ADBA
Information Technology in Economics and Business
Cutting-Edge Scientific Solutions

e-ISSN: 3023-8943
RESEARCH ARTICLE
Vol.3 / No.1 / 2026 / pp.37-40
https://doi.org/10.69882/adba.iteb.2026016

Renewable Energy in Türkiye: Principles, Applications and Sustainability Challenges

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ABSTRACT This study examines the development of renewable energy installed capacity in Türkiye between 2013 and 2023 within the context of resource-based shifts and policy frameworks. Utilizing data from the Ministry of Energy and Natural Resources (ETKB), TEİAŞ, and IRENA, the analysis evaluates annual growth rates and fluctuations in the share of total capacity. The findings reveal that the total installed capacity, which stood at 64,008 MW in 2013, reached 110,914 MW by the end of 2023; notably, solar energy experienced a growth rate exceeding 1,000% during this period. In alignment with the Paris Agreement targets, the study emphasizes the strategic importance of grid flexibility and storage technologies, providing critical implications for future energy policies.

KEYWORDS
Renewable energy
Installed capacity analysis
Energy policy of Türkiye
Energy transition

INTRODUCTION

The environment is a medium in which humans, other living organisms, and non-living entities exist in continuous interaction. Since the dawn of existence, humanity has maintained a constant relationship with the environment and utilized its surroundings. With the advancement of industry and technology, the use of fossil fuels has become widespread, resulting in increased atmospheric emissions of greenhouse gases such as carbon dioxide and methane. It is projected that rising carbon dioxide emissions will increase the global temperature by at least 1.5°C between 2030 and 2050 (Adebayo and Kirikkaleli 2021; Asongu *et al.* 2020).

Sustainable and eco-friendly energy sources are gaining increasing importance as solutions to global environmental problems. As an alternative to fossil fuels, renewable energy sources can generate power with minimal environmental impact and are capable of regenerating within a short timeframe (Yıldırım 2016). Despite these constraints, it is stated that renewable energy consumption exhibits a strong linear relationship with economic development and exerts positive effects on environmental sustainability (Bhattacharya *et al.* 2016; Kirikkaleli and Adebayo 2021). Accordingly, developed nations are accelerating their transition toward carbon-free energy sources (Ali and Seraj 2022).

In this context, ensuring a balanced relationship between economic growth and environmental protection has become one of the most critical challenges of the modern world. Rapid population growth, urbanization, and rising energy demand place increasing pressure on natural resources, making efficient energy use and environmental responsibility indispensable components of development strategies. Therefore, integrating environmental considerations into economic and energy policies is essential not only for mitigating climate-related risks but also for achieving long-term social and economic stability. The pursuit of sustainable development thus requires coordinated efforts that align technological progress, policy frameworks, and environmental awareness.

MATERIALS AND METHODS

This research employs descriptive analysis and time series analysis methodologies to examine Türkiye's renewable energy profile. The regional distribution of Türkiye's solar and wind energy potential was visualized using heat maps generated through Geographic Information Systems (GIS) analysis.

Data Sources and Scope

Dataset: The analyses are based on official statistical reports from the Ministry of Energy and Natural Resources (MENR), the Turkish Electricity Transmission Corporation (TEİAŞ), and the International Renewable Energy Agency (IRENA), covering the period between 2013 and 2023.

Manuscript received: 14 November 2025,
Revised: 21 January 2026,
Accepted: 21 January 2026.

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Analytical Approach: Data processing was conducted using Microsoft Excel and Tableau to calculate annual growth rates and the percentage shares of individual energy sources within the total installed capacity.

Scope and Definitions: In this study, the concept of "installed capacity" was analyzed in units of MW (Megawatts). In the comparative analyses, 2013 was designated as the base year to evaluate the ten-year cumulative growth performance of the energy sources.

Data Collection and Analysis Process

During the data collection process, renewable energy sources were categorized by type: solar, wind, hydroelectric, geothermal, and biomass. Based on this classification, the following analytical steps were implemented:

- Time-series analyses were conducted to determine the annual changes in Türkiye's renewable energy installed capacity (TEİAŞ 2023).
- Regional distribution analysis was carried out using Geographical Information Systems (GIS); maps were generated for sunshine duration, wind speed, and hydroelectric potential (IRENA 2022; ETKB 2023).
- The graphical analysis method was utilized to visualize the share of renewable energy sources within total power generation.
- Furthermore, within the framework of energy policy analysis, Türkiye's carbon reduction targets under the Paris Agreement and its renewable energy incentive policies were examined (Adebayo and Kirikkaleli 2021; Kirikkaleli and Adebayo 2021).

Tools and Software Utilized

Microsoft Excel and Tableau software were utilized for data processing. These tools were employed to calculate the annual rates of change in energy generation and to generate trend analyses. For mapping procedures, Geographic Information Systems (GIS) analyses were applied. Through this methodology, the regional distribution of Türkiye's solar and wind energy potential was visualized using heat maps (IRENA 2022; TEİAŞ 2023).

Limitations of the Study

This research is limited to Türkiye's current renewable energy policies and publicly available data. Difficulties in accessing up-to-date or granular data in certain regions have partially constrained the regional accuracy of the analysis (ETKB 2023). Furthermore, comprehensive data regarding private sector energy investments could not be fully accessed. Nevertheless, the data obtained in this study are of sufficient quality to demonstrate the general trends of Türkiye's energy transition process.

Objectives and Contribution of the Study

The primary objective of this research is to present a scientific perspective on how energy policies can be improved in terms of sustainability by revealing the current status and developmental trajectory of Türkiye's renewable energy capacity. It is intended that the findings will both contribute to the academic literature and serve as a guide for decision-makers in energy policy planning (Xu *et al.* 2019; Balbağ and Balbağ 2019; Kirikkaleli and Adebayo 2021).

Fig. 1 presents the spatial distribution of solar energy potential across Türkiye, indicating regions with high solar irradiation levels that are suitable for large-scale photovoltaic investments. Fig. 2 illustrates the geographical distribution of wind energy potential

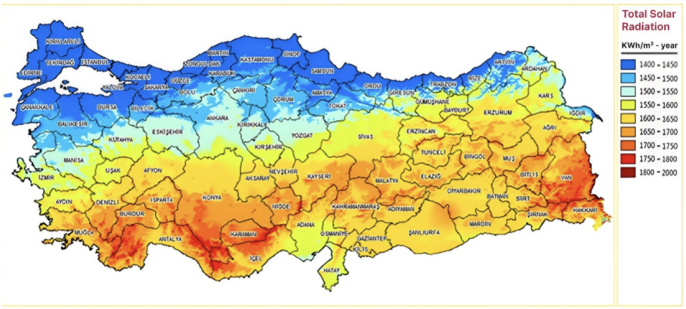

Figure 1 Mapping of Solar Energy Potentials in Türkiye

in Türkiye, highlighting coastal and elevated regions where wind power generation is most feasible.

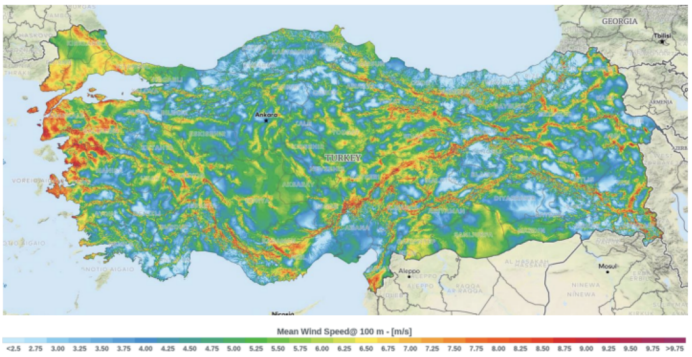

Figure 2 Mapping of Wind Energy Potentials in Türkiye

RESULTS AND DISCUSSION

Türkiye's total installed capacity, which stood at 64,008 MW in 2013, rose to 110,914 MW by the end of 2023, representing an increase of 73.2%.

Growth Analysis by Energy Source

The data reveal that the most dramatic increase among renewable sources over the ten-year period occurred in solar energy. While solar energy had no significant installed capacity in 2013, it reached 15,613.4 MW in 2023, accounting for 14.08% of the total capacity. Similarly, wind energy exhibited steady growth, increasing its share from 4.31% in 2013 to 10.64% in 2023.

Technical and Economic Challenges

The intermittent nature of renewable energy (i.e., periods without wind or sunlight) entails significant grid flexibility issues. Current findings indicate that the need for battery energy storage systems (BESS) and smart grid infrastructure has reached a critical level to ensure the sustainability of this rapid increase in installed capacity. Furthermore, although high initial investment costs pose a barrier, particularly for local investors, the economic feasibility of these investments remains high in terms of long-term energy price stability.

Moreover, advancements in energy storage technologies and digital grid management solutions are expected to significantly alleviate these challenges by enhancing system reliability and operational efficiency. Policy support mechanisms, incentive schemes, and regulatory frameworks also play a crucial role in reducing

Table 1 Installed Capacity Amounts and Shares: 2013–2023 (Unit: MW)

Year	Unit	Coal	Liquid	Nat. Gas	Ren.+Waste	Multi-fuel	Hydro	Geoth.	Wind	Sun	Total
2013	MW	12,605.7	616.3	17,170.6	235.0	8,020.4	22,289.0	310.8	2,759.7	0.1	64,008
	%	19.69	0.96	26.83	0.37	12.53	34.82	0.49	4.31	-	100.00
2018	MW	18,997.5	652.1	25,567.8	1,061.0	3,189.6	28,291.4	1,282.5	7,005.4	5,062.8	88,550.8
	%	21.45	0.74	28.87	1.20	3.60	31.95	1.45	7.91	5.72	100.00
2023	MW	21,099.1	135.4	21,285.6	2,446.4	4,874.3	31,962.4	1,691.3	11,806.1	15,613.4	110,914
	%	19.02	0.12	19.19	2.21	4.39	28.82	1.52	10.64	14.08	100.00

investment risks and accelerating the adoption of flexible energy systems. In this regard, the integration of renewable energy sources with storage and smart grid technologies emerges as a key pillar for achieving resilient and sustainable energy systems.

Fig. 3 illustrates the evolution of Türkiye's total installed power capacity over the years, revealing a sustained upward trend that reflects both increasing energy demand and long-term capacity expansion strategies. A more detailed perspective on this transformation is provided in Fig. 4, which compares the installed capacity by primary energy sources in 2013 and 2023 and clearly demonstrates a structural shift toward renewable energy sources within the national energy mix. This transition is further emphasized by the renewable energy growth curve shown in Fig. 5, indicating a steady and accelerated increase in renewable capacity throughout the 2013–2023 period.

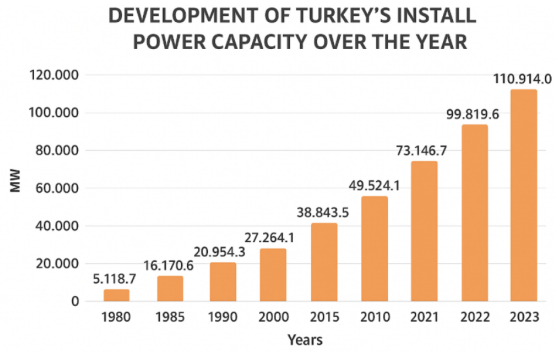

Figure 3 Development of Türkiye's Installed Capacity Over the Years

Fig. 6 presents the distribution of renewable energy sources in 2023, highlighting the dominant roles of hydropower, wind, and solar energy in shaping Türkiye's renewable portfolio. In parallel, Fig. 7 compares fossil-based and renewable energy capacities over the same period, showing a gradual decline in the relative dominance of fossil fuels as renewable sources gain prominence. Finally, