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RESEARCH ARTICLE

A Low-Carbon Pathway for the Turkish Electricity Generation Sector

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Abstract: Türkiye is a developing economy, so its population, economic activities, and overall prosperity are increasing. However, economic and social development leads to an increase in greenhouse gases, especially CO_2 emissions. Türkiye's emissions need to be reduced. The aim of this paper is to analyze the decarbonization options of Türkiye's electricity generation sector. First, the main drivers (Gross Domestic Product, population, energy and carbon intensity of primary energy sources, etc.) of CO_2 emissions of electricity between 2008 and 2020 are analyzed. The methodology of this inquiry is based on the Logarithmic Mean Divisia Index. Second, Türkiye's climate policy for the decarbonization of the electricity sector is analyzed. For this purpose, electricity supply and demand projections are made. Once these projections are completed, decarbonization policy options are evaluated in the Low Emissions Analysis Platform model. Mitigation potential and costs for CO_2 emissions will be calculated according to the policy options. The projections will be extended until 2053 because Türkiye has declared a net zero emission target by 2053. The electricity sector will have a significant emission reduction and decarbonization potential, so its contribution to the overall net zero emission target is crucial for Türkiye's long-term low emission development strategy. In 2053, 379,484 metric tons of emissions can be reduced for the net zero scenario with renewable energy and energy efficiency measures. The annual cost of this reduction is 16,872 million USD, and the cost of emission reduction per ton is estimated to be 44.46 USD.

Keywords: low-carbon development, LMDI, electricity emissions

1. Introduction

Industrialization, rapid urbanization, population growth, and economic growth have led to an increase in energy demand and greater use of natural resources. With the industrial revolution, the consumption of fossil fuels has increased to meet the increasing energy demand and accordingly, the concentration of greenhouse gas (GHG) emissions has increased rapidly in the atmosphere (Intergovernmental Panel on Climate Change, 2007). In addition, increasing agricultural activities to meet the needs of the increasing population has also led to an increase in GHG emissions. Changes in land use have reduced the earth's reflection (albedo) of short wavelengths from the sun, and deforestation has reduced the amount of sinks that absorb GHG emissions in the atmosphere (Houghton, 2009). All these elements have disrupted the natural climate system. Global warming has increased due to the increasing greenhouse effect on a global scale. Due to the natural ecosystem as a whole, global climate change has caused not only global warming but also acidification of the oceans, drought, extraordinary weather events, irregular, sudden and rapid precipitation, and loss of biodiversity (Intergovernmental Panel on Climate Change, 2014). The first steps to combat climate change on a global scale began to be taken in 1988 with the cooperation of the World Meteorological Organization and the United Nations Environment Program, and the Intergovernmental Panel on Climate Change (IPCC) was established with the efforts of these organizations (Intergovernmental Panel on Climate Change, 2020).

Türkiye has continuously participated in global climate change negotiations starting from the Intergovernmental Negotiations Committee period. Being among the founding countries of the Organization for Economic Cooperation and Development (OECD), Türkiye continues to state that it is not a developed country under the UNFCCC although it is a member of the OECD. Türkiye's position in global climate policies and the regime is in line with the principles of historical responsibilities and common but differentiated responsibilities and relative capabilities. However, an unforeseen classification while preparing for the UNFCCC at the beginning of the 1990s prevented Türkiye from expressing itself adequately under the UNFCCC and pushed Türkiye into a country that constantly explains its status due to the country class it is negotiating with. In addition, Türkiye's discourse has lost its effectiveness in the dynamism of the global climate regime, as it constantly reminds us that Türkiye has different and special conditions from other countries. On the other hand, although Türkiye's participation in climate negotiations has increased in quantity, it has had ups and downs in quality. Although Türkiye has taken steps to transform active participation in the negotiations from quantity to quality, this situation has not been continuous.

