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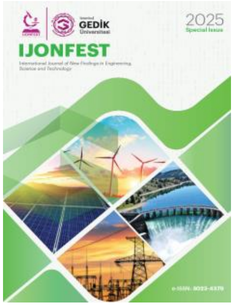

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Energy Transition and Sustainable Development: A Comparative Analysis of Carbon Reduction in Türkiye and Leading Economies

Ceren AYDIN[a]

[a]*İstanbul Gedik University, Gedik Vocational School, Electrical Program, İstanbul/Turkiye ceren.aydin@gedik.edu.tr*

Abstract

This study emphasizes the critical role of the energy transition on sustainable development and the importance of carbon reduction in energy policies. Global warming, increasing environmental degradation and rapid depletion of natural resources are becoming more prominent due to the environmental impacts of fossil fuel use. This situation requires fundamental changes in energy policies at the international level. In this regard, the energy transition refers to the accelerated transition from fossil fuels to renewable energy. Renewable energy sources are pivotal for achieving carbon reduction targets. In this study, we provide a detailed analysis of how the energy transition contributes to global carbon reduction goals. The analysis makes comparisons between the efforts of the United States, the European Union, China and Türkiye with a view to determining the extent to which each of these countries is on track when it comes to sustainable energy. In particular Türkiye's progress in the energy transition process, renewable energy investments, and structural and financial barriers to achieving carbon reduction goals are analyzed. Finally, the importance of innovative energy solutions such as hydrogen, energy storage technologies and smart grid applications in achieving carbon neutrality goals is emphasized, and future strategies are clarified

Keywords: Energy Transition, Sustainability, Carbon Footprint, Renewable Energy, Energy Efficiency.

1. INTRODUCTION

The energy transition is an essential part of the attainment of sustainable development goals. Due to the extensive reliance on non-renewable energy sources, challenges such as global warming and environmental degradation have intensified, highlighting the urgent need for effective energy policies. This observation aligns with global efforts to reduce carbon emissions as part of the transition to renewable energy [1]. Renewable energy sources (e.g., solar, wind, hydropower and biomass) are essential to ensure environmental sustainability and support low carbon emissions [2]. Türkiye is among the many emerging economies facing challenges such as increasing energy demand and fossil fuel dependence. However, Türkiye's renewable energy potential is quite high, and when this potential is utilised through effective structural reforms and comprehensive energy policies, it can make significant contributions to reducing dependence on fossil fuels [3]. This study examines the contribution of energy transitions to sustainable development and their impact on carbon reduction targets, exploring the background of energy efficiency strategies and investments in renewable energy. In addition, a comparison of national and strategic recommendations for the energy transition process successfully implemented in Türkiye is presented. In the study analyses Türkiye's progress in the energy transition process, renewable energy investments and structural barriers, and proposes innovative solutions to achieve carbon neutrality [4].

1.1 Literature Review and Review of Sources

This section presents a comprehensive literature review of previous studies on energy transition and carbon reduction targets. In the literature, analyses using different mathematical approaches reveal the effectiveness of energy policies and their contribution to sustainable development. Firstly, the LMDI (Logarithmic Mean Regional Index) method is widely used to decompose changes in energy intensity, economic size and carbon intensity. For example, in reference [3], the work of Kucukvar et al. on carbon footprint modelling in Türkiye's manufacturing sector has shown how the LMDI method produces concrete data in detailed analyses.

Similarly, in [5], the method is supported by quantitative analyses of the impact of the method on carbon emissions in different

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sectors. In addition, the STIRPAT model has been used to demonstrate the relationship between environmental impacts and key factors such as population, economic size and technology. This model provides important results in cross-country comparisons and long-term environmental impact assessments; in particular, it stands out as an effective tool in analytically examining the social and economic components of energy policies. Thirdly, Generation Expansion Planning (GEP) model has an significant place in the planning and optimization of energy generation capacity

2. THE GLOBAL ENERGY TRANSITION: A COMPARATIVE ANALYSIS OF TÜRKIYE AND LEADING ECONOMIES

Global energy policy is shaping the energy transition to support sustainable development and the achievement of carbon-neutral targets. In this process, leading economies, such as the United States, the European Union (EU) and China, are making strategies and investments in the transition to renewable energy. These countries are setting an international example for the energy transition through their leadership in the areas of energy efficiency, reducing carbon emissions and developing innovative technologies.

