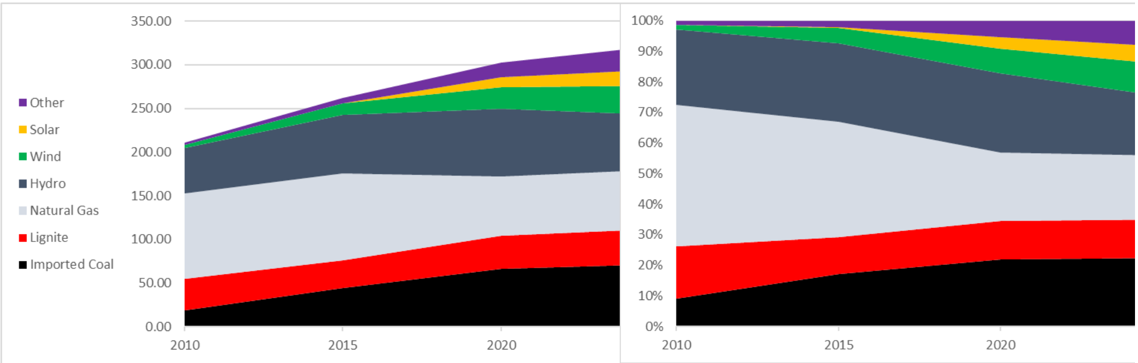
The rest of this section summarizes the current capacity composition in the Turkish power sector, as well as how the generation profile and the concomitant emissions have recently evolved. Moreover, it reveals the sector's role in the overall economy.

Figure 2 illustrates the installed capacity profile of the Turkish power sector at the end of 2023. As seen in this figure, hydroelectric power plants (including dams as well as run of river type turbines) constitute the leading capacity with 31.96 GW. It should be noted here that this capacity is close to its maximum potential and full utilization is expected by early 2030s. Next technology with the highest capacity is the natural gas power plants with 25.40 GW. Although the natural gas technology still keeps its importance in the generation fleet, the utilization rates have been gradually decreasing in recent years. Maybe the most striking values in this graph are the solar and wind capacities: they are almost negligible at the beginning of 2010s. Fossil-fired power plants that have high emission intensities, i.e., imported hard coal and lignite, each stand for more than 10 GW capacities. “Other” with a total capacity of 5.60 GW, in this figure, includes geothermal, biomass, asphaltite, domestic hard coal, LNG, LPG, fuel oil, diesel, naphta and waste heat.

Figure 2. Installed Capacity by technology, 2023: GW.

Sources: TEIAS, 2024b

Figure 3, on the other hand, presents the evolution of generation amounts and shares since 2010. This figure clearly shows that the natural gas based generation has been mainly being replaced by intermittent renewable technologies. That is, the share of natural gas power plants decreased from 46.5% in 2010 to 20.9% in 2023 while sum of intermittent technologies increased from 1.6% in 2010 to 16.3% in 2023. The remaining decrease in natural gas generation has been mainly substituted by the imported coal plants. This grift evolution, i.e., a moderate level polluting technology such as natural gas, is substituted by the technologies at two different ends: renewables and coal, resulted in a decrease in the overall emission intensity of the sector as illustrated in Figure 5a. However, the increasing demand substantially offsets this reduction and total emissions continue to rise as seen in Figure 4.



a) Generation, TWh *b) Generation, %*

Figure 1. Generation by technology, 2023..

Sources: TEIAS, 2024b

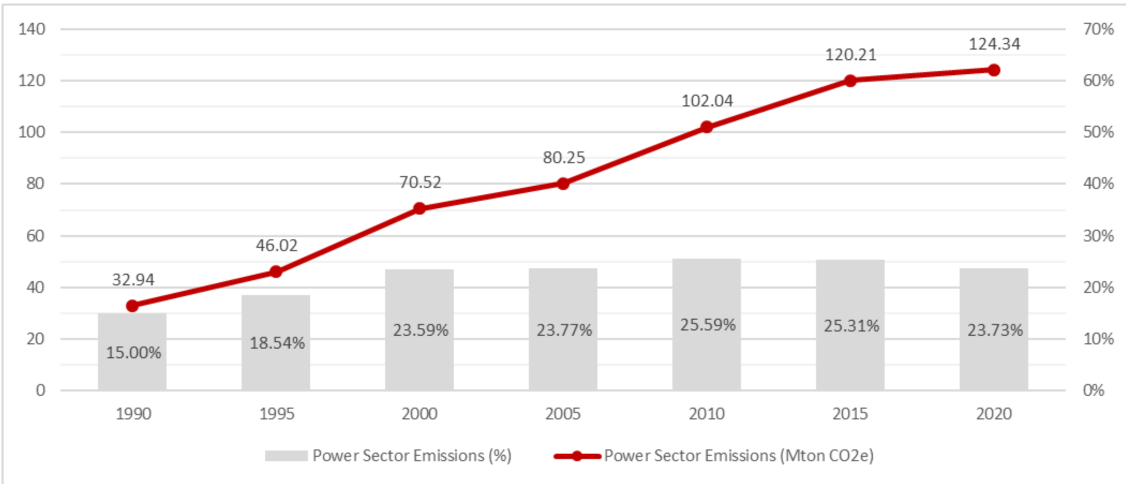
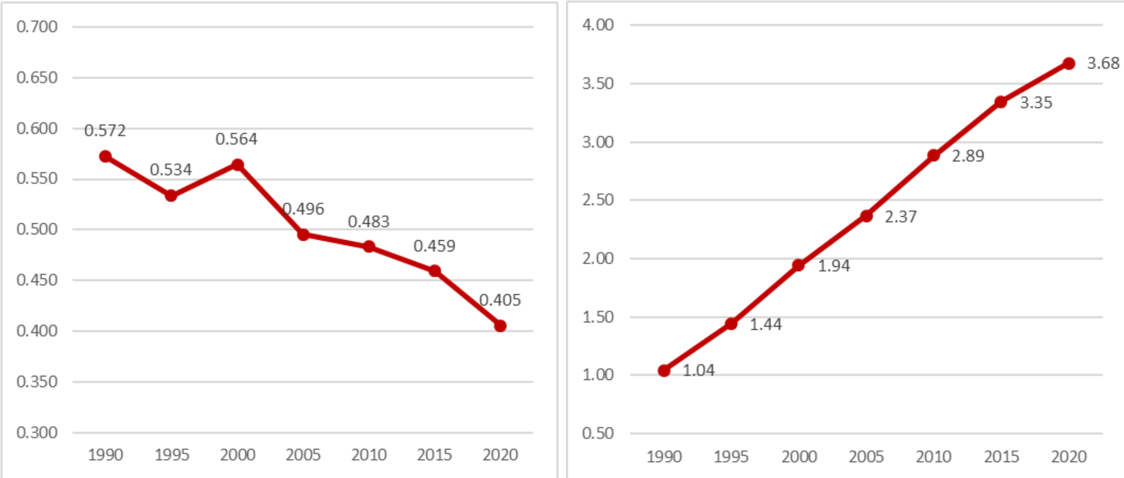


Figure 2. Power Sector Emissions: Mton CO2e (left axis), % of overall emissions (right axis).