Türkiye declares itself as a developing country in climate change negotiations. With Türkiye's growing population and growing economy, energy demand is rising rapidly (SBB, 2019). It has to use

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*Corresponding author: Izzet Ari, Social Sciences University of Ankara, Türkiye. Email: izzet.ari@asbu.edu.tr fossil fuels, primarily coal, lignite, and natural gas to meet its energy demand (MENR, 2022b). Although a significant acceleration has been gained in the use of renewable energy sources in recent years, fossil fuels dominate the total primary energy supply. Natural gas and oil imports are increasing to meet the energy demand, especially in electricity generation, transportation, buildings, and industry sectors (MENR, 2022b). This situation causes the Turkish economy to produce based on imports, to increase its dependence on fossil fuels, and to emit high levels of GHG emissions. In 2022, Türkiye announced its GHG emissions inventory and the emissions 523.9 million tons and increased (TURKSTAT, 2022). The determining factors in this increase can be stated as economic growth, population growth, the continuation of the industrialization process, and the fact that technological developments have not yet been widely reflected in the production processes. On the other hand, consumption habits change and more emission-intensive individual and social activities become widespread depending on the increasing level of welfare. Türkiye ratified the Paris Agreement in 2021 and announced its new or updated Nationally Determined Contributions (NDC) according to deviation from the business-as-usual (BaU) scenario. The First NDC of Türkiye was reducing GHG emissions by up to 21% from the BaU scenario. The updated NDC increase the emissions mitigation commitment by 41%. Besides, Türkiye politically declared its net zero emissions target by 2053. Therefore, Türkiye is expected to reveal its GHG emissions reduction potential in all sectors.

The transition toward the low-carbon development model is not only the agenda of the UNFCCC and the Paris Agreement. It is also supported by the OECD, the International Energy Agency (IEA), and multilateral development banks such as the World Bank (Fay et al., 2015; Organisation for Economic Cooperation and Development, 2013, 2015; UNFCCC, 2015). The main motivation of this model is tackling global climate change without compromising on achieving sustainable development. Particularly, alleviating poverty and unemployment with sustainable production and consumption patterns will contribute to this model. Since each country has unique conditions, there are no uniform policy bundles and scenarios. While low-carbon development allows countries to reduce GHG emissions, the cost of this should be estimated and the realization of the model for the energy system should be investigated. The aim of this paper is to analyze the drivers of emissions increases in electricity generation and to estimate the reduction potential and cost of the sector to a low-carbon development model.

2. Literature Review

The low-carbon development model has emerged frequently in recent years (Blumberga et al., 2014; Gu et al., 2015; Institut du développement durable et des relations internationales, 2017; Organisation for Economic Cooperation and Development, 2015; Sjoerd et al., 2015). This model aims to reduce GHG emissions in production and consumption chains in many sectors, especially in the electricity generation sector (Fragkos et al., 2017; Pearson & Foxon, 2012; Yao et al., 2015). Within the model's scope, the transition from higher carbon-intensive sources and technologies to lower carbon and zero emissions intensities are the main objectives (Bodnar et al., 2018; Foxon, 2011; Rüdinger et al., 2018). Using renewable energy sources and nuclear energy, the preference for natural gas with a lower carbon intensity instead of coal and lignite is the primary measure in the initial steps (Intergovernmental Panel on Climate Change, 2011; Organisation for Economic Cooperation and Development, 2015). According to Bekun (2022), there is one-way causality among renewable energy consumption and CO_2 emission, economic development, and energy investment. Some other studies focus on essential introducing advanced technology for mitigation of environmental impacts of economic activities (Fatai Adedoyin et al., 2021). The second step for the model is to ensure energy efficiency at every stage, from energy production to consumption. For example, technological changes in the electricity generation, optimizing distribution and transmissions lines and renewing transformers, promoting the use of efficient products and vehicles on the demand side can increase overall energy efficiency. (Edenhofer et al., 2011, Intergovernmental Panel on Climate Change, 2015). The third and final stage is using the carbon capture and storage (CCS) option in the cement, iron, steel, and chemical sectors, which is not technically possible to reduce the carbon intensity to zero with the existing technology and innovation opportunities. Although the CCS method has not completed its technology readiness level, it is being applied by countries at pilot scales. Scientific research is ongoing on this method to increase the risks in storage, the high cost, and the fact that it has not yet reached the level of technological maturity. On the other hand, the first and second priorities for low-carbon development, such as fuel and technology change and the handling of energy efficiency in the life cycle, are widely used (Edenhofer et al., 2011, Intergovernmental Panel on Climate Change, 2015).

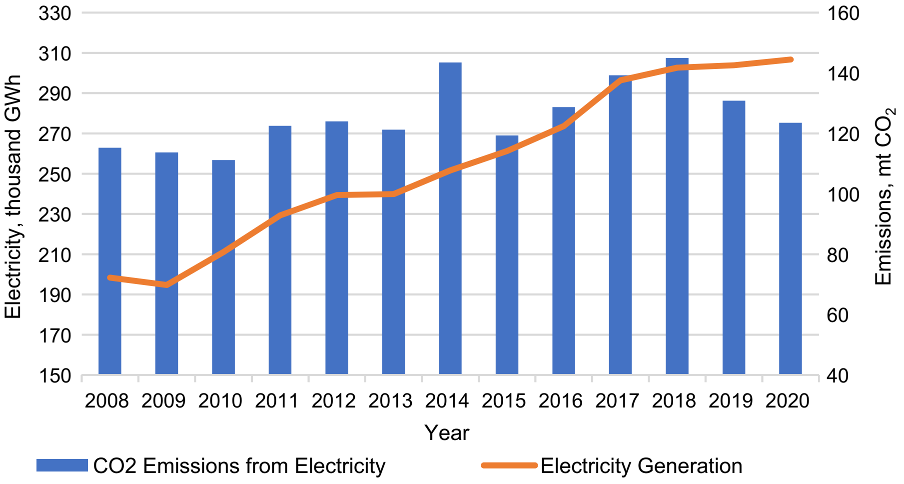
Before conducting low-carbon development measures in the power sector, drivers of emissions need to be determined. The Logarithmic Mean Divisia Index (LMDI) is a measure of the intensity of changes in a variable over time, taking into account the contribution of each subperiod to the overall change. It is often used in economics to measure changes in energy use or emissions (Fan & Lei, 2016; Hoekstra & van den Bergh, 2003; Wang & Wang, 2019). There have been several studies that have used the LMDI method to analyze the relationship between electricity generation and CO_2 emissions. The LMDI method has been widely used in studies on CO_2 emissions from electricity generation as it allows for a detailed analysis of the factors contributing to emissions and can provide useful insights for policy-makers in reducing emissions (Isik et al., 2020).

LEAP (Long-range Energy Alternatives Planning) model is used to evaluate and compare energy and emission scenarios. It is often used to assess the potential impacts of different policy options on energy use and emissions in the power sector. The LEAP program is widely used worldwide for electricity demand and supply projections, such as projecting the GHG emissions generated by different policy options of the Japanese energy sector (Takase & Suzuki, 2011), analysis of China's energy-based low-carbon development scenarios (Zhou et al., 2014) and modeling the reduction of CO_2 emissions in electricity sector (Cai et al., 2007), modeling Lebanon's electricity sector with alternative scenarios (Dagher & Ruble, 2011), making long-term supply-demand forecasts for Pakistan's electricity generation (Mirjat et al., 2018), evaluation of long-term alternative scenarios of the Panamanian electricity sector (Kim et al., 2017), and development and evaluation of renewable energy policies of Bulgaria (Nikolaev & Konidari, 2017).

3. Material and Method

Electricity generation of Türkiye increased from 194,736 to 306,703 GWh between 2008 and 2020 as Figure 1 shows (UNFCCC., 2022). CO_2 emissions from fossil fuel combustion are gathered from the National GHG Emissions Inventory report of Türkiye (TURKSTAT, 2022). The CO_2 emissions from electricity generation fluctuated for the same period, but the overall trend increased. For example, it was more than 115 million tons (mt) in 2008, 144 mt in 2018 (as a maximum level), and 123 mt in 2020. The electricity sector is one of Türkiye's major emission sources. In 2020, emissions from electricity generation, which amounted to 130.7 $MtCO_{2e}$, had a share of 25.1% in total emissions. Since 2018,

Figure 1
Electricity generation and its related CO_2 emissions between 2008 and 2020



emissions from electricity generation have decreased in absolute value. Generation from renewable energy sources can explain this decrease.

Within the scope of the article, driving factors affecting the emission structure of the Turkish electricity sector will be investigated between 2008 and 2020. The reason for selecting 2009 as a starting year is Türkiye's ratification process of the Kyoto Protocol. The decomposition analysis method has been selected since it is widely used in determining the factors affecting CO_2 emissions. This method is most often used to decompose electricity and other energy sectors. Under the decomposition analysis, index decomposition analysis (Ang, 2004; Hoekstra & van den Bergh, 2003) which has been widely performed to detect CO_2 emissions from electricity generation (Huang et al., 2019), provides a sub-method, namely LMDI.

In the LMDI method to be used for Türkiye, the change in the control year and target year will be examined (equation (1)).

$$\Delta C_{tot} = C^T - C^0 \tag{1}$$

In equation (1), CT indicates CO_2 emissions in the target year, and C_0 indicates emissions in the control year. Then five main factors are identified that can effectively change CO_2 emissions. These are: ΔC_g, ΔC_p, ΔC_m, ΔC_u, ΔC_e (Ang, 2004; Hoekstra & van den Bergh, 2003; Wang & Wang, 2019). These factors are expressed as additive decomposition. Emissions for 1 year are based on the change of factor five by representation in equations (2) and (3).

$$\Delta C_{tot} = C^T - C^0 = \Delta C_g + \Delta C_p + \Delta C_m + \Delta C_u + \Delta C_e \tag{2}$$

First factor is ΔC_g. It is based on effects of absolute change on electricity generation for monitoring electricity demand of countries related to population growth, economic and social activities. ΔC_p, as shown in equation (5), captures the change in fossil fuel intensity. It represents the effect of non-fossil-based energy source penetration on electricity generation. Second factor is ΔC_p capturing the change in fossil fuel intensity during the electricity generation. This factor reflects penetration of renewable energy sources for electricity generation in the country. Third factor is ΔC_m. It explains sharing any fossil fuel as a primary energy sources in total fossil fuel mix of the electricity generation. Fourth factor is ΔC_u. It aims to follow the effects of technological improvement and efficiency increase while generating electricity as an output and used fossil fuels as an input. The final factor is ΔC_e, which represents change of emissions factor of fossil fuels (Isik et al., 2021).

In the LMDI, variables (G, p, m_i, u_i and e_i) are:

- C: CO_2 emissions from the combustion of fossil fuels
- G: total electricity generation
- Q: electricity generated by fossil fuel using thermal power plants
- F: fuel consumption
- p (Q/G): proportion of electricity generated from fossil fuels
- m_i (Q_i/Q): ratio of electricity generated from fossil fuel (i) to total electricity production
- u_i (F_i/Q_i): electricity generation (i) based on fossil fuel (i)
- e_i (C_i/Q_i): the emission factor of fossil fuel (i)

$$C = \sum\nolimits_i G\frac{Q}{G} \times \frac{Q_i}{Q} \times \frac{F_i}{Q_i} \times \frac{C_i}{F_i} = \sum\nolimits_i Gpm_iu_ie_i \tag{3}$$

$$\Delta C_G = \sum\nolimits_i \frac{(C_i^T - C_i^0)}{(lnC_i^T - lnC_i^0)} ln\left(\frac{G^T}{G^0}\right) \tag{4}$$

Change in total electricity generation

$$\Delta C_p = \sum\nolimits_i \frac{(C_i^T - C_i^0)}{(lnC_i^T - lnC_i^0)} ln\left(\frac{p^T}{p^0}\right) \tag{5}$$

Change in the share of fossil fuels in electricity generation

$$\Delta C_m = \sum\nolimits_i \frac{(C_i^T - C_i^0)}{(lnC_i^T - lnC_i^0)} ln\left(\frac{m_i^T}{m_0^T}\right) \tag{6}$$

Change in the share of fossil fuel (i) in electricity generation from fossil fuels

$$\Delta C_u = \sum\nolimits_i \frac{(C_i^T - C_i^0)}{(lnC_i^T - lnC_i^0)} ln\left(\frac{u_i^T}{u_0^T}\right) \tag{7}$$

Input/output share for fossil fuel (i)

$$\Delta C_e = \sum\nolimits_i \frac{(C_i^T - C_i^0)}{(lnC_i^T - lnC_i^0)} ln\left(\frac{e_i^T}{e_0^T}\right) \tag{8}$$

Emission factor $c(i)/f(i)$

The second objective of this study is to explore emissions mitigation in the electricity sector between baseline, in other words, business as usual (BaU) and low-carbon development policies. According to the policy options, the reduction potential and cost for CO_2 emissions will be calculated. Low Emissions Analysis Platform (LEAP) will be used to achieve this goal. LEAP is an integrated, scenario-based modeling tool that can monitor energy consumption, production, and resource extraction across all sectors of an economy. Both the energy sector and the non-energy sector are used to account for GHG emissions sources and sink areas. The LEAP program was chosen because it allows the use of a comprehensive database and provides the opportunity to analyze energy supply and demand projections in terms of cost, environmental impact, and GHG emissions.