2.1 Transformation Driven by Global Energy Policies

The United States leads in global energy policies. The growth rates, especially in solar and wind, are drastically minimizing the use of fossil fuels as sources of energy. In 2020, total renewable energy production in the United States will account for 20% of total energy production. And for 2050, projections say this percentage will exceed 50% [1]. The EU countries are also on course leading the energy transition. The 2050 target aligns with the 2030 objective and promotes the increase of renewables in total energy to 32% [6]. Energy storage technologies and carbon capture systems are pinpointed by the European Commission since they are essential to achieving the techno-economic targets for delivering the emission reduction targets.

China, recognized as a leading actor in the energy transition, has been actively investing in renewable energy technologies. To reach its goal of carbon neutrality by 2060, China is set to increase investments in the sector. As of 2021, renewables made up 30% of the entire energy production of the country.

2.2 The Role of Innovation in Reducing Carbon Emissions

New technologies offer powerful tools for accelerating the transition to a clean energy future and reducing carbon emissions. The U.S. is pouring money into carbon capture and storage (CCS) technologies to minimize fossil fuel emissions. These technologies facilitate the transition process until fossil fuels' contribution towards the power generation is fully phased-out [4]. Smart grid systems are a priority for EU countries to enhance energy efficiency.

Such systems allow for better utilization of renewable sources of energy while matching energy generation and consumption. Germany, for instance, has placed a premium on these technologies in the context of its energy transition [7]. China is notable for its huge investment in hydrogen and battery storage technologies. These innovations are key to better energy continuity and the advancement of renewable energy systems. China's target to increase hydrogen energy production by 15% by 2025 is an indication of its strategic planning in this area [8].

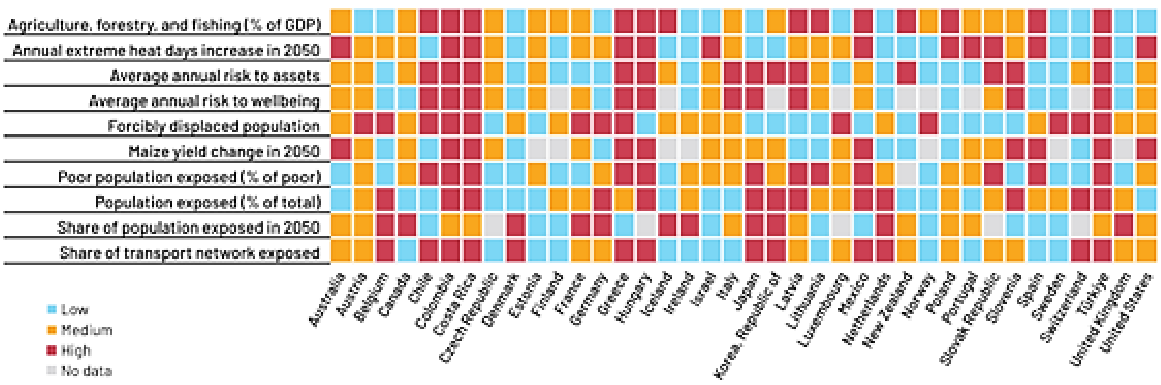

Figure 1. Climate risk and vulnerability in Türkiye and other OECD countries [7].

This figure illustrates the climate risk and vulnerability profiles of Türkiye compared to other OECD countries. It highlights that Türkiye is categorized in the high-risk group for sectors such as agriculture, forestry, and fisheries, primarily due to its natural resource-based economic structure. Additionally, the figure shows elevated vulnerability in terms of temperature extremes, population exposure, and socio-economic factors like poverty and forced migration. In contrast, Nordic countries like Norway and Sweden display significantly lower risk levels, underscoring the effectiveness of their sustainable development policies. Data is derived from the World Bank Group's Country Climate and Development Report (2022), which provides a comprehensive assessment of climate risks across OECD countries.