Sources: UNFCCC, 2024

The emissions produced due to the electricity generation for the period 1990-2020 can be seen in Figure 4. This figure shows an ever increasing trend although there has been the mitigating impact of the COVID19 pandemic on the emissions in 2020. Figure 4 also presents the share of power sector originated emissions over the total emissions on the right axis. It is seen that 15% in 1990 increased to around 25% after 2000 in line with the significant increase in electrification and concomitant per capita electricity consumption. There has been a slight decreasing trend in recent years and this trend is expected to continue in the following years (although the official statistics does not include this detail after 2020).



a) Emission Intensity (Mton CO2e/TWh), (UNFCCC, 2024)

b) per Capita Electricity Generation (MWh/person), (Our World in Data, 2024a).

Figure 3. Emission Intensity and per capita generation: 1990-2020.

Figure 5 summarizes the historical change in two important indicators of the power sector, i.e., emission intensity and per capita electricity generation. The increase in natural gas plants resulted in a significant decrease after 2000s and the decreasing trend continues owing to the penetration of solar and wind technologies. Per capita generation, on the other hand, shows a rapid upward trend in line with the economic growth as well as with the increasing electrification in the country. Note that, as declared at the outset, all the population in Türkiye has access to electricity. However, the generation and consumption levels over the regions differ based on the location of plants and economic activities in each region. A large portion of the hydroelectric power plants are in the Fırat-Dicle and Çoruh basins; domestic coal power plants are near the regions with coal mines, e.g., Soma, Afşin-Elbistan, Yatağan; imported coal power plants are in coastal cities, e.g., Zonguldak, Adana, Çanakkale; natural gas power plants are located in regions with high electricity consumption, i.e., Kocaeli, İsanbul, İzmir, Bursa; wind power plants are mostly located in the Aegean coast and the eastern Mediterranean; and solar power plants are located mainly in the southern half of the country.

As further illustrated in Figure 6, although this upward trend has enabled Türkiye to exceed the world average, it is still well below the EU average. These observations should be interpreted given the fact that the significant energy efficiency improvement efforts of the developing countries in the last decades has a retarding even a decreasing effect in the per capita generation/consumption as observed for the EU after 2005 on the graph.

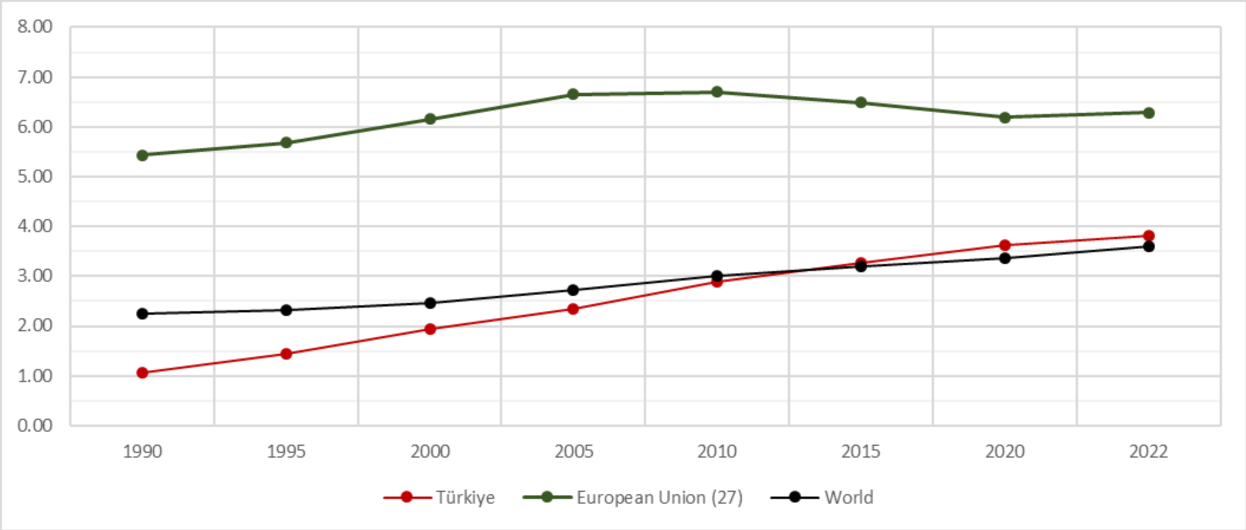


Figure 4. Per capita generation: comparison with EU and World averages.

Sources: Our World in Data, 2024a

Finally, Figure 7 shows the share of “Electricity, gas, steam and air conditioning supply” sector over the GDP between the years 2000 and 2022. It is hard to identify per capita generation of the power sector separately since the statistics are published in aggregate terms including gas, steam and air conditioning; however, it is still useful to see that the sector constitutes 1-2% of the overall economy.

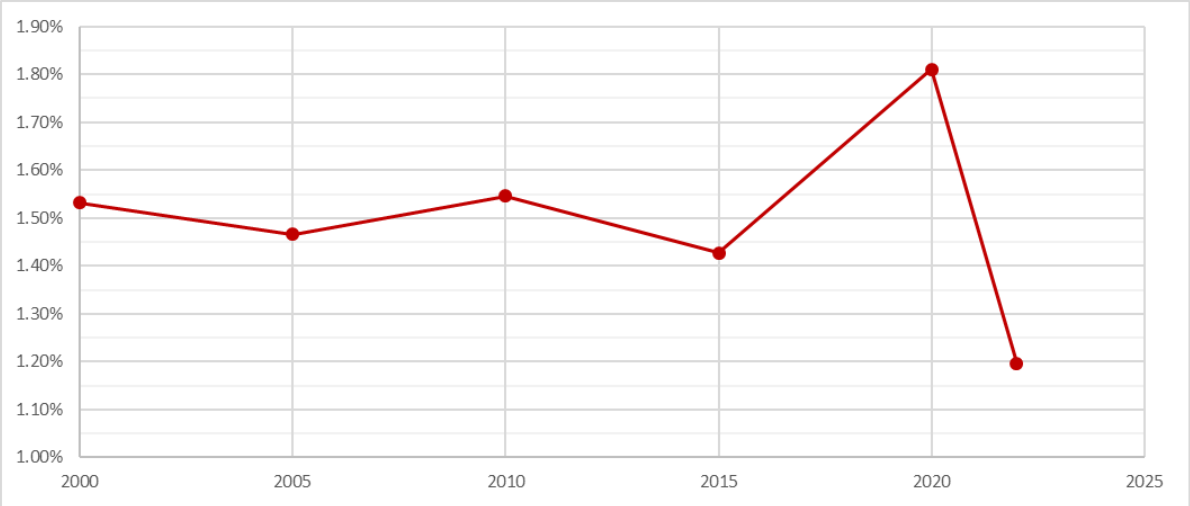


Figure 5. Share of “Electricity, gas, steam and air conditioning supply” sector in the GDP..

Sources: TURKSTAT, 2024b

3. Challenges and Opportunities

Considering Türkiye’s ambition to achieve net-zero emissions by 2053, there are several challenges and opportunities for the power sector. This section first reveals the challenges that may prevent Türkiye from achieving the proposed targets, the interim targets introduced in the revised NDC (Republic of Türkiye, 2023), national action plan (MENR, 2022) and the ultimate 2053 net-zero targets. These challenges can be summarized under four main headings: coal power plants, substantial investment requirements, technical and operational challenges due to the intermittency and challenges in implementing effective policy and regulatory frameworks. Next, a discussion on the opportunities such as high renewable potential and job creation opportunities will be provided.

Coal-Fired Power Plants

Achieving net-zero emissions requires a complete reduction in carbon-intensive energy sources by the target year, 2053. The generation by imported coal and lignite power plants constitute one third of the total generation in recent years. This situation constitutes one of the most important obstacles to achieving net zero targets including the creation of stranded asses. Although there are studies that reveal the technical feasibility of phasing-out coal power plants by 2030 or 2035, e.g., (Kat et al., 2023; SEFIA, 2021); national energy plan (MENR, 2022) does not propose a concrete phase-out plan for the coal power plants. Moreover, the plan mentions minor expansions in coal-fired power plants and positions them as a flexibility option. In fact, not only hitting the 2053 net-zero targets but also the pathway while reaching this ultimate goal is important, even more critical. Because, the pathway determines the cumulative emissions, i.e., the carbon budget, throughout the planning horizon. Then, each year of phase-out postponement would result in significant increase in the carbon budget, which is crucial in satisfying 1.5 °C target by the end of the century.

Financing the Transition

Transitioning to renewable energy sources necessitates substantial investments in infrastructure, technology, and human capital where only the investment requirements for new plants are projected to be an annual amount of 4-7 billion US$ (Acar et al., 2023; Kat, 2023) in the medium-term. Securing financing and mobilizing resources for such investments may pose a challenge, particularly in the context of economic constraints and competing priorities. Although the external benefits of the clean transition eliminate some of these costs (Şahin et al., 2022), the investment requirements would be costly and difficult to meet in case of long-term continuity of high inflationary economic conditions in the financial markets. In the current situation, financing is limited by the inability to access alternative financing sources and models. Specifically, a shortcoming in terms of financing the green transition is the insufficiency in financing models and policy instruments in the distributed generation and energy efficiency markets, e.g., energy service companies (ESCOs) are lagging behind the global trends as addressed in (Acar et al., 2023).

A recent document published by the Ministry of Trade (MoT) brings together all of the support, subsidy and financing instruments and mechanisms provided by different ministries and institutions (MoT, 2024). The document reveals that international funds such as EU's the Instrument for Pre-Accession assistance (IPA) will play a crucial role in financing the green transition projects in addition to the public budget. However, it is obvious that there will be a tough competition among the sectors to benefit from these instruments.

Grid Reliability under High Penetration of Intermittent Renewable Technologies

Integrating intermittent renewable energy technologies, i.e., wind and solar, into the grid while maintaining grid stability and reliability presents technical challenges. The power system needs effective balancing mechanisms to match supply with demand in real-time where inadequate balancing mechanisms may lead to voltage fluctuations, frequency deviations, and even blackouts. Then, at the first stage, upgrading the transmission and distribution infrastructure to accommodate the increased capacity of renewable energy sources needs to be on the agenda. This includes expanding transmission lines and upgrading substations to transport electricity from remote renewable energy sites to population centers. Ensuring adequate grid infrastructure, storage capacity, and flexibility mechanisms to manage fluctuations in supply and demand is essential for a smooth transition to a low-carbon power system.

The Nuclear Program

Throughout 2021-2022 period, energy prices in the European Union increased significantly as seen in Figure 8. Moreover, the prices turned out to be more volatile especially after Russia-Ukraine conflict. As a result, both households and industries faced with higher energy bills although there has been a gradual decrease in the cost of renewables. These occurrences clearly revealed the shortcomings of the EU's electricity system, i.e., dependency on imported fossil fuel sources and a lack of flexibility other than non-fossil fuels, and resulted in a market reform in 2023 that mainly aims to phase-out natural gas in the system and make electricity prices less reliant on imported fossil fuels. This reform also brings with it a drastic departure from EU's traditional declarations about nuclear power. The reform opens the doors for two-way contracts for difference (CfDs) or equivalent schemes with the same effects (compensating the producers in case the market prices fall too much, but collecting payments if prices are too high.) not only for the renewable technologies but also for the nuclear power.

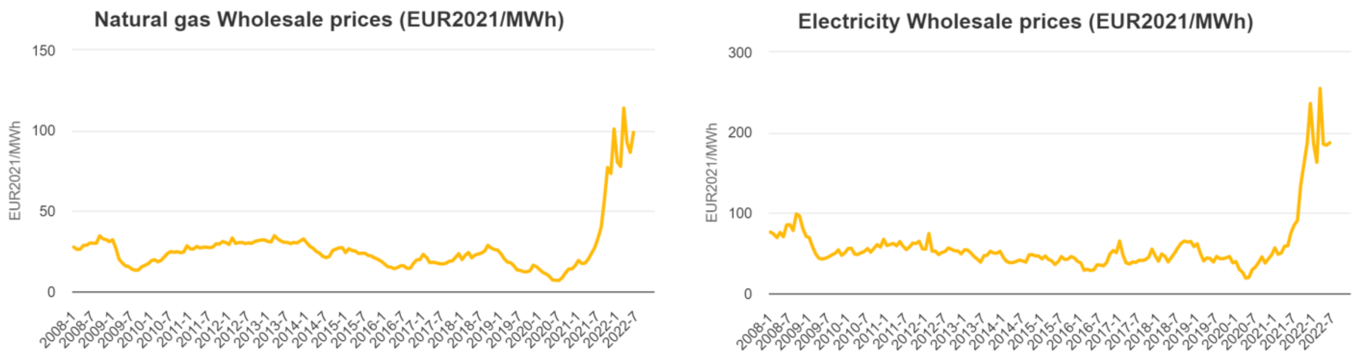


Figure 6. EU energy prices : 2008-2022.

Sources: European Commission, 2024

The nuclear power plant debate in the Turkish energy sector dates back to 1970s in line with the global discussions due to the oil crises experienced in the given era. Without concrete actions for nearly fifty years, the attempts accelerated after 2004 resulting in legal regulations and bilateral agreement between Türkiye and Russia. Year 2012, which was announced as the target commissioning year has been changed several times. The recent declarations of the ministry indicate that the first unit of the Akkuyu Power Plant will be commissioned in the second half of 2024 and all four units would be functioning by 2030. Moreover, recent official declarations imply that the preliminary work for the second power plant planned to be built in Sinop has been accelerated. Considering the 7.2 GW target by 2035 in the national action plan, second BPP which is understood to be realized in partnership with Russia will be targeted to be completed around 2035-2040. Although there are not explicit target values for the capacity of NPPs by 2053; 29.3% share target for nuclear in the total energy mix implicitly corresponds to more than 40 GW nuclear power plants by 2053.

The high amount of nuclear capacity projected in NEP brings with it many questions to answer about its economic and technical feasibility as well as the security problems related to accidents and the cyclical situation of the country. Recent EU reforms may have a positive impact on these projections; however, the countries have not still declared concrete roadmaps on their nuclear programs other than a limited number of ongoing projects. Moreover, the small modular reactors (SMRs) which are claimed to eliminate the financial difficulties and security risks of current technologies have not been matured yet. The modeling results in several studies (e.g., APLUS-Energy, 2021; Şahin et al., 2021) indicate that the transition without a nuclear program would still be technically feasible and plausible.

Policy and Regulatory Frameworks
Establishing clear, consistent, and supportive policy and regulatory frameworks is crucial for driving the transition to net-zero emissions. This includes setting ambitious renewable energy targets, implementing effective carbon pricing mechanisms, and providing incentives for clean energy investments. Addressing these issues requires a comprehensive approach involving collaboration between government agencies, regulatory bodies, industry stakeholders, and civil society to create an enabling environment for sustainable and resilient energy sector development in Türkiye. In this context, although the policy documents such as NEP by MENR, Green Deal Action Plan by MoT, Green Growth Roadmap by TUBITAK or accelerated studies for development of the National Emissions Trading System by the Ministry of Environment, Urbanisation and Climate Change (MEUCC) have determined the general framework for the green transition; political and regulatory uncertainty in the implementation phases may hinder the proposed progress.

High Potential of Renewable Resources
Türkiye has significant untapped renewable energy potential, particularly in wind, solar, and hydropower. A recent study reveals that only the rooftop PV potential in Türkiye is 120 GW (Alparslan & Yıldırım, 2023) which is higher than the current total installed capacity and can satisfy more than three times the current residential electricity demand. Leveraging these indigenous resources can enhance energy security, reduce dependence on imported fossil fuels, and create new economic opportunities in the renewable energy sector. Recent modeling studies (Şahin et al., 2021, 2022) indicate that meeting 2053 net-zero targets would be technically feasible to a large extent, i.e., the emission intensity of the sector is shown to be decreased to 0.019 Mt CO2/TWh (Kat et al., 2024) where this negligibly small value can be further decreased by additional advances in storage or carbon capturing technologies.

Economic Growth and Job Creation
A low-carbon economy would bring with it opportunities for economic growth, innovation, and job creation. Investing in renewable energy projects, energy efficiency measures, and green technologies can stimulate economic activity, attract private investment, and foster entrepreneurship in emerging sectors. A recent study by Acar et al. (2023) for the target year of 2030 shows that the transformation would bring about net benefits in terms of economic growth, job creation, income levels and income distribution. These positive impacts are mainly driven by higher skilled and better-paid jobs. Specifically, the results of the study highlight that the green transformation would generate 85,000 additional jobs in machinery and white goods, 85,000 in installation & repair, 63,000 in automotive and 42,000 in chemicals industry. Besides, a total of 132,000 additional jobs have been observed in services sector. Mining sector, on the other hand, faces with a decrease of 21,000 jobs under the transformation scenario compared to the business-as-usual scenario.

Rapid Penetration of Electric Vehicles
The number of EVs has been increasing steadily and significantly for the last several years, e.g., the number has been risen from nearly 15 thousand at the beginning of 2023 to around 100 thousand by May 2023 (EMRA, 2024). In line with penetration of EVs, the number of charging points (sockets) across Turkey, which was 3,081 at the beginning of 2023, increased to 17,233 as of April 2024. The number of EVs is expected to exceed 3.3 million in the mean scenario and 4.4 million in the high-demand scenario by 2035 (EMRA, 2024). The projections for charging points, on the other hand, are 273 thousand and 348 thousand under the mean and high demand scenarios, respectively.

The projected number of EVs corresponds to at most 2% of the total demand presented in the national energy plan in line with global projections and analysis (Engel et al., 2018). However, this does not imply that the share will be similar beyond 2035. Although the official projections do not extend to 2050, the share of EVs in the fleet would be at least two thirds (even complete penetration would be possible) of the total fleet in line with projections for the other countries. This means a huge increase in the number of EVs. However, the high share of penetration is shown to provide new opportunities via coordinated charging, i.e., an integrated perspective that coordinates residential and transportation demand with the power generation under a modernized grid would help to introduce effective policy instruments.

Green Hydrogen
Hydrogen Technologies Strategy and Roadmap was published in January 2023. It is seen from the roadmap and the NEP that a low rate of increase is foreseen until 2035 followed by a rapid increase after 2035 until 2053, i.e., the projection of 5 GW of electrolyzer capacity in 2035 increases to 70 GW by 2053. As addressed by Yilmaz et al. (2024), Türkiye has significant strengths in prospective green hydrogen market by having a favorable geographical location, abundant renewable potential and ongoing research and execution developments. Hence, becoming a key player especially for supplying to EU countries would be possible under effective subsidy schemes and policies, e.g., investment subsidies for new or upgraded facilities, feed-in tariffs, accelerating hydrogen valley projects, auction mechanisms such as EU Hydrogen Bank, in addition to domestic and foreign investments.

4. Feasibility of Net-Zero by 2053: National Energy Plan, Related Studies, Expected Impacts and An Analysis based on Demand Side Management

This section thoroughly discusses the feasibility of net-zero emissions in the power sector by 2053 under three main headings. First, a snapshot of the official plan to achieve the decarbonization of the power sector is briefly discussed. Next, the studies that present a roadmap or analyzes different pathways using various types of models, i.e., as stand-alone or in an integrated manner, are elaborated. This subsection is followed by the discussion of expected outcomes with reference to the transformation in EU. Finally, one of the key flexibility mechanism to satisfy the feasibility of a reliable grid, i.e., managing the peak load by demand-side management, is presented by employing a sensitivity analysis by smoothing the load curves in different levels.

4.1. National Energy Plan

The most recent National Energy Plan, published by the Ministry of Energy and Natural Resources (MENR) in 2022 (MENR, 2022), mainly focuses on the period 2020-2035 while providing projections beyond 2035 to address 2053 net-zero targets. The plan gives detailed capacity and generation projections until 2035. The target values for 2053, on the other hand, are presented in an implicit manner where inferences can be made based on given aggregate indicators.

	Solar	Wind	Nuclear	Battery	Emissions
NDC 2030	33 GW	18 GW	4.8 GW	2.1 GW	41% decrease compared to BAU
NEP 2035	52.9 GW	29.6 GW	7.2 GW	7.5 GW	NA
NEP 2053	61.4%		> 40 GW	NA	Net-zero

Figure 7. Targets declared in NDC and NEP.

Figure 9 summarizes the targets presented in the revised NDC (Republic of Türkiye, 2023) and NEP targets for years 2035 and 2053. It is seen from this figure that total installed capacity of solar and wind exceeds 50 GW by 2030, 80 GW by 2035. Although only the share of generation is available for 2053; 61.4% of total generation considering the declaration of 4.5% growth rate of electricity demand on the average indicates that the total capacity will exceed 300 GW by 2053. The most distinguishing and striking point in this figure is the significantly large capacity of nuclear power plants. The 40 GW value in the figure is approximated based on the forecast that share of energy generated by nuclear power plants will be 29.3% of the total primary energy.

Remarks regarding to the coal and natural gas are not clear enough in the NEP. The plan definitely addresses that coal phase-out will not materialize but the utilization would gradually decrease based on the carbon prices. Natural gas capacity, on the other hand, is projected to decrease while it would contribute to some extent in case of requirement. Then, it is implied that these fossil-fired plants are assumed to be used as reserve capacity. However, no discussion on how net-zero target would be possible under the existence of these fossil-fired plants.

The plan also gives clues on the electrification of the sectors by projecting the share of electricity in the final energy consumption as 55.6% while this share was 21.8% in 2020. Moreover, as indicated in the previous part, the plan proposes a rapid development on the green hydrogen technology after 2035, i.e., the projection of 5 GW by 2035 increases to 70 GW by 2053.

4.2. Studies on Medium/Long Term Decarbonization Pathways of the Turkish Power Sector

Determining the optimal decarbonization pathways for the countries is a thorny and controversial issue. After the acceleration of global efforts on combating the climate change and concomitant commitments under global agreements, modeling studies, i.e., to determine optimal pathways or to assess the impacts of proposed scenarios, also started to gain momentum. These studies vary in terms of many aspects such as sectoral coverage, geographical coverage, planning horizon, methodology, policy focus etc. Although the studies on the Turkish economy or Turkish power sector used to be limited compared to international benchmarks, comprehensive modeling studies to clarify decarbonization pathways in different aspects and with different perspectives have been conducted in recent years. This section summarizes these studies (Acar et al., 2023; Aksoy et al., 2020; APLUS-Energy, 2021; Kat et al., 2023; Kat, 2023; Kilickaplan et al., 2017; Şahin et al., 2021, 2022; Taranto et al., 2021) in a comparative manner with the NEP.

Kat (2023) developed a Generation Expansion Planning (GEP) model for the Turkish power sector, TR-Power, which takes its roots from (Tapia-Ahumada et al., 2015). The proposed model is a large-scale linear programming model with an objective of minimizing the total cost in the power system under the given demand projections over the planning horizon of 2019-2042 period. The model has hourly resolution, which is the first attempt for the Turkish power system. The model consists of three groups of constraints, i.e., the cost accounting constraints; constraints related to the technical aspects, and the emission accounting/limiting constraints. A detailed disaggregation of costs, i.e., annualized investment costs, start-up/shut-down costs, fuel costs, operational costs and the cost of non-served electricity, are taken into account in the model. Technical aspects such as capacity additions/retirements, generation under capacity and potential constraints, constraints that links the total capacity and available capacity, forecast errors, min/max loads, reserve margins, start-up/shut-down decisions, are represented in the model as realistically as possible. The model has the capability of calculating the total emissions in the sector with the precise emission accounting constraints where the implicit cost of emissions can also be calculated using the shadow prices of the associated constraints. The study examines seventeen scenarios that cover a wide range of policy options, which are also prevalent in most countries in a similar transition. These scenarios include cases with different demand levels, with/without a renewable subsidy scheme, with/without nuclear program and various levels of emission reduction targets. The model results indicate that the share of renewable capacity would be significantly increased, i.e., exceeds 50% by 2032 and 55% by 2042, with a moderate level of additional annual investments, i.e., $887M. Moreover, implicit price of CO2 emissions in the sector is approximated as 17-34 $/per ton CO2 by 2042 under different mitigation paths. Finally, the Wind power has an increasing trend under all scenarios without any subsidy scheme. Another noteworthy result of the model is that the wind is able to increase independently of the subsidies, while the solar technology would need subsidies for a certain period of time.

Another study that also aims to determine the optimal pathway for the transition in the power sector is conducted by Aksoy et al. (2020). The study proposes a market simulation model that makes decisions based on merit order according to the levelized cost of electricity (LCOE) values for the generation technologies. Aksoy et al. (2020) approximates that the total installed capacity will be 129.2–139.3 GW by 2030, where the sum of intermittent technologies, i.e., solar and wind, will reach to 48.0–63.6 GW while total renewable generation would be 43.5%–51.5% under the given scenarios, i.e., market-based, low-demand, local-resources, carbon-cost, and balanced-policy scenarios.

Acar et al. (2023) aims to estimate the social and economic benefits for the transformation in Turkish power system through improved energy efficiency and high penetration of renewable energy. The study covers the period until 2030 where a revised version of the TR-Power model is coupled with a macro-economic model developed following the methodology of applied general equilibrium (AGE). In line with Kat (2023), the paper shows that the power grid can support 55% renewable energy generation (installed capacity of solar and wind sums up to 54.7 GW) by 2030 under the assumption that the projected demand would decrease by 10% due to the proposed energy efficiency improvement. Moreover, this significant increase also brings net socioeconomic benefits nearly 1% of GDP and wage income growth driven by higher skilled and better-paid jobs. The paper also addresses the just transition needs of the proposed transformation and recommends precisely designed regional development programs to compensate the workers currently working in the fossil fuel sector clustered in certain regions of the country.

In parallel to aforementioned studies, Istanbul Policy Center (IPC) published two consecutive reports focusing on the decarbonization of the overall Turkish economy, i.e., achieving net-zero targets, by 2050 (Şahin et al., 2021, 2022), where the former examines the technical feasibility of the transition and the latter reveals the associated costs and benefits of the proposed transition. The purpose of the reports are declared as “to initiate a scientifically based climate policy debate on Türkiye’s new emissions reduction pathway and to contribute to scientific studies that will determine the roadmap for this transformation”. In addition to the comprehensive analysis in the transportation, buildings and industry sectors, a novel approach is employed for the power sector in which two bottom-up power sector models and a macro-economic model are integrated under a single framework. As the first bottom-up model, TR-Power model is extended by the integration of energy storage technologies and additional backstop technologies (off-shore wind and concentrated solar power - CSP) as well as by defining inter-connection constraints. The other bottom-up model is a market simulation (MS) model (Cebeci et al., 2019) that represents the day-ahead wholesale electricity market in Türkiye via the merit order principle. The top-down AGE model, on the other hand, utilizes a consistent macroeconomic/sectoral dataset for Türkiye based on GTAP (Global Trade Analysis Project) 10 Database (Aguiar et al., 2019). The proposed framework examines two main scenarios: Baseline (BS) and Net-Zero Scenarios (NZS). Unlike the studies mentioned above, NZS scenario assumes the coal-phase out by 2035 which results in a higher interim share of renewables and intermittent technologies by 2030, i.e., 63.9% and 34.4%., respectively. Moreover, same figures for 2050 indicates the feasibility of 89.8% and 65.1%, respectively, under the existence of 40 GW energy storage systems and 9.2 GW of inter-connection capacity. The results also show that the total installed capacity will be 158.9 GW and 360.8 GW by years 2030 and 2050, respectively.

Kilickaplan et al. (2017) seeks to answer the question of how the 100% renewable powered electricity can be achieved by 2050. The study that utilizes the LUT energy system model projects the total PV capacity as 387 GW and total wind capacity as 92.2 GW by 2050 under an integrated power scenario. The results show that all demand can be satisfied by renewable technologies where the proposed system relies on more than 750 GWh of energy storage generation. The interim projections for solar and wind, on the other hand, are more than 120 GW and nearly 70 GW, respectively.

Another study that focuses on the transition in the Turkish power sector with the target of phasing out coal power plants is (APLUS-Energy, 2021). The study aims to identify the pathways through the horizon of 2021-2035 that phase-out coal power plants with (coal phase-out scenario) and without the proposed nuclear program (nuclear-free coal phase-out scenario). The results indicate that both paths are feasible under high penetration of solar and wind, i.e., 101.2 GW and 112.1 GW, respectively, and with the help of energy storage capacity of 136 GWh by 2035. Moreover, the analysis claims that the increase in electricity generation cost will be very low such as 2.5 USD/MWh.

As summarized in this section, although there is a limited number of studies on the transition to a clean power sector in Türkiye, they provide in-depth analysis through critical aspects. Although these studies differ in terms of the methodology, planning horizon, scenario definitions and assumptions, there are several issues for which a consensus has been reached:

- 2030 targets addresses in the NDC are reachable both in terms of technical and economical aspects. It is possible to reach even more ambitious levels of intermittent technologies.

- High penetration of intermittent technologies is feasible in two ways: either relying on the continuation of fossil fuel power plants in addition to substantial nuclear power plants (as proposed in NEP) or with significant amount of energy storage systems.

- It can be concluded that the total installed capacity would exceed 150 GW by 2030 (in line with NEP). On the other hand, it is hard to specify a clear projection of installed capacity for 2050/2053 since the assumptions would result in significant deviations due to the difference in capacity factors of the prominent technologies. However, the installed capacity of solar would certainly be several hundred GWs while wind will be around more than 50 GW.

- Unlike the proposed capacity fleet in NEP, the studies do not address the nuclear power as a critical component in the transition.

- The demand projections are generally lower than those provided in the NEP that relies on a 4.5% economic growth until 2053.

4.3. Expected Impacts within the Framework of the Green Transformation in EU

In this subsection, the EU has taken as a reference case in order to understand the expected interim impacts of pursuing decarbonization in the power sector. The reasons of selecting EU for the benchmark can be summarized as follows:

- EU introduced a range of instruments and policies to achieve a green transformation in the power sector, aiming to reduce GHGs, increase renewable energy deployment, and enhance energy efficiency. Some of them are first major attempts such as the EU ETS.

- EU has made substantial progress in reducing coal dependency and increasing renewable energy sources although the progress is not even across the members or has taken steps back on some issues such as nuclear power.

- EU has also established ambitious targets under the Green Deal, aiming for net-zero emissions by 2050 and significant intermediate targets for renewable energy adoption.

- Leading in renewable energy technologies has positioned some EU countries as exporters of green technologies and services, boosting their economies.

Drawing lessons from the EU's transformation, Turkey can leverage technological advancements and policy frameworks to accelerate its transition to a sustainable energy future. However, in order to estimate the potential effects of such a transition, it would be useful to have a closer look at the interim impacts observed in EU. Some of these critical impacts can be seen below:

- The studies indicate a positive impact on employment at the global level under a transition to renewable technologies (Pai et al., 2021). In line with this finding; net positive impacts on employment at EU level has been observed with differences at national or regional level (Czako, 2020).

- Transition results in increases in regional GDP or value-added for nearly all regions (Stainforth et al., 2021). One of the reasons of this result is the reduction in imported fossil fuels, which would lead to more striking benefits for Türkiye.

- Especially in countries that undergo a sharper and faster transformation, significant increases in electricity prices have been observed for the residential consumers. Moreover, analysis showed that these price increases have a substantial impact on low-income households more than high-income households and caused negative impacts in income distribution (Priesmann et al., 2022). In line with EU case, Acar et al. (2023) indicate an increase in market clearing price by 2030 under the transformation scenario for Türkiye; however, the rate of increase (less than 20%) is quite lower than the 71% experienced by EU during 2003-2018 period (Priesmann et al., 2022).

4.4. Impact of changes in load curves

Previous sections clearly revealed that achieving net-zero emission targets cannot be feasible unless a certain amount of fossil/nuclear backup technologies or flexibility mechanism, i.e., energy storage technologies, cross-border transmission capacities, demand side management strategies, exist in the grid. The former requires carbon-capturing technologies in case the remaining capacity is of fossil type. Otherwise, a substantial amount of capacity is required as nuclear power plants. For the latter, on the other hand, again a large amount of energy storage technologies or cross-border transmission capacities would be needed. All of these situations pose significant risks, e.g., delay in the economic and technical feasibility of proposed technologies such as carbon-capture and energy storage, risks related to the delays on the commissioning of proposed nuclear plants etc. Then, a plausible solution to decrease the need for these technologies would be to introduce policies to decrease the peak load demand such as demand-side management instruments. This approach, considering the expected widespread use of electric vehicles and the development of smart grid technologies; would be easier to implement in the future than today. However, since it is not straightforward to set plausible targets to assess the impacts of demand-side management, a kind of sensitivity analysis is proposed to investigate these impacts, i.e., the version of the TR-Power model developed within (Şahin et al., 2021, 2022) is run under load curves smoothed to different levels while keeping the demand projections unchanged. The proposed smoothing procedure is applied as follows in (Eq. 1):

$$\hat{L}_{th} = L_{th} - \alpha \cdot \left(L_{th} - \overline{L}_t\right) \qquad \forall h \in \{1, \dots, 8760\}, \forall t \in T \qquad \text{(Eq. 1)}$$

The smoothing expression decreases the loads at a given hour h of year t (L_th) by α percent of its deviation from the mean hourly load in the same year if it is above the mean load (¯L_t). Loads below the mean load, on the other hand, are increased by α percent of its deviation from the mean load.

As mentioned above, the proposed smoothing scheme guarantees that the sum of smoothed values over a given year is equal to the original total demand for the same year as shown through (Eq. 2)-(Eq. 6). Note that 8760 (365 days x 24 hours/day) is the number of hours in a year. (Eq. 2) gives the expression for the hourly mean load for a given year. Annual total smoothed load in the given year is expressed in (Eq. 3) as the sum of hourly smoothed loads where the same expression is written in disaggregated form in (Eq. 4). In (Eq. 5), (Eq. 4) is rewritten using the equality in equality (Eq. 2). Finally, (Eq. 6) demonstrates the equality of the original total annual load and the smoothed annual total load.

$$\overline{L}_t = \frac{\sum_1^{8760} L_{th}}{8760} \rightarrow \sum_1^{8760} L_{th} = 8760 \cdot \overline{L}_t \qquad \forall t \in T \qquad \text{(Eq. 2)}$$

$$\sum_1^{8760} \hat{L}_{th} = \sum_1^{8760} [L_{th} - \alpha \cdot (L_{th} - L_t)] \qquad \forall t \in T \qquad \text{(Eq. 3)}$$

$$\sum_1^{8760} \hat{L}_{th} = \sum_1^{8760} L_{th} - \alpha \cdot \sum_1^{8760} L_{th} + \alpha \cdot \sum_1^{8760} \overline{L}_t \qquad \forall t \in T \qquad \text{(Eq. 4)}$$

$$\sum_1^{8760} \hat{L}_{th} = \sum_1^{8760} L_{th} - \alpha \cdot 8760 \cdot \overline{L}_t + \alpha \cdot 8760 \cdot \overline{L}_t \qquad \forall t \in T \qquad \text{(Eq. 5)}$$

$$\sum_1^{8760} \hat{L}_{th} = \sum_1^{8760} L_{th} \qquad \forall t \in T \qquad \text{(Eq. 6)}$$

α values are taken as 25% and 50%, and are assumed to increase linearly through 2020-2050 period. The values correspond to 6.87% and 13.75% decrease in peak loads, respectively, by 2050. Loads become more stable and oscillate in a narrower interval as α increases. Figure 10 illustrates the smoothed load profiles in addition to the original one for the whole year while Figure 11 presents the profile on a specified day. Note that the extreme case (where α equals to 1) would result in a single constant line in Figure 10, i.e., mean value of the loads over 8760 hours.

The main aim of this analysis is to reveal the impact of the smoothing on the installed capacities where two types of analysis are conducted for these purposes. First, the change in installed capacities of the generation fleet is analyzed under the smoothed load profile while keeping the storage capacity constant. For this part, three scenarios reflecting the proposed three levels of smoothing are denoted as s25a and s50a. In the next step, it was examined that how much the storage technologies needed by the network, which involve both economic and technological uncertainties can be reduced to obtain feasible pathways under an additional scenario (s50b) with α=0.50 and lower levels of energy storage.

Figure 8. Original normalized loads and smoothed loads to different degrees: annual values under 25% and 50% smoothing.

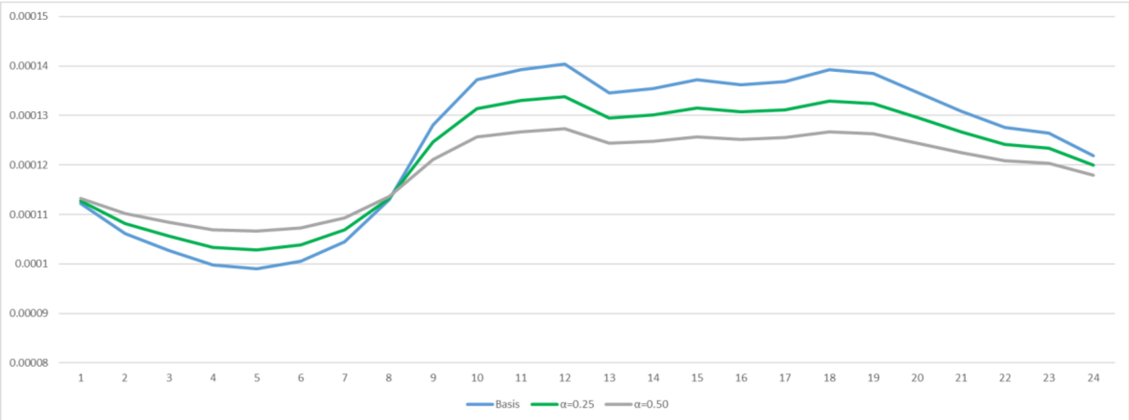


Figure 9. Original normalized loads and smoothed loads to different degrees: values for a specific day under 25% and 50% smoothing.

Figure 12 illustrates the percentage change in installed capacities by 2050 under the proposed smoothing levels. The values in this figure are the deviations from the original net-zero pathway in (Şahin et al., 2021). Note that the smoothing of the load profiles have an impact on only the solar and natural gas capacities. The reason lying behind this observation is that the renewable potential other than solar have been fully utilized after2035. Then, the increasing demand after 2035 is mainly met by the additional solar plants and the base capacities, i.e., natural gas plants, that backup these additional solar plants. An important remark about this analysis is that the change in natural gas installed capacity does not have an impact on the generation by these plants in line with the analysis in (Kat et al., 2024) that reveals the low utilization of natural gas plants which are idle nearly two thirds of the time. Besides, the curtailment rate decreases to 7.3% and 4.7% under s25a and s50a, respectively, from 9.1% of the NZS.