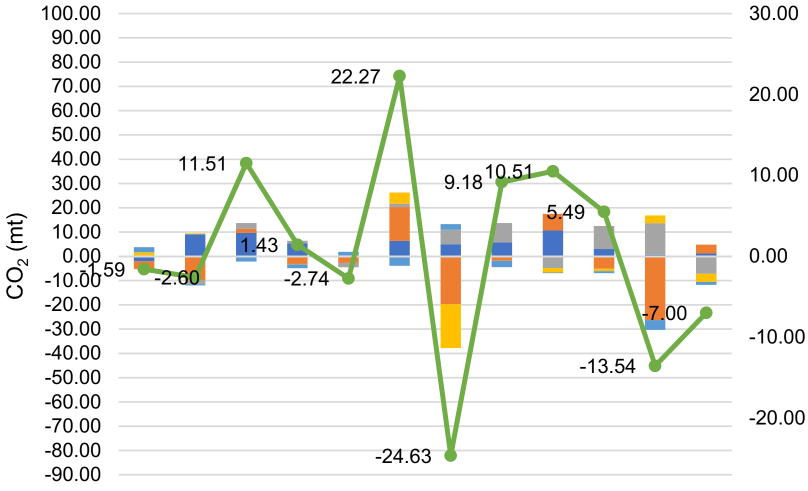
For data collection, energy-related data such as final energy consumption, electricity installed capacity and generation, electricity prices, the calorific value of coal, lignite, natural gas, oil, and socio-economic data (GDP and population) are gathered from TURKSTAT and Turkish official databases located in line ministries. Technical coefficients and variables are obtained from the LEAP databases, and capacity credit, capacity factor, and merit order for power plants are discussed with energy experts of public and private institutions.

4. Results and Discussion

The reason behind this fluctuation is explained in Figure 2. Five decompositions of drivers (ΔC_g, ΔC_p, ΔC_m, ΔC_u, ΔC_e) on CO_2 emissions have different impact and magnitudes. For ΔCG, except for 2009, the global financial crisis year, electricity generation continuously raised and has an increasing effect on emissions. ΔC_p has increasing and decreasing effects on emissions because of the changing share of fossil fuel inputs in electricity generation. ΔC_p has a mitigation effect of 45.79 mt emissions between 2008 and 2020. Particularly between 2014 and 2015, ΔC_p is negative because of increased precipitation, new hydro installed capacity, and wind- and solar-based electricity generated started to increase. Similarly, ΔC_m has a fluctuating role in emissions. Still, it has an increasing effect of more than 25 mt for the same period because the share of primary energy sources among fossil fuels came from more carbon-intensive (i.e., imported coal and lignite) than before. On the other hand, there has been energy efficiency improvement in fossil fuel-based power plants ΔC_u. Even though there has been a lack of efficiency improvements in some years, the efficiency improvement has contributed to more than 15 mt emissions reduction. Last but not least, changes in emission factors (ΔC_e) have positive and negative effects on emissions reduction. For this driver, the reduction of emissions factors contributed to almost 11 mt. Emissions from electricity generation increased by only 8.3 mt between 2008 and 2020.

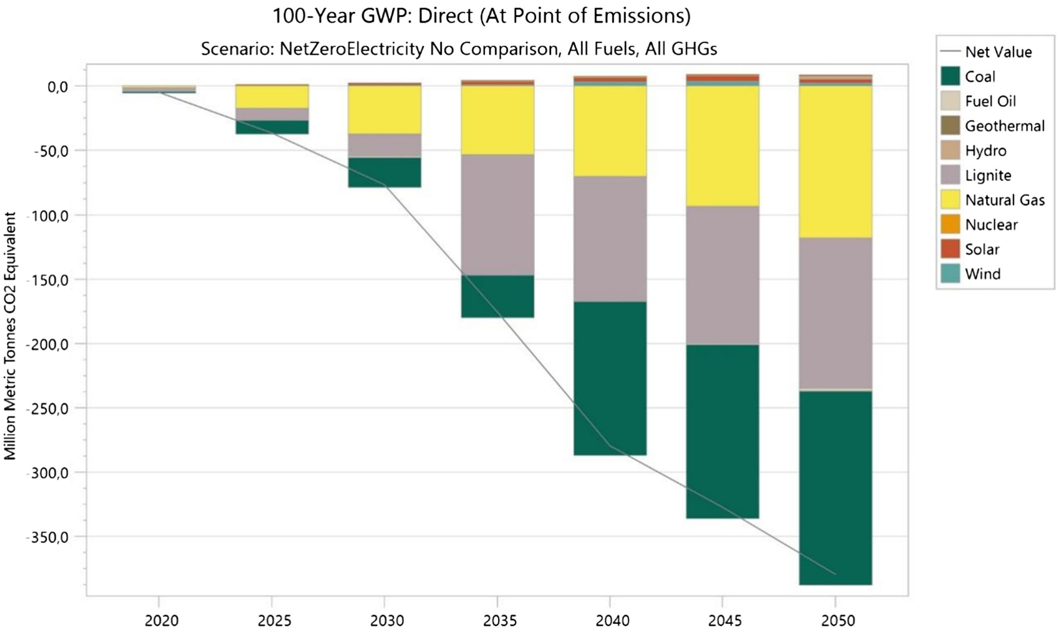
301,100 GWh of electricity was generated in Türkiye in 2019. According to the Ministry of Energy and Natural Resources projection, Türkiye's electricity demand will be 591 thousand GWh in 2040 (MENR, 2022a). The projected electricity generation is extrapolated by 2053 to obtain demand for the final year. Two scenarios (baseline and net zero electricity) are conducted in the LEAP. Assumptions of baseline, in other words, BaU scenario, are based on reducing electricity transmission and distribution losses by 10% by 2053. Besides, using primary energy sources (both renewable and non-renewable) by 2053 is accepted as the 2019 ratio. Assumptions of the net zero electricity scenario focus on further reduction in electricity transmission and

Figure 2
Decomposition of CO_2 emissions in electricity generation between 2008 and 2020



	2008-2009	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020
ΔCe	2.07	-0.50	-1.70	-1.61	1.50	-3.97	2.29	-2.62	-0.27	-0.82	-4.05	-1.17
ΔCu	1.67	0.38	-0.46	-0.14	0.07	4.61	-18.0	-0.13	-1.81	-1.08	3.22	-3.34
ΔCm	-0.10	-1.61	2.43	1.06	-1.81	1.37	6.01	7.97	-4.86	9.51	13.05	-7.26
ΔCp	-3.13	-9.92	1.65	-3.18	-2.74	13.96	-19.7	-1.74	6.85	-5.08	-26.3	3.61
ΔCg	-2.10	9.05	9.60	5.30	0.25	6.31	4.92	5.71	10.60	2.96	0.54	1.16
CO2 Change	-1.59	-2.60	11.51	1.43	-2.74	22.27	-24.6	9.18	10.51	5.49	-13.5	-7.00

Figure 3
Interpretation of the mean scale for belief, concern, and practice



distribution losses (5%), and utilization of economically feasible renewable energy sources in Türkiye. In that regard, hydro (50,000 MW), biogas and waste (20,000 MW), wind (30,000 MW), solar (50,000 MW), and geothermal (10,000 MW) will be utilized for generating electricity. The remaining demand will be supplied by fossil and nuclear energy sources. Figure 3 presents the emission difference between baseline and net zero scenarios. Baseline and net zero's Emissions are estimated to be 396.015 and 16.531 mt by 2053. Therefore, 379.484 mt of emissions can be mitigated in 2053.

The additional cost of the net zero scenario is shown in Figure 4. Cost parameters in LEAP are feedstock and auxiliary fuel costs, capital, fixed and variable operating and maintenance costs, module costs, and any stranded costs associated with pre-existing processes. Baseline and net zero scenarios cost USD 20.381 billion and USD 37.253 billion in 2053. Therefore, additional cost in 2053 will be USD 16.872 billion. When additional cost is considered with mitigated emissions amount, it can be inferred that cost per ton of carbon reduction will be 44.46 USD.

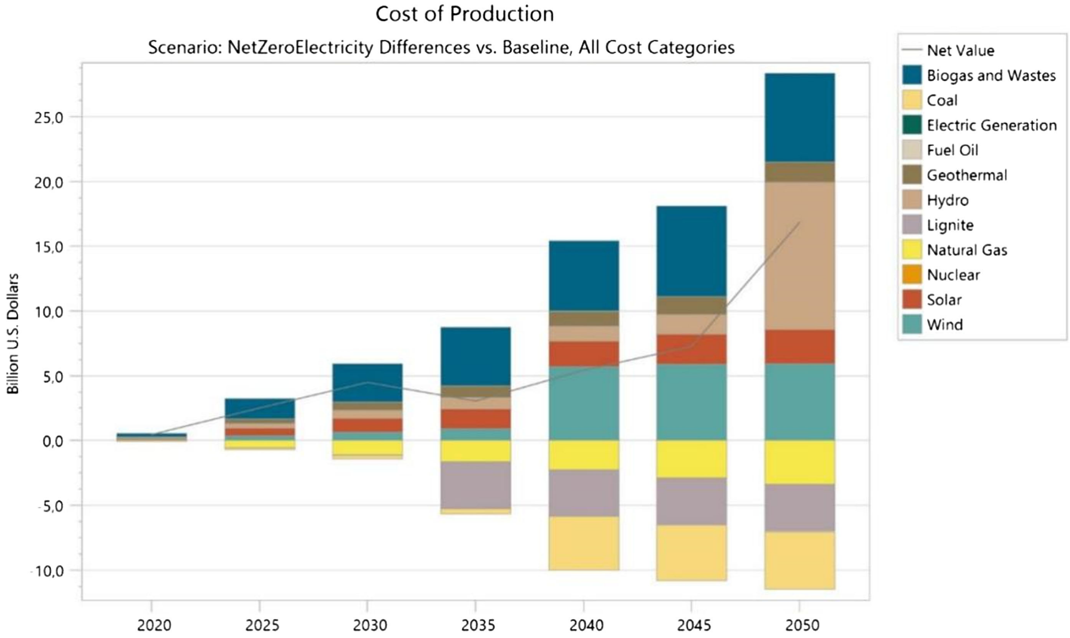
5. Conclusions and Policy Recommendations

Utilization of renewable energy sources, increasing energy efficiency, reduction of demand without compromising welfare, and introducing new and innovative emissions reduction technologies are strategies and policies for climate change mitigation. In that regard, the electricity generation sector still has room for energy efficiency and renewable energy measures for emissions mitigation. In this study, energy efficiency measures in the electricity sector reduce electricity transmission and distribution losses. For renewable energy sources, economically feasible potential sources are replaced with fossil fuels by 2053. When drivers of electricity-originated emissions are decomposed by the LMDI method, the main contribution to emission mitigation (45.79 mt) between 2008 and 2020 comes from replacing fossil fuels with renewable energy sources. Besides, for the same period, total energy efficiency improvement contributes to around 15 mt. Both renewable energy and energy efficiency are considered as main measures in the net zero scenario, 379.484 mt of emissions can be reduced in the electricity sector in 2053. The annual cost of this reduction is estimated at 16,872 million USD for the same year. This implies that the cost of per ton of emission mitigation can be 44.46 USD. When carbon price instruments such as tax or trade are higher than 44.46 USD, it is rational to mitigate emissions rather than purchase carbon credits/allowances or pay a carbon tax.

Policy recommendations:

- Energy policies are intertwined with climate policies and have become one of the most important elements and tools of combating climate change. As a requirement of the Paris Agreement and Türkiye's 2053 vision, it requires a greater focus on renewable energy. By increasing the use of renewable energy sources, Türkiye has significant potential for renewable energy generation, including solar, wind, and hydroelectric power. By increasing the use of these sources, Türkiye could reduce its reliance on fossil fuels and lower its emissions. Türkiye needs to further increase the installed capacity based on solar and wind, which have high potential, both to reduce the current account deficit and to ensure energy supply security.
- Strong transmission and distribution infrastructures are needed to strengthen the electricity infrastructure. In this context, it is important to make grid operations more secure and efficient and to increase support for distributed generation and self-consumption based on renewable energy sources. There is a need for a decentralized electricity infrastructure where electricity is generated close to where it is consumed and can cope with the peak loads required by electric charging capacities, allowing generating consumers to participate in the market, allowing bi-directional energy flows, converting electricity into different types of energy, and storing it.
- Executing a carbon pricing system, such as a carbon tax or cap-and-trade system, can incentivize the use of low-carbon technologies and mitigate emissions.

Figure 4
The additional cost of production of net zero scenario



- Future studies can consider carbon capture utilization and storage (CCUS) potential of the power sector in Türkiye. Beyond renewable energy technologies, coal and lignite-based power plants will not seem to decommissions in the short term. Therefore, it is recommended that CCUS should be considered in the thermal power plants.

In conclusion, Türkiye has significant potential to reduce emissions in the electricity sector by using renewable energy sources and technologies and improving energy efficiency in transmission and distribution lines.

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Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

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