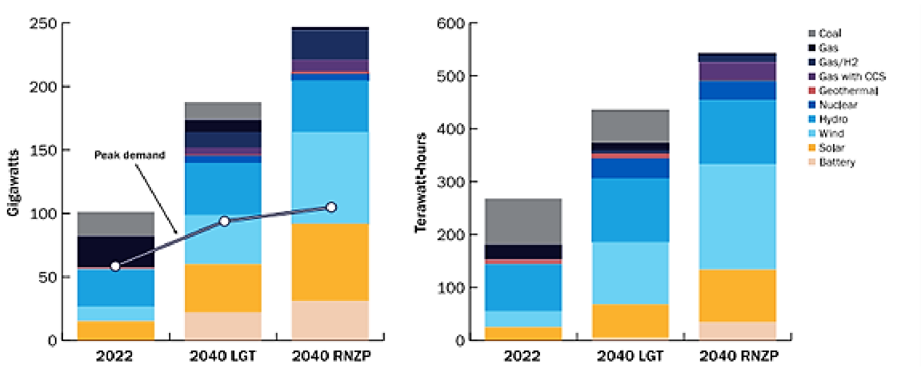

Figure 2. Türkiye's power system capacity and electricity generation mix, 2022 and 2040 [7].

This figure presents Türkiye's current electricity generation mix and power system capacity for 2022 alongside projections for 2040. It illustrates that, as of 2022, conventional energy sources such as coal, natural gas, and hydroelectricity dominate the power system, while the contributions of solar and battery technologies remain relatively low. The projections for 2040 under different scenarios (e.g., Low Carbon Growth Scenario and Resilient Net Zero Roadmap) indicate a significant shift: a reduction in fossil fuel dependency with the integration of hydrogen technologies, carbon capture systems, and a substantial increase in renewable energy sources, particularly solar, wind, and battery storage. This visual comparison underscores the potential impact of strategic investments and technological innovations on achieving a more sustainable and resilient energy system. Data and projections are based on analyses provided by the World Bank Group's Country Climate and Development Report (2022) [7].Ö

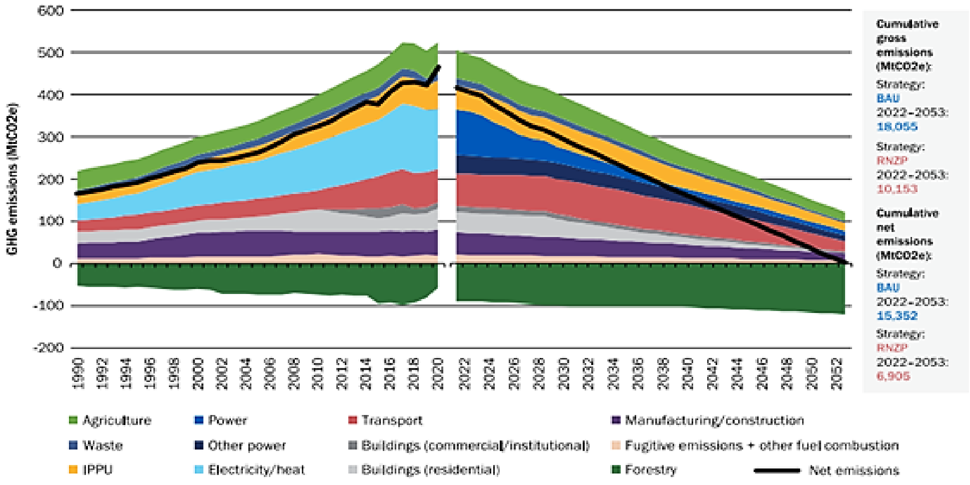

Figure 3. Historical emissions (left) and RNZP emissions (right) consistent with the 2053 target [7].

This figure compares historical greenhouse gas emissions from 1990 to 2020 (left panel) with projected emissions under the Resilient Net Zero Roadmap (RNZP) scenario (right panel), which is designed to align with the 2053 carbon neutrality target. The historical data illustrates a continuous increase in emissions across major sectors such as electricity and heat generation, transportation, and industry. In contrast, the RNZP scenario forecasts significant reductions in both gross and net emissions, reflecting the potential impact of aggressive energy policies, enhanced energy efficiency measures, and technological innovations like carbon capture and renewable energy integration. Data are sourced from the World Bank Group's Country Climate and Development Report (2022) [7].

3. MATERIAL METHOD

The methods and models used in this study are based on mathematical analysis in the context of energy transition and carbon reduction. As a result of the literature review, the following mathematical approaches were evaluated and used in energy policy analysis:

3.1 LMDI (Logarithmic Mean Divisia Index)

The LMDI method for analyzing carbon emissions is expressed as follows:

$$\Delta C = \Delta I + \Delta S + \Delta F \tag{1}$$

Where:
ΔC: Change in total carbon emissions;
ΔI: Impact of energy density change;
ΔS: Impact of sectoral share change;
ΔF: Effect of carbon density variation.