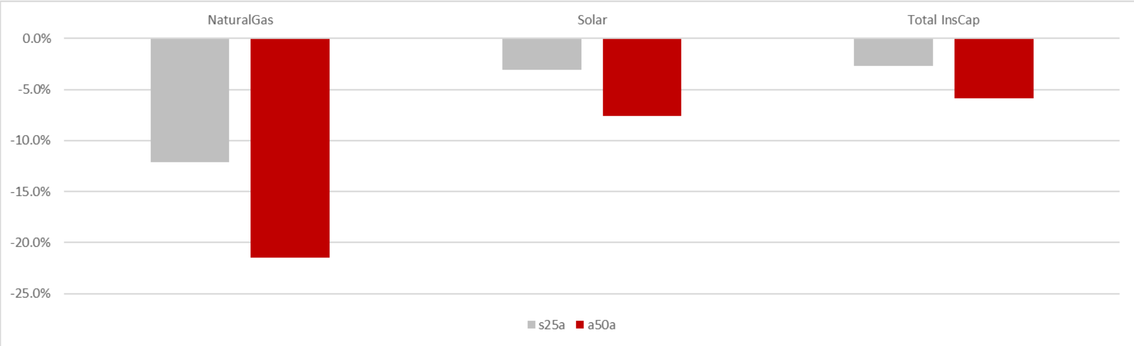


Figure 10. Change in installed capacities under $s25a$ and $s50a$ with respect to NZS : %.

The second type of analysis, i.e., investigating the minimum required storage capacity for understanding the extents of the grid, shows that a 14.3% decrease (from 39.6 GW to 33.6 GW) would be possible under s50b. However, this scenario results in a higher level of natural gas plants (27.6 GW) compared to s50a. Moreover, there is a sharp increase in solar capacity with a high curtailment rate.

The proposed analysis is important to understand the extents of the grid and to approximate an upper bound on the potential demand-side management policies. For the analysis to be meaningful, concrete policies such as peak load shaving strategies (Uddin et al., 2018) must be discussed as further explained in the conclusion section.

5. Conclusion and Policy Recommendations

The threats created by human activities, which are responsible for the climate change, make the earth about to hit an irreversible point of no return thus need urgent actions. As a party to the global efforts to combat climate change, Türkiye has proposed net-zero emission targets aiming for the year 2053 where the power sector would be the leading component of the proposed transformation. This report provides an overview of the sector in terms of economic and environmental aspects, and discusses the policy landscape relevant to structurally transforming the sector including the key challenges and opportunities. Besides, a critical review and evaluation of the various pathways proposed in recent studies is presented comparatively with the recent national energy plan with an additional analysis that examines the impact of smoothing the load profiles. Considering all of these aforementioned aspects and analysis, the rest of the section addresses the relevant policy recommendations.

First, continuation and enhancement of the policies that support the development of renewable energy sources as well as storage technologies are crucial. This includes maintaining encouraging feed-in tariffs (offering guaranteed and above-market price via long-term contracts), implementing transparent and efficient auction mechanisms, and providing incentives for renewable energy investments. Moreover, although there has been a significant progress in unlicensed production pursuant to updates at the beginning of 2023, a substantial part of this potential remains idle, e.g., a recent study reveals that the rooftop PV potential (i.e., solar panels mounted on the rooftop of a residential or a commercial building or a structure) is 120 GW (Alparslan & Yıldırım, 2023). Then, a more well-defined regulatory framework is needed to encourage and operationalize new business models, e.g., aggregation of consumers or cooperation among consumers, to overcome the existing barriers and limitations such as the perception that costs are high, lack of finance and information and complex institutional procedures. Then, promoting electrification and decentralization of the energy system by encouraging the deployment of distributed generation, micro-grids, and renewable energy technologies at the local level is utmost importance.

Another crucial aspect in effectively supporting the proposed transformation is continuation of investments in upgrading and expanding the power infrastructure, including transmission and distribution networks, to accommodate the integration of renewable energy sources, to enhance system reliability and to have a ready infrastructure for the increasing cross-border transmission capacities. Moreover, the infrastructure would also play a crucial role in implementing smart grid technologies and digitalization initiatives to optimize grid operations, enable real-time monitoring, and facilitate demand response programs. Additionally, considering the fact that extreme weather events have been significantly increasing in Türkiye (MEUCC, 2023) and high earthquake risk that was recently painfully experienced once again; resilience planning and investments to mitigate risks associated with extreme weather events and disasters should also be taken into account.

Regardless of the need for the transition to clean technologies under the commitments due to the international agreements, such a transition had become inevitable for Türkiye to alleviate the impacts of heavy dependency on imported energy. As mentioned in the previous pages, this high dependency in addition to limited and long-term supply agreements resulted in energy security risks in the first years of liberalization in the electricity markets in early 2000s. Owing to the abundant potential of solar and wind in addition to the hydro resources that Türkiye has been already utilizing for a long time, the progress experienced in recent years helped to decrease the severity of energy security issues. However, the import dependency problem is still on the table unless there exists a significant share of domestic production for the equipment needed in renewable power plants. In this context, the developments in line with the recent progress in domestic production of PV cell and module should go on continuously with increasing efforts. Similarly, current efforts on encouraging and prioritizing research & development activities and domestic production of promising technologies including energy storage systems and hydrogen should gradually increase. Besides, reorienting employment towards the sectors that would benefit from the clean transition is crucial to alleviate the impact of job losses in the sectors those will be phased-out or will shrink on the way of a net-zero economy.

The analysis conducted to reveal the impact of potential demand-side management policies shows that any improvement decreasing the peak load would directly decrease the sole remaining fossil power plants, i.e., the natural gas capacity. As demonstrated in (Kat et al., 2024), this capacity is idle in most of the hours and It is kept within the scope of the capacity mechanism to be activated only at certain times of the year when demand is very high or in case of technical problems that may occur in the system or in case high fluctuations occur in the intermittent renewable generation. Then, this issue, i.e., demand-side management, which is also treated in a superficial manner in the national energy plan, needs introduction of concrete policies and strategies such as peak load shaving (Uddin et al., 2018), i.e., smoothing the load curve by eliminating short-term spikes in demand. On the other hand, the analysis also implies that smoothing the load profiles would not provide significant decrease in storage capacities. Besides, this limited decrease in storage capacity would bring with it other disadvantages such as sharp increase in solar capacity with higher curtailment rates. While such demand side management outcomes do not propose a complete solution for the grids with high penetration of intermittent technologies, they would play a key role as a flexibility option in case the flexibility on the supply-side is very limited. In this study, the proposed smoothing procedure changes the shape of the load profile while keeping the total load constant. It should be noted that decreasing the peak load would be much more effective with energy efficiency policies, e.g., decreasing transmission and distribution losses in the grid, promoting energy efficient appliances and equipment both in residential and industrial use or promoting improvements in space heating/cooling, which decrease the total load.

By focusing on the aforementioned policy recommendations, Türkiye can accelerate its transition towards a sustainable, reliable, and competitive power sector that meets the country's growing electricity needs while addressing environmental concerns in line with its Paris Agreement goals.

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