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***Research paper***

# Decomposition Analysis of $CO_2$ Emissions from Türkiye's Electricity Generation: Evidence of Structural Change and Decarbonization Challenges (1990–2022)

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**Abstract**

This study investigates the driving forces behind changes in carbon dioxide emissions from Türkiye's electricity generation sector over the period 1990–2022 by applying the Logarithmic Mean Divisia Index (LMDI) decomposition method. The analysis disaggregates total emissions into four main effects, carbon intensity, thermal efficiency, fossil share, and total generation, to identify how each component has shaped the evolution of emissions across distinct development phases. The results indicate that the expansion of total electricity generation has been the dominant driver of emission growth, reflecting Türkiye's rapidly rising electricity demand driven by industrialization, urbanization, and economic growth. Improvements in thermal efficiency and carbon intensity contributed modestly to emission mitigation in the early years but proved insufficient to counterbalance the growing scale of electricity production. After 2010, the influence of carbon intensity became particularly pronounced due to the increasing reliance on coal within the fossil fuel mix. In contrast, the gradual rise of renewables, especially wind, solar, and geothermal, began to exert a moderating effect by reducing the overall share of fossil fuels in total generation. These findings highlight a critical structural transition in Türkiye's power sector: the coexistence of expanding electricity demand and a slowly diversifying energy mix. Achieving sustained emission reductions will require accelerating renewable deployment, improving power plant efficiency, and reducing dependence on coal. Strengthening policy instruments, such as renewable incentives, carbon pricing, and grid modernization, will be essential to align the electricity sector with Türkiye's 2053 net-zero target.

***Keywords***: *Electricity Generation; CO2 Emissions; LMDI Decomposition; Fossil Fuels; Renewables; Türkiye.*

## 1. Introduction

Sustainable development has been widely acknowledged as a global priority and is firmly integrated into international frameworks such as the United Nations 2030 Agenda and the Sustainable Development Goals (SDGs). These frameworks emphasize the balance between economic growth, social inclusion, and environmental sustainability, aiming to ensure prosperity without compromising the needs of future generations. (Yan et al., 2024; Zhou et al., 2024). Nevertheless, the realization of sustainable development faces serious barriers, the most pressing of which is climate change resulting from global warming. The root cause of global warming lies predominantly in anthropogenic greenhouse gas (GHG) emissions, and a substantial portion of these emissions is energy-related (Yadoo & Cruickshank, 2012).

According to the Intergovernmental Panel on Climate Change (IPCC), global surface temperature has already risen by approximately 1.1°C above pre-industrial levels during the 2011–2020 period. This warming has triggered widespread and unprecedented impacts, including more frequent and intense heatwaves, accelerating sea-level rise, glacier retreat, and biodiversity loss. The IPCC warns that without immediate and deep reductions in carbon dioxide ($CO_2$) and other GHG emissions, the world will surpass the 1.5°C threshold in the coming decades, substantially increasing risks to human and natural systems. (Calvin et al., 2023). Such developments directly endanger the foundations of sustainable development by undermining ecological stability, economic resilience, and social well-being.

In response to these threats, the Paris Agreement established a global framework to limit temperature rise to well below 2°C, preferably 1.5°C, above pre-industrial levels (Barroso et al., 2024). Central to this agreement are Nationally Determined Contributions (NDCs), which outline each country's commitments to reduce emissions and adapt to climate impacts (Mohan, 2024). NDCs serve as both a benchmark for national climate ambition and a mechanism to align mitigation pathways with SDGs (Ofori et al., 2025). They highlight the shared global responsibility while recognizing differentiated national circumstances. These principles make them a cornerstone of climate governance and sustainable growth strategies. Within this energy dimension, electricity generation holds a particularly critical role. As fossil fuels still account for the majority of global electricity production, the sector remains one of the largest contributors to $CO_2$ emissions (Farooq et al., 2025). Addressing this challenge requires not only technological transformation but also carefully designed planning and policy frameworks that align emission reductions with both NDC commitments and SDGs (Kim et al., 2020). Accurate identification of emission trends and the underlying driving forces is a fundamental prerequisite for effective strategies (Zheng et al., 2019). In this regard, factors such as the share of fossil fuels in the electricity mix, the carbon intensity of these fuels, and the efficiency of power generation technologies emerge as decisive determinants shaping the emission trajectory of the sector.

The objective of this study is to analyze the historical trends of $CO_2$ emissions from electricity generation in Türkiye and to identify the key factors driving these emissions. Specifically, the study examines the role of the fossil fuel share in electricity generation, the carbon intensity of fossil fuels, and generation efficiency in influencing overall emission dynamics. To this end, the contributions of these factors are decomposed using the Log-Mean Divisia Index (LMDI) method. This approach enables a systematic evaluation of the structural determinants of emission changes and provides an evidence-based foundation for the formulation of sustainable energy policies in Türkiye.

This paper is organized as follows: Section 2 provides an overview of the relevant literature on impacts of emissions on sustainable development, emission trends, and the LMDI decomposition method. Section 3 presents the data sources and methodology, focusing on the application of the Kaya Identity and LMDI method. Section 4 reports the empirical results of the LMDI analysis. Section 5 discusses the findings in relation to existing literature. Finally, Section 6 concludes the paper by highlighting key insights, limitations, and potential directions for future research.

## 2. Review of Literature

Previous research has extensively examined the relationship between GHG emissions and sustainable development, with particular emphasis on the energy sector as the dominant source of anthropogenic $CO_2$. Within this sector, electricity generation has attracted significant attention due to its high dependence on fossil fuels and its substantial contribution to global emissions. Scholars have also explored the underlying determinants of these emissions, highlighting the roles of fuel mix, carbon intensity, and generation efficiency. In parallel, decomposition techniques such as the Kaya Identity and the LMDI have been applied to disentangle the contributions of these factors and to assess their implications for emission reduction strategies.

### 2.1. Emissions as the major threat to sustainable development

GHG emissions have become the primary driver of global climate change, posing profound economic, environmental, and social challenges that undermine progress toward sustainable development. Empirical research consistently demonstrates that emissions and climate change impose significant economic costs, particularly in developing and emerging economies. (González et al., 2021; Mele et al., 2021; Tawiah & Alessa, 2025). Beyond their economic repercussions, emissions and climate-induced shocks cause widespread environmental degradation through complex interactions within natural systems. Climate change alters species' behavior, phenology, and distributions, reshaping ecosystem structure, productivity, and resilience, and threatening the continuity of ecosystem services essential to human well-being. (Talukder et al., 2022; Wang et al., 2024; Weiskopf et al., 2020). Such environmental disruptions also have profound social consequences, particularly for vulnerable communities whose livelihoods depend on natural resources. Climate change and related emissions increasingly exacerbate social vulnerabilities through interconnected effects on health, inequality, migration, and conflict. Rising global temperatures have dramatically intensified heat exposure, with heat-related mortality among people over 65 increasing by 167% since the 1990s, underscoring the growing health burden of a warming climate. (Romanello et al., 2024). Climate-induced disasters also amplify inequality, creating a "disaster–inequality trap" in which poorer populations suffer greater losses and slower recovery, thereby reinforcing intergenerational vulnerability. (Beine & Jeusette, 2021; Cappelli et al., 2021). In addition, environmental stress heightens the likelihood of social unrest: rainfall variability across Africa has been shown to increase protests, riots, and anti-government actions through intensified competition over scarce resources. (Hendrix & Salehyan, 2012). Finally, climate variability rarely acts as a direct cause of war but rather serves as an accelerant of instability, intensifying existing political and social tensions. (Salehyan, 2014). Collectively, these studies reveal that emissions-driven climate change extends beyond environmental degradation to deeply reshape social structures, livelihoods, and security systems worldwide.

### 2.2. Historical evolution and emission trends in the power sector

Climate change, recognized as the greatest threat to sustainable development, is primarily a consequence of anthropogenic GHG emissions that have intensified global warming (IPCC, 2022). The energy sector remains the dominant contributor to these emissions, accounting for nearly three-quarters of total global $CO_2$ emissions in 2022, while electricity and heat generation alone were responsible for about 40% of the total. (IEA, 2024). This makes the power sector a central arena for mitigation efforts and a decisive factor shaping the world's carbon trajectory.

Global electricity generation has expanded rapidly since the 1990s, driven by industrialization, urbanization, and the electrification of end-use sectors. Despite notable efficiency improvements and the steady growth of renewables, progress has been gradual. The share of fossil fuels in global power generation has declined only slightly, from 63% in 1990 to 60% in 2022, revealing the structural persistence of carbon-intensive systems. Although energy intensity has decreased in most regions, these efficiency gains have been outweighed by rising demand, particularly in emerging economies. The Electricity 2025 report highlights that electricity demand is entering a new growth phase, driven by the electrification of transport, heating, and industry, and is expected to rise by nearly 4% per year through 2027 (IEA, 2025a). As a result, total $CO_2$ emissions from the power sector reached record highs in 2023, despite the rapid expansion of clean energy sources. (IEA, 2024).

Nevertheless, the carbon intensity of electricity generation, which is measured as $CO_2$ emissions per kilowatt-hour, has shown a gradual decline. In 2023, the global average intensity reached its lowest level on record, as renewables supplied around 30% of total generation. (Ember, 2024). By 2024, clean sources surpassed 40% of global electricity production for the first time, with solar and wind generation together exceeding hydropower. (Ember, 2025). Yet coal remained the single largest source of power-related emissions, particularly in Asia, underscoring persistent regional disparities in decarbonization progress. (Vinichenko et al., 2021). According to the IPCC (2022), low-carbon sources must account for more than 90% of global electricity generation by 2050 to limit warming below 2°C, reaffirming the pivotal role of the power sector in achieving global climate goals.

### 2.3. Renewables, technology, and the pathway toward Paris-aligned decarbonization

Technological innovation and steep cost reductions in renewables have significantly altered the feasibility of power-sector decarbonization. Solar photovoltaics and onshore wind are now among the most cost-effective generation technologies globally, supported by improvements in grid flexibility, storage, and digital efficiency (Loftus et al., 2015). Scenarios consistent with the Paris Agreement emphasize that achieving net-zero electricity requires an accelerated phase-out of unabated fossil generation and large-scale deployment of renewables. They also highlight the need for enhanced energy efficiency and complementary solutions such as carbon capture, utilization, and storage. (IPCC, 2022). Global decarbonization pathways also indicate that electricity will supply nearly half of total final energy consumption by mid-century, with near-zero carbon intensity (Rogelj et al., 2018). However, the pace of current transitions remains insufficient; meeting Paris-aligned trajectories demands sustained policy commitment, technological investment, and international cooperation (van Sluisveld et al., 2015).

Crucially, the slow decline in fossil fuel use within the power sector suggests that achieving deep emission cuts will depend not only on expanding renewables but also on identifying the underlying drivers of emission change. Since fossil fuels still account for about 60% of global electricity generation, it is essential to decompose and quantify the drivers behind emission changes within the electricity generation sector. Specifically, the variation in $CO_2$ emissions can be attributed to three key components: the share of fossil fuels in total electricity generation, the carbon intensity of the fossil fuels used, and the efficiency of electricity generation. Understanding the relative influence of each of these factors is critical for developing targeted mitigation strategies and assessing the potential for low-carbon transitions in the power sector. In this context, the LMDI decomposition approach provides a robust analytical framework to isolate and measure their contributions, offering empirical insights into how structural, technological, and efficiency-related changes shape emission trends and the sector's alignment with the Paris Agreement. (Ang, 2015).

### 2.4. Applications of the LMDI method in electricity-sector studies

The LMDI method has become one of the most prominent analytical frameworks for decomposing changes in energy-related $CO_2$ emissions due to its perfect decomposition properties, ease of interpretation, and theoretical consistency (Ang, 2005, 2015). Building on this methodological foundation, the LMDI has been widely applied across the energy sector to assess the relative influence of activity, energy intensity, fuel structure, and emission coefficients on emission trends. These applications provide deep insights into the drivers of carbon change across different economies and time periods. (Xu & Ang, 2013).

Given its dominant contribution to total energy-related emissions, the electricity generation sector has drawn particular attention as it represents both a major source of global emissions and a focal point for decarbonization strategies. The LMDI method is particularly effective in this field, as it allows researchers to isolate the impact of key components such as the fossil fuel share in generation, generation efficiency, and the carbon intensity of fossil fuels, all of which are directly influenced by technological progress and policy decisions. (Ang & Su, 2016).

One of the earliest applications in this domain is Malla (2009), who analyzed $CO_2$ emissions from electricity generation in seven Asia-Pacific and North American countries, found that electricity output growth was the dominant driver of emission increases, while efficiency improvements played only a minor mitigating role. Zhang et al. (2013) Examined China's electricity sector between 1991 and 2009 and found that although economic expansion significantly raised emissions, gains in generation efficiency and cleaner fuel structures partially offset this trend. The study also showed that the thermal power structure effect (fuel mix) plays a minor role in increasing $CO_2$ emissions. At the global scale, Ang et al. (2011) Benchmarked 129 countries, concluding that global electricity-sector emissions could decline by nearly 20% if all countries achieved median levels of efficiency and non-fossil fuel shares. Building on these global findings, Ang and Su (2016) Analyzed the changes in aggregate carbon intensity (ACI) for electricity production at the global and country levels. The study focused on 124 countries that together accounted for 97% of global electricity production in 2013. Decomposition analysis showed that the main driver of the global ACI reduction was improvements in the thermal efficiency of fossil fuel electricity generation, while the contributions from reducing fossil fuel share and switching to cleaner fossil fuels were relatively small. Zhang et al. (2020), employed the LMDI analysis for Beijing's production-based electricity emissions from 2007 to 2015 and showed that electricity consumption was the main driver of emission growth, while improvements in fuel structure, energy efficiency, and electricity trade consistently mitigated increases, particularly after 2010.

Mohlin et al. (2018) Used the LMDI method and found that in the United States between 2007 and 2013, the expansion of renewable energy contributed as much to emission reductions as the shift from coal to natural gas. Extending the regional scope to developing economies, Goh et al. (2018) Performed LMDI analysis with different identities using data on $CO_2$ emissions from electricity generation in the Association of Southeast Asian Nations (ASEAN) countries between 1990 and 2013. Decomposition results showed that the main driver of rising $CO_2$ emissions from electricity generation was the growth in electricity demand, while improvements in generation efficiency only partially offset this increase. Collectively, empirical research demonstrates that the LMDI method provides a robust and transparent framework for identifying the structural, technological, and intensity-related factors driving $CO_2$ emissions in the electricity sector. By decomposing total emissions into quantifiable effects, LMDI-based studies have offered critical diagnostic insights into how changes in fossil fuel dependency, fuel carbon intensity, and efficiency improvements shape emission trajectories—thereby contributing to a clearer understanding of the pathways toward Paris Agreement–aligned decarbonisation (IEA, 2024).

### 2.5. From global to national perspectives: LMDI applications for Türkiye

In the case of Türkiye, several studies have applied the LMDI to analyze the evolution of $CO_2$ emissions across sectors, reflecting the country's ongoing industrial and energy transitions. Although not specifically focused on electricity generation, one of the earliest decomposition studies for Türkiye analyzed the drivers of $CO_2$ emissions between 1980 and 2003, revealing that economic growth was the dominant contributor, while improvements in energy intensity only slightly mitigated the increase (Lise, 2006). Another early decomposition study for Türkiye applied the LMDI method over the period 1970–2006, identifying economic activity as the main driver of rising $CO_2$ emissions, while energy intensity improvements had only a modest mitigating impact and structural changes remained insignificant (İpek Tunç et al., 2009). A study focusing on the Turkish manufacturing sector applied the LMDI method to 57 industries for the 1995–2001 period. The results indicated that industrial activity growth and energy intensity changes were the main drivers of $CO_2$ emission variations, while coal use remained the dominant source of industrial emissions—particularly within the iron and steel industry, identified as the most carbon-intensive subsector (Akbostancı et al., 2011). Using the LMDI method, a comprehensive decomposition of Türkiye's $CO_2$ emissions for the 1990–2013 period covered five major sectors, including public electricity and heat production. The results showed that energy intensity and economic activity were the main factors shaping emission trends, while the fuel mix component helped reduce $CO_2$ emissions during economic downturns. Among GDP sectors, electricity and heat production, together with manufacturing and construction, were identified as the dominant sources of emission change (Akbostancı et al., 2018). Another study applied the extended Kaya identity and the LMDI method to examine Türkiye's $CO_2$ emission trends over the 1990–2016 period. The results indicated that economic growth and population were the dominant drivers of emission increases, while technological and efficiency-related factors had only limited effects in reducing emissions. Overall, the analysis highlighted the persistent influence of activity-driven factors on Türkiye's $CO_2$ trajectory, with structural and intensity improvements contributing only marginally (Karakaya et al., 2019). A more recent study focused on electricity generation and renewable energy use, examining how the increasing share of renewables has affected Türkiye's GHG emissions from power production. The analysis showed that emission intensity in electricity generation declined from 563 $gCO_2e$/kWh in 2008 to 437 $gCO_2e$/kWh in 2020, reflecting an average annual decrease of about 2.1%. The findings highlight that Türkiye's expanding renewable capacity has contributed to gradual emission reductions in the power sector, although further utilization of its renewable potential is needed to align with European benchmarks (Sahin & Esen, 2022). Using the LMDI and Tapio frameworks, Ozdemir (2023) found that economic growth was the main driver of Türkiye's electricity-related $CO_2$ emissions (1990–2020), while efficiency and intensity factors partly offset increases. Coal was identified as the most carbon-intensive source, underscoring the need to expand non-fossil energy in power generation. Overall, LMDI-based research in Türkiye has primarily focused on economy-wide or sectoral emission trends, with very few studies explicitly addressing $CO_2$ emissions from electricity generation. This gap underscores the need for more detailed decomposition analyses in the power sector to better understand the structural and technological dynamics shaping Türkiye's pathway toward low-carbon development. In light of this research gap, the present study applies the LMDI decomposition method to electricity-related $CO_2$ emissions in Türkiye, aiming to identify the key driving factors behind emission changes and to evaluate the sector's alignment with national and international mitigation targets.

## 3. Methodology

This study employs the LMDI decomposition approach to quantify the driving factors of $CO_2$ emissions from Türkiye's electricity generation. Following the Kaya identity, the total change in $CO_2$ emissions from electricity generation is decomposed into a set of multiplicative effects representing key determinants such as activity (generation output), generation efficiency, fossil fuel share, and $CO_2$ intensity of fossil fuel mix, which together describe the structural and technological dynamics of the sector.

The methodological specification used in this study draws on previous electricity sector decomposition studies for China. (M. Zhang et al., 2013), Spain (Alcántara et al., 2022), and Ghana (Oteng-Abayie et al., 2024), all of which applied the LMDI formulation to disaggregate emission changes into carbonization, transformation, fossil intensity, electricity-intensity, and production effects. Consistent with these studies, total emissions from electricity generation (C) can be expressed as:

$$C = \frac{C}{FEI} \times \frac{FEI}{FEG} \times \frac{FEG}{TEG} \times \frac{TEG}{GDP} \times GDP \tag{1}$$

In this context, FEI stands for the total fossil energy input used to generate electricity, FEG indicates the amount of fossil-based electricity produced, TEG is the total electricity generated from all sources, and GDP reflects the country's overall economic output. While the traditional Kaya identity includes GDP to represent economic activity, this study intentionally omits it from the model. This choice is based on two main reasons: first, because the study concentrates solely on the electricity generation sector, where emission changes are more directly linked to generation activities, efficiency, and fossil fuel share rather than macroeconomic factors; second, incorporating GDP alongside electricity output could lead to double-counting, as electricity generation already captures economic and demand-related aspects of production. Accordingly, by excluding the GDP component to focus solely on sector-specific factors, the equation is reformulated as follows:

$$C = \frac{C}{FEI} \times \frac{FEI}{FEG} \times \frac{FEG}{TEG} \times TEG \tag{2}$$

The ratio C/FEI indicates the carbonization factor (cf) of fossil fuel energy used in electricity generation, representing emissions per unit of fossil fuel energy. FEI/FEG is the transformation factor (tf), the inverse of the efficiency in converting fossil fuel inputs into electricity. FEG/TEG is the fossil intensity factor (if), showing the proportion of fossil-origin electricity within the total electricity generated in the system. TEG is the generation factor (gf). Subsequently, (2) is expressed in the identity form shown in (3).

$$C_t = cf_t \times tf_t \times if_t \times gf_t \tag{3}$$

The change in electricity-related $CO_2$ emissions over the period from t to t-1, $\Delta C$, can be calculated by (4).

$$\Delta C = C_t - C_{t-1} = cf_t \times tf_t \times if_t \times gf_t - cf_{t-1} \times tf_{t-1} \times if_{t-1} \times gf_{t-1} \tag{4}$$

Following the complete additive LMDI decomposition approach proposed by Ang (2005), which ensures perfect decomposition with no residual term, $\Delta C$ can be expressed as follows:

$$\Delta C = \Delta C_{cf} + \Delta C_{tf} + \Delta C_{if} + \Delta C_{gf} \tag{5}$$

Where the terms on the right-hand side of (5) represent the changes in the effects of carbonization, transformation, fossil intensity, and generation factors, respectively, over the $\Delta C$. Each effect can be computed as follows:

$$\Delta C_{cf} = \frac{C_t - C_{t-1}}{\ln C_t - \ln C_{t-1}} \times \ln \frac{cf_t}{cf_{t-1}} \tag{6}$$

$$\Delta C_{tf} = \frac{C_t - C_{t-1}}{\ln C_t - \ln C_{t-1}} \times \ln \frac{tf_t}{tf_{t-1}} \tag{7}$$

$$\Delta C_{if} = \frac{C_t - C_{t-1}}{\ln C_t - \ln C_{t-1}} \times \ln \frac{if_t}{if_{t-1}} \tag{8}$$

$$\Delta C_{gf} = \frac{C_t - C_{t-1}}{\ln C_t - \ln C_{t-1}} \times \ln \frac{gf_t}{gf_{t-1}} \tag{9}$$

All data used in this study were compiled from the International Energy Agency's (IEA) Energy Statistics Data Browser. (IEA, 2025b) and World Energy Balances (IEA, 2025b) Databases. Utilizing a single, consistent source for key indicators such as $CO_2$ emissions from electricity generation, electricity generation from fossil fuels, total electricity output, and fossil fuel inputs used for electricity generation ensures methodological coherence and comparability across variables. This approach minimizes discrepancies arising from differences in data-collection methodologies, definitions, and boundary settings across alternative sources. Moreover, the IEA's harmonized and internationally recognized datasets enhance the reliability, transparency, and replicability of the analysis, providing a robust empirical basis for decomposition and scenario-based assessments. The evolution of $CO_2$ emissions from electricity generation in Türkiye between 1990 and 2022, and the corresponding trends in FEI, FEG, and TEG over the same period are shown in Figure 1 and Figure 2, respectively.