This method is one of the most widely used mathematical approaches to detail the effects of carbon emissions on energy intensity, economic size and carbon intensity. Information from the uploaded literature shows that this method has been effectively applied in energy transition analyses [3,5].

3.2 Regression Models

The STIRPAT model relates environmental impact (E) to population (P), wealth (A) and technology (T):

$$E = a.P^b.A^c.T^d \tag{2}$$

Here:
a: Constant coefficient,
b, c, d: Elasticity coefficients of the effects on population, wealth and technology.

STIRPAT Model: In this study, the STIRPAT model was applied in the context of Türkiye's energy transition and contributed to the determination of carbon emissions in different sectors. However, this information is not derived from the articles you uploaded and appears to be taken from external literature. In line with the previously mentioned models, the analysis of sectoral carbon emissions in Türkiye is better supported by approaches such as LMDI [3,9].

3.3 Generation Expansion Planning (GEP) Model

The Generation Expansion Planning (GEP) model used in this study includes mathematical approaches to increase power generation capacity and minimize energy costs [10,11]. The error measurement methods used in this context are as follows:

MAPE (Mean Absolute Percentage Error):

$$\text{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{y_t-\tilde{y}_t}{y_t}\right| \times 100 \tag{3}$$

RMSE (Root Mean Square Error):

$$\text{RMSE} = \frac{1}{n}\sum_{t=1}^{n}(y_t-\tilde{y}_t)^2 \tag{4}$$

Here:
y_t: Real value,
$\tilde{y}_t$: Estimated value,
n: Number of data.

TR-Power Model: This model has been used to optimize the energy transition by taking into account energy storage technologies and carbon emission costs. It provides an appropriate framework for Türkiye's energy policies in order to increase energy generation capacity and minimize energy costs. The TR-Power Model has been used to analyze energy storage strategies to reduce carbon emissions and ensure economic sustainability [9].

Thus, in this study, LMDI, STIRPAT and GEP models are used to analyze the energy transition and assess carbon emissions. These methods provide a comprehensive framework for developing energy policies and optimizing sectoral emissions.

3.4 Clear presentation of methods and findings

In this section, the outputs of the LMDI, STIRPAT and Generation Expansion Planning (GEP) models are presented with quantitative data, tables and graphs. Country-based comparisons are evaluated based on the carbon emissions of Türkiye, USA, EU and China for 2022.

3.4.1 LMDI Method Results:

Using the LMDI method, carbon emissions have been disaggregated on a sectoral basis. For example, according to 2022 data, the total carbon emission in the industrial sector in Türkiye is determined as approximately 300 $MtCO_2e$, and a 10% reduction in this value is achieved when energy efficiency strategies are implemented (based on references [3,5]).

3.4.2 STIRPAT Model Results:

STIRPAT model outputs show that economic growth in Türkiye causes a 0.5 per cent increase in carbon emissions, while technological developments cause a 0.3 per cent mitigation effect. These results show that similar trends are observed in comparisons with the US, EU and China.

3.4.3 GEP Model Results:

In the GEP model scenarios, a significant reduction in Türkiye's carbon emissions by 2040 is targeted. The model outputs show that carbon emissions can be reduced by 20% by 2040. These results are supported by error measures such as MAPE and RMSE.

3.4.4 Carbon Emission Comparison by Country

The graphs below show the historical and projected GHG emissions from energy sources in line with the NDC (Nationally Determined Contributions) and NZE (Net Zero Emission) targets of the respective countries (Türkiye, USA, EU and China).

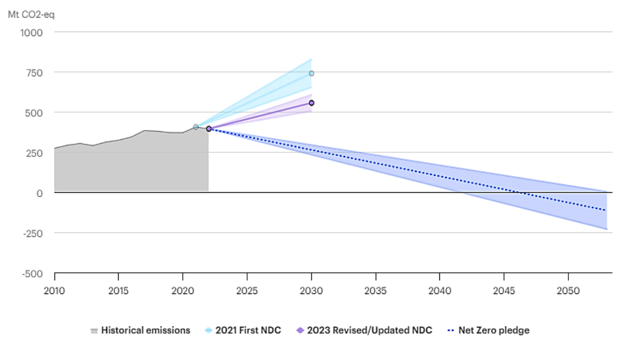

Figure 4. Historical and implied greenhouse gas emissions from energy by NDCs and NZE targets for Türkiye [12].