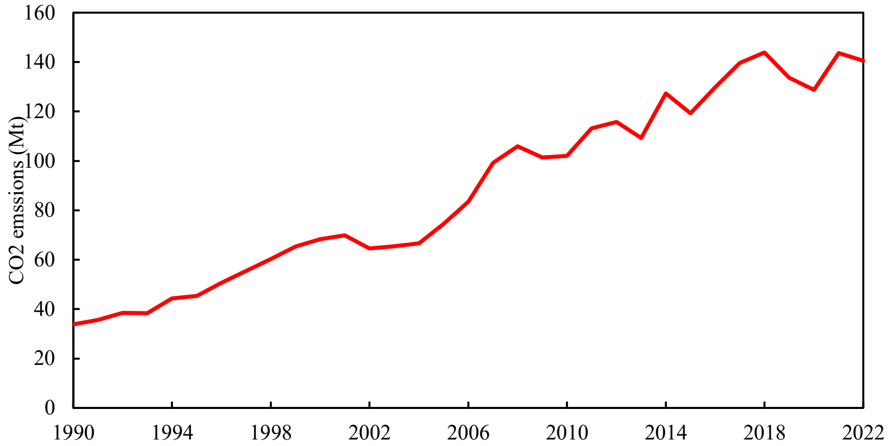


**Fig. 1:** Trends in $CO_2$ Emissions from Electricity Generation in Türkiye, 1990–2022.

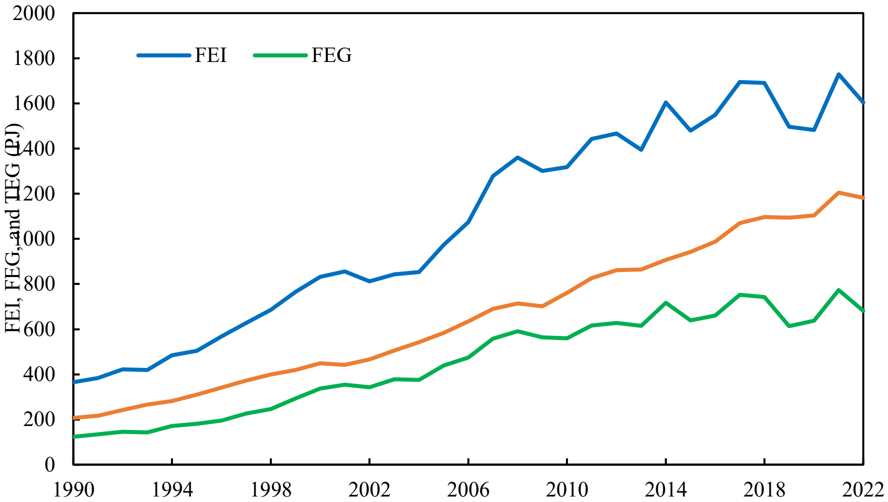


**Fig. 2:** Trends in Fossil Energy Input (FEI), Fossil-Based Electricity Generation (FEG), and Total Electricity Generation (TEG) in Türkiye, 1990–2022.

Overall, $CO_2$ emissions display a continuous upward trend, rising sharply from the early 2000s onward and reaching their highest levels around 2018–2019 before showing minor fluctuations in recent years. A similar increasing pattern is observed in FEI, FEG, and TEG, indicating a consistent growth in energy input and electricity output throughout the period. The increase in TEG reflects the expansion of total electricity generation, whereas FEG follows a comparable but slightly lower trajectory, suggesting a gradual diversification of the energy mix. Meanwhile, FEI shows a stronger rise than FEG, implying that the amount of fossil energy input has grown faster than the fossil-based electricity produced. This divergence may point to variations in thermal efficiency or shifts in the types of fossil fuels used in power generation. Taken together, Figures 1 and 2 show that Türkiye's electricity sector has undergone a marked expansion since 1990, accompanied by a steady increase in fossil fuel consumption and associated $CO_2$ emissions.

Figure 3 further complements these findings by presenting the indexed values of C, C/FEI, FEI/FEG, FEG/TEG, and TEG, all normalized to 2000 = 100, which facilitates comparison across variables with different units and scales by emphasizing proportional rather than absolute changes. Thus, Figure 3 enables a comparative assessment of the relative changes in emissions and their underlying factors over time, with the baseline year (2000) represented by a dashed horizontal line for reference. Both C and TEG show a pronounced upward trend after 2005, while C/FEI, FEI/FEG, and FEG/TEG remain relatively stable around the baseline, indicating limited variation in carbon intensity, fossil fuel input efficiency, and the share of fossil-based generation.

While the figures above provide valuable insight into the general direction and magnitude of changes, they do not explain how much each factor has contributed to the overall variation in $CO_2$ emissions. Therefore, applying the LMDI decomposition method is essential to disentangle and quantify the individual effects of key driving factors on emission changes. Accordingly, the following section presents the

LMDI-based results, offering a systematic decomposition of the observed emission trends and identifying the dominant factors shaping the evolution of $CO_2$ emissions from electricity generation in Türkiye.

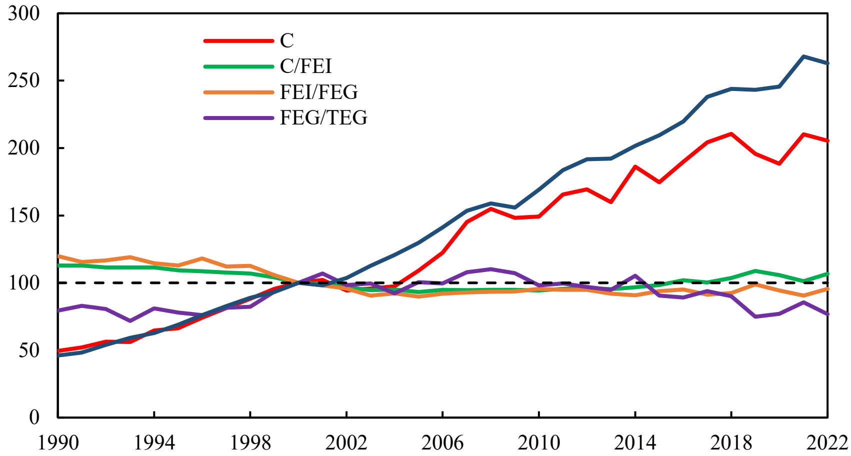


**Fig. 3:** Comparative Index of $CO_2$ Emissions and Associated Generation Factors (C/FEI, FEI/FEG, FEG/TEG, TEG) Normalized to 2000 = 100.

## 4. Results

Figure 4 presents the decomposition of changes in $CO_2$ emissions from electricity generation in Türkiye over three subperiods, 1990–2000, 2000–2010, and 2010–2022, based on the LMDI approach. Figure 4 visually displays the contribution of each factor, including C/FEI (carbon intensity of fossil fuel input), FEI/FEG (inverse of thermal efficiency), FEG/TEG (share of fossil-based generation in total output), and TEG (total electricity generation). Positive bars represent factors contributing to emission increases, while negative bars indicate mitigating effects that reduced total emissions within each period.

During the 1990–2000 period, total electricity generation exerted a strong positive influence on emissions, consistent with rapid growth in electricity demand and generation capacity. The rising share of fossil-based generation further reinforced this increase, amplifying the emission growth driven by the expansion of the electricity sector. In contrast, improvements in the carbon intensity of fossil fuel input and slight gains in thermal efficiency provided modest mitigating effects, but these reductions were not sufficient to offset the strong upward pressure from generation growth and the higher fossil share.

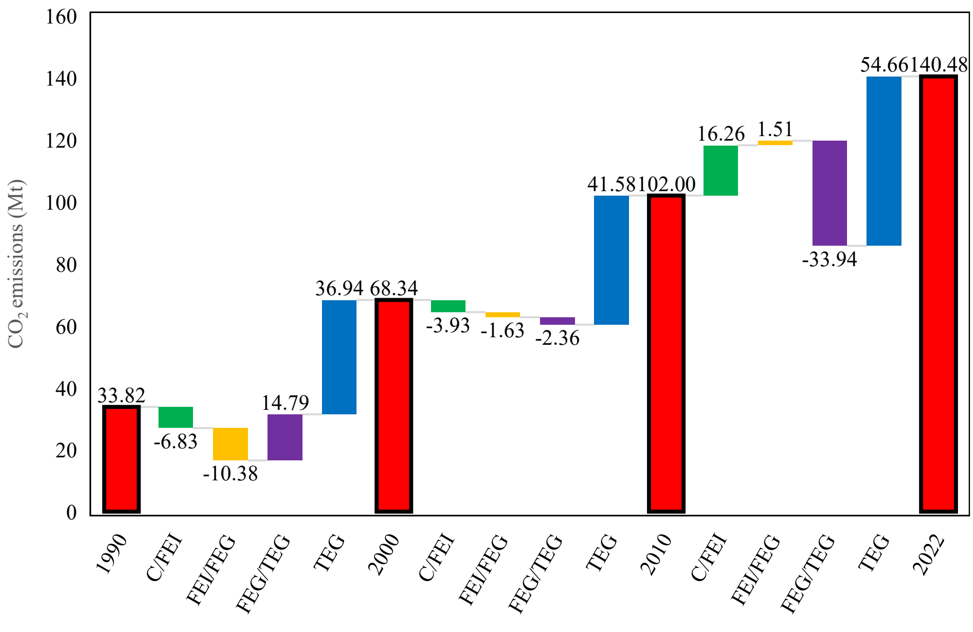


**Fig. 4:** Changes in $CO_2$ Emissions from Electricity Generation in Türkiye Decomposed by Contributing Factors for Selected Periods (1990–2000, 2000–2010, and 2010–2022) Based on the LMDI Method.

In the 2000–2010 period, the expansion of total generation again emerged as the dominant driver of emission growth, accounting for the largest positive contribution among all factors. The share of fossil-based generation in total electricity output exerted a modest counterbalancing effect, as the relative share of non-fossil sources began to rise slightly during this period. Efficiency improvements also provided a small mitigating influence but were insufficient to offset the strong activity effect. Meanwhile, the carbon intensity of fossil fuel input declined, reflecting the growing role of natural gas and a partial shift toward less carbon-intensive fuels within the fossil mix. The 2010–2022 period exhibits a distinct pattern compared with the previous decade. While the expansion of total electricity generation remained as the major positive driver of emissions, the carbon intensity of fossil fuel input increased notably, indicating a shift toward more carbon-intensive fuels such as coal in the generation mix. Thermal efficiency, in contrast, slightly deteriorated, suggesting that fossil-based power plants operated with lower average efficiency relative to the 2000–2010 period. Meanwhile, the share of fossil-based generation in total electricity output declined more substantially than in earlier periods, exerting a stronger counterbalancing influence on total emissions.

However, this mitigating effect was still insufficient to offset the combined upward pressure from rising generation levels and higher carbon intensity. To complement the graphical representation of the LMDI results, Table 1 summarizes the numerical contributions of each driver to total $CO_2$ emission changes across subperiods, expressed as the percentage share of the total increase within each period.

**Table 1:** Contributions of Decomposition Factors to Total $CO_2$ Emission Changes by Subperiods (Percentage Share of Total Increase)

| Period | C | C/FEI | FEI/FEG | FEG/TEG | TEG |
|---|---|---|---|---|---|
| 1990–2000 | 100 (34.52 Mt) | -19.77 | -30.07 | 42.84 | 107.00 |
| 2000–2010 | 100 (33.65 Mt) | -11.68 | -4.85 | -7.02 | 123.55 |
| 2010–2022 | 100 (38.48 Mt) | 42.25 | 3.92 | -88.21 | 142.03 |

Overall, Figure 4 and Table 1 demonstrate that the growth of total electricity generation has been the primary factor driving Türkiye's $CO_2$ emissions upward across all three periods. During all periods, the effect of total electricity generation has exhibited a steady upward trend on an annual basis, driving continuous growth in $CO_2$ emissions. Specifically, this effect accounted for an average annual increase of 3.7 Mt during 1990–2000, 4.2 Mt during 2000–2010, and 4.6 Mt during 2010–2022, indicating a persistent intensification of the generation-driven contribution to total emissions over time. This reflects Türkiye's expanding electricity demand driven by economic growth, industrialization, and population rise. The liberalization of the electricity market and large-scale capacity additions in the 2000s and 2010s further intensified this effect.

The efficiency improvements seen in the 1990s, along with reductions in the carbon intensity of fossil fuel use, could not be maintained in the 2000s, revealing a significant weakness in emission mitigation during that decade. Especially between 2010 and 2022, the rise in emissions caused by the carbon-intensity effect became more pronounced. This trend was largely linked to the increasing share of coal within fossil-based electricity generation. Figure 5 displays the shares of fossil fuels used in electricity production since 1990, clearly illustrating how coal's contribution to the generation mix expanded after 2014.

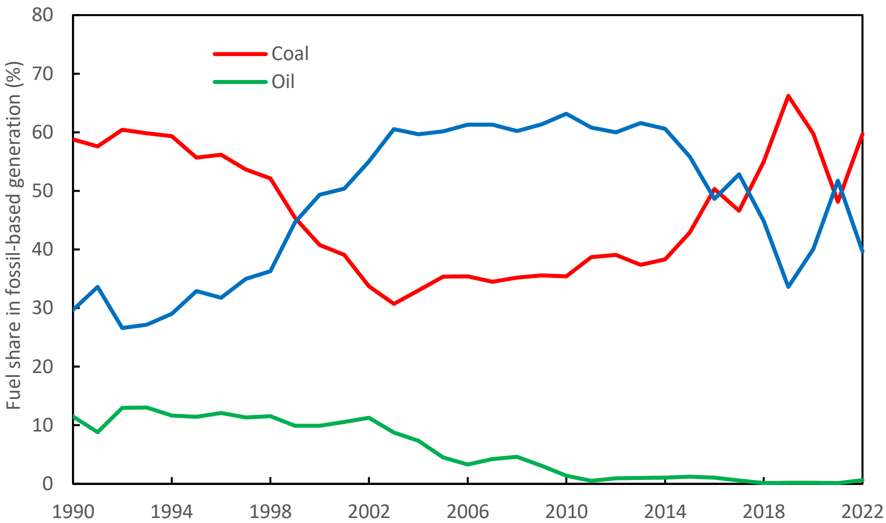


**Fig. 5:** Shares of Fossil Fuels in Electricity Generation in Türkiye Since 1990.

As shown in Figure 5, the share of coal within fossil-based electricity generation has risen sharply since 2014, overtaking natural gas as the dominant fuel source. The sharp rise in the share of coal within fossil-based electricity generation after 2014 primarily reflects Türkiye's energy security strategy, which emphasized the utilization of domestic lignite resources to reduce dependency on imported natural gas. Government incentives and capacity payments made coal investments more attractive, while rising natural gas prices and supply risks further weakened the competitiveness of gas-fired plants. As a result, the policy-driven expansion of coal capacity reshaped the fossil mix, making coal the dominant fuel source in Türkiye's electricity generation. This structural shift in the fuel mix significantly contributed to the increase in the carbon intensity effect observed in the 2010–2022 period. The declining share of natural gas, combined with the policy-driven expansion of domestic coal utilization, led to a more carbon-intensive generation structure, thereby amplifying total $CO_2$ emissions from the power sector. Nevertheless, the overall share of fossil fuels in total electricity generation declined slightly during the same period, producing a moderate counterbalancing effect that partially offset the upward pressure of higher carbon intensity. The change in the shares of fossil fuels, hydropower, and other renewables (including geothermal, biofuels, wind, waste, and solar) in Türkiye's electricity generation since 1990 is shown in Figure 6.

Over the long term, fossil fuels have remained the dominant energy source, yet their trajectory reveals several distinct phases. In the early 1990s, fossil fuels accounted for roughly two-thirds of total electricity generation, with hydropower providing most of the remainder. The fossil share increased markedly during the 1990s and 2000s, reaching a peak of around 83% in the mid-2000s as electricity demand expanded and fossil-based capacity, especially coal- and natural gas-fired plants, grew rapidly. After 2010, however, a gradual but persistent decline in the fossil share became evident. This downward trend was primarily driven by the rapid expansion of other renewable sources, particularly wind, solar, and geothermal, whose contribution to total electricity generation increased markedly after 2010. Hydropower, by contrast, remained relatively stable due to the near-saturation of economically viable large-scale sites and shifting policy incentives that favored new investments in wind and solar energy. By 2022, fossil fuels supplied roughly 58% of total electricity, while renewables, especially solar and wind, occupied a visible and steadily growing share of the generation mix. Overall, Figure 6 highlights the ongoing structural transformation in Türkiye's electricity sector: despite the continued dominance of fossil sources, the steady growth of renewables has started to erode that dominance, providing the foundation for the moderating effect of the fossil-share factor observed in the decomposition results for the 2010–2022 period.

Beyond the empirical findings, these results align with the broader theoretical frameworks of the energy–growth–emissions nexus and the Environmental Kuznets Curve (EKC) hypothesis. The persistent dominance of electricity generation as an emission driver reflects the scale effect of economic growth, while the emerging influence of renewable deployment suggests the onset of a potential decoupling phase. This pattern supports the EKC notion that, at higher stages of industrial and technological development, structural transformation and cleaner energy investments can offset the emission pressures of economic expansion. Therefore, the decomposition outcomes not only provide a detailed quantitative breakdown of emission drivers but also offer theoretical evidence that Türkiye's energy transition is gradually moving toward a more sustainable growth pathway.

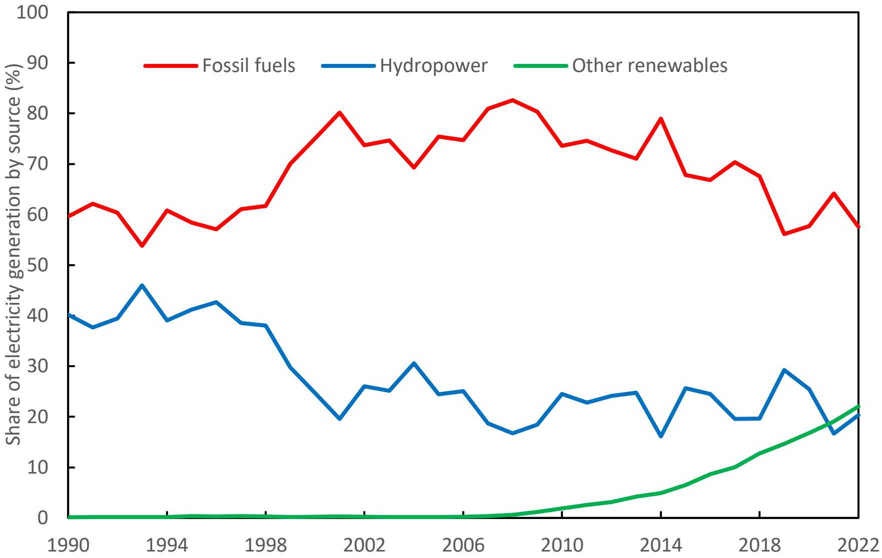


**Fig. 6:** Shares of Fossil Fuels, Hydropower, and Other Renewables in Electricity Generation in Türkiye, 1990–2022.

## 5. Discussion

The results of this study provide a comprehensive understanding of the key drivers of $CO_2$ emissions from Türkiye's electricity generation over more than three decades, highlighting the dynamic interaction between generation scale, fuel composition, and technological performance. The decomposition analysis revealed that the growth in total electricity generation remained the dominant contributor to emissions across all periods, reflecting Türkiye's rapid industrialization, population growth, and rising living standards. This persistent activity effect highlights the difficulty of meeting rapidly growing electricity demand while simultaneously reducing $CO_2$ emissions in the power sector. These findings are consistent with those of Malla (2009) and Goh et al. (2018), who identified electricity output growth as the dominant driver of emission increases across Asia-Pacific and North American, and ASEAN countries, respectively, while efficiency gains contributed only marginally to mitigation. Similar to those cases, Türkiye's electricity sector exhibits a strong scale effect that continues to outweigh efficiency-related improvements. This study finds that efficiency improvements contributed modestly to emission reductions during the 1990s in Türkiye, yet their influence almost disappeared in the following decades, suggesting that the potential for further efficiency-driven mitigation had largely been exhausted.

The findings of this study also underscore the evolving role of fossil fuel composition in shaping Türkiye's power-sector emissions. During the 1990s, changes in the fossil fuel mix contributed moderately to emission reductions, primarily due to the gradual shift from coal to natural gas in electricity generation. However, in the 2010-2022 period, this mitigating influence weakened and eventually reversed, as the share of coal increased within the fossil-based generation mix. After 2016, coal became the dominant fuel source, leading to a sharp rise in the carbon intensity effect. The findings regarding the role of coal are also consistent with those reported by Özdemir (2023), who identified coal as the most carbon-intensive energy source contributing significantly to emission growth in Türkiye's electricity generation. This transition reflects the impact of policy-driven support for domestic coal utilization and capacity expansion programs, which outweighed the benefits of earlier shifts toward cleaner fossil fuels. The effect of the share of fossil fuels on $CO_2$ emissions has shown a clear temporal evolution over the analysis period. During the 1990s, the increasing share of fossil-based electricity generation contributed positively to emission growth, as fossil fuels expanded their dominance in the power mix amid rapidly rising electricity demand. In the 2000s, this structural effect shifted direction and began to exert a mild mitigating influence, reflecting the gradual introduction of natural gas and a slight diversification of the generation portfolio. In the most recent period (2010–2022), the fossil-share factor played a notably stronger emission-reducing role, driven by the accelerated deployment of renewables, particularly wind, solar, and geothermal, which steadily displaced fossil sources in total electricity generation. This progressive decline in the fossil share represents a key structural driver behind the partial decoupling between generation growth and emission increases observed in Türkiye's electricity sector. These results are consistent with the findings of Sahin and Esen (2022), who reported a substantial decline in emission intensity from Türkiye's electricity generation between 2008 and 2020, largely attributed to the growing share of renewables in the power mix.

From a broader perspective, Türkiye's emission trajectory lies between the patterns observed in emerging and developed economies. While total electricity generation growth continues to drive emissions, as in many developing countries, the rising share of renewables since the 2010s signals an early move toward a lower-carbon pathway similar to that of advanced economies.

These trends have direct implications for sustainable development. Expanding electricity access and supporting industrial growth are central to Türkiye's development agenda, SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation and Infrastructure), but the current emission trajectory challenges progress toward SDG 13 (Climate Action). Balancing these goals will require an integrated energy strategy that simultaneously promotes renewable deployment, enhances system flexibility, and accelerates efficiency improvements across generation and transmission systems. At the same time, the transition toward a low-carbon electricity system can deliver important socio-economic co-benefits. Expanding renewable energy and improving efficiency can create employment opportunities, enhance energy affordability, and foster a more inclusive and resilient energy transition in Türkiye.

# 6. Conclusion and Policy Implications

## 6.1. Conclusion

This study employed the LMDI method to decompose the driving factors of $CO_2$ emissions from Türkiye's electricity generation between 1990 and 2022. The analysis focused on four main effects, carbon intensity, thermal efficiency, fossil share, and total electricity generation, to assess how technological performance and structural change have shaped emission dynamics. The results indicate that the expansion of total electricity generation has been the dominant contributor to emission increases throughout the entire period. Efficiency improvements contributed modestly to emission reductions during the 1990s but became nearly ineffective in subsequent decades, while the growing share of coal after 2010 intensified the carbon intensity effect. Conversely, the gradual increase in renewable energy deployment, particularly wind, solar, and geothermal, significantly reduced the share of fossil fuels in total generation, marking a structural turning point in Türkiye's electricity sector.

## 6.2. Policy implications

The findings highlight that achieving deep decarbonization in Türkiye's power sector requires an integrated and consistent policy framework that aligns short-term energy security needs with long-term sustainability objectives. To translate these findings into actionable policy, Türkiye should prioritize a coherent set of strategies that reinforce the energy transition and align with long-term decarbonization goals. Accelerating renewable energy deployment through continued feed-in tariff mechanisms, competitive auctions, and grid modernization is essential to enhance system flexibility and reliability. At the same time, phasing down coal dependence by retiring inefficient plants and redirecting investment toward low-carbon technologies and storage solutions would significantly reduce the carbon intensity of generation. In parallel, improving efficiency performance via digital monitoring systems, power plant retrofits, and the adoption of advanced thermal technologies can further curb emissions from existing facilities. Finally, introducing an effective carbon pricing mechanism would internalize environmental costs and create stronger market incentives for cleaner energy investments, supporting a more sustainable and resilient power system.

## 6.3. Limitations and future research directions

Although the LMDI framework provides a robust decomposition of emission drivers, this study is limited to energy-related factors and does not incorporate broader economic or behavioral variables that may influence electricity demand and carbon outcomes. Future studies could integrate the Tapio decoupling model or extended Kaya identity formulations to link economic growth and industrial activity with emission trajectories. Additionally, sectoral-level analyses (e.g., industrial, residential, and transport electricity consumption) and scenario-based projections could provide more granular insights into the potential pathways for achieving Türkiye's long-term decarbonization goals.

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