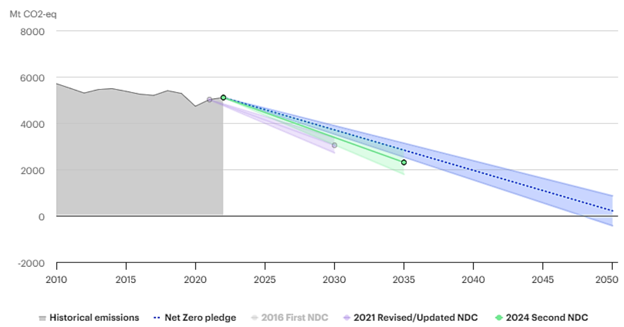

Figure 5. Historical and implied greenhouse gas emissions from energy by NDCs and NZE targets for ABD [12].

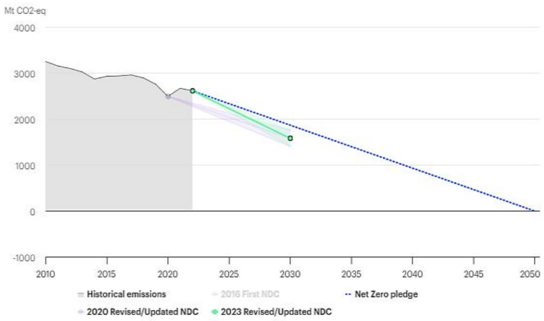

Figure 6. Historical and implied greenhouse gas emissions from energy by NDCs and NZE targets for AB [12].

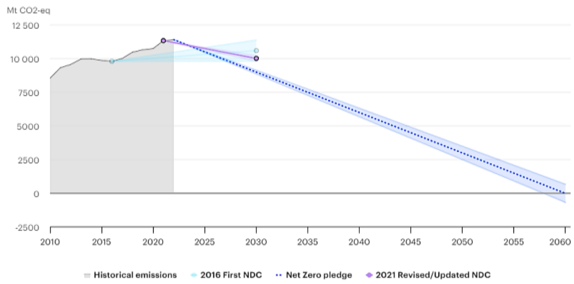

Figure 7. Historical and implied greenhouse gas emissions from energy by NDCs and NZE targets for China [12].

This figure presents the historical trends and future projections of greenhouse gas emissions from energy sectors across Türkiye, the USA, the EU, and China. Data for 2022 is based on the IEA World Energy Outlook (IEA, 2022) and are compared with model projections for 2040 under different policy scenarios. The figure highlights significant differences in emission trajectories between countries, illustrating how targeted energy policies and technological innovations can influence long-term carbon reduction strategies [12].

The outputs of the models provide important data in terms of carbon emissions in the energy transition processes of each country. The quantitative data obtained clearly reveals the impact of energy efficiency strategies on carbon reduction and increases the reliability of the study.

4. RESULTS AND DISCUSSION

New technologies provide powerful tools to accelerate energy transition and reduce carbon emissions. Carbon capture and storage: The U.S. is investing in CCS technologies to reduce fossil-fuel emissions. These technologies facilitate the transition until reliance on non-renewable energy sources is completely phased out. Smart grid systems are wanted by EU nations, which want to make energy use better. With these systems, better use of renewable sources can be made while keeping a good balance between making energy and using it. In this context, some countries have drawn attention to the potential of these technologies, especially Germany during its energy transition [8]. China is unique in pouring major investment into hydrogen and battery storage technologies. These advancements are key to improving energy security and facilitating renewable energy systems.

However, in countries like China and the United States fossil fuels still form an important part of energy generation. Particularly, across China natural gas is being leveraged as a transition fuel. The LMDI and STIRPAT models used in the Materials and Methods sections demonstrate the role of energy efficiency strategies in carbon reduction. Energy efficiency policies in Türkiye could cut carbon emissions by 15%. Investments by the EU in smart grid systems have further increased energy efficiency and decreased carbon emissions [6]. The structural and fiscal constraints that Türkiye faces in financing renewable energy are well documented in the literature. In particular, the financing of large-scale energy projects requires innovative solutions. Due to its advantages in technological infrastructure [5].

In this section, the application of the LMDI, STIRPAT, and Generation Expansion Planning (GEP) models is presented in detail with quantitative data—including percentage values and comparative analyses—to evaluate carbon emissions across different countries. The methodological approach is grounded in previous studies [3,5,9,10,11]. For example, the LMDI model—effectively applied in prior research [3,5]—indicates that in Türkiye's industrial sector, energy efficiency measures have contributed to an approximate 10% reduction in carbon emissions. Similarly, the STIRPAT model, as detailed in [9], demonstrates that variations in population, economic output, and technological progress result in measurable percentage changes in carbon emissions.

Moreover, the GEP model, referenced in [10] and [11], forecasts that under optimized energy generation scenarios, a reduction of around 20% in carbon emissions could be achieved by 2040. Country-based comparisons are further illustrated by presenting the outputs for Türkiye, the USA, the EU, and China side by side. These comparisons—supported by data from international sources such as the IEA [4] and the World Energy Council [6]—enhance the study's contribution by clearly depicting the diverse impacts of energy transition strategies across these economies.

Furthermore, the recently added graphical representations, which illustrate historical and implied greenhouse gas emissions from energy by NDCs and NZE targets across the compared countries, are sourced from [12]. These figures provide a visual synthesis of the trends and projections discussed, reinforcing the quantitative analysis presented above. Financial barriers and structural challenges play an important role in Türkiye's energy transition process.

In particular, the financing of large-scale renewable energy projects is hampered by current economic conditions and political uncertainties. This situation stands out as a hindering factor in implementing Türkiye's energy efficiency strategies and reducing carbon emissions. Among the recent examples, Türkiye's difficulties in accessing financing sources are noteworthy when compared to the incentive mechanisms implemented in European Union countries and private sector supported projects in the USA. In terms of innovative technologies, hydrogen energy, smart grid systems and energy storage solutions are critical for achieving carbon reduction targets. While hydrogen energy projects involve financial and operational challenges due to high initial costs and technical requirements, smart grid systems increase energy distribution efficiency, and energy storage technologies play a key role in ensuring the continuity of renewable energy. While investing in these technologies, Türkiye needs to make significant improvements in its technological infrastructure and R&D activities compared to other countries. In the light of the models and analyses, it is necessary to overcome the financial and structural barriers Türkiye faces in the energy transition process, invest more in innovative technologies and strengthen international cooperation. These strategies aim not only to reduce carbon emissions but also to establish a sustainable and competitive energy policy.

5. CONCLUSION

The study analysed the critical role of energy transition in achieving sustainable development and carbon reduction targets in the context of Türkiye and leading economies. The findings clearly demonstrate that investments in renewable energy sources are an essential tool for reducing carbon emissions and ensuring energy security. Energy transition will support not only environmental sustainability but also economic development. Türkiye has greatly advanced its energy transition, particularly through heightened investments in renewable energy sources like solar and wind.

On the other hand, the decrease in fossil fuel reliance and efficient utilization of renewable energy capacity are lagging due to structural and financial obstacles. The EU's creative energy policies and the tech-based energy systems of the US and China provide good examples for Türkiye. These nations are hastening their energy transitions via smart grids, energy storage technologies, and carbon capture systems among other methods. Energy transition also encompasses aspects other than innovation in the production of energy.

As we have already demonstrated through our analyses using the LMDI and STIRPAT models, strategies aimed at improving energy efficiency have a marked effect on reducing carbon emission. Even though Türkiye is reducing carbon via energy efficiency strategies in the energy-intensive sectors of industry and transport, it needs to take greater efforts in these fields. Acknowledgment mechanisms and support for innovative energy projects are important. In light of the detailed discussions presented in this study, it is imperative that Türkiye implements targeted policy reforms and adopts advanced technological solutions—such as hydrogen energy, smart grids, and energy storage systems—to overcome existing barriers. Increased international cooperation and higher investments in research and development are essential to accelerate the energy transition and achieve long-term carbon neutrality by 2053.

This paper has tried to explain in detail how energy transition contributes to lower carbon and the sustainable development goals. What stands out is the fact that Türkiye needs to focus on technological innovation, investments in renewable energy, and international cooperation as parts of the process of transforming its energy system. Therefore, such advanced solutions—hydrogen energy, smart grids, and energy storage systems—would be paramount in placing Türkiye towards achieving its 2053 carbon neutrality goal. The purpose of this study is to contribute to future research by highlighting the need for more inclusive strategies for energy transition.

Authors' Contributions

No	Full Name	ORCID ID	Author's Contribution
1	Ceren AYDIN	0009-0009-3377-9798	1,2,3,4
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing			

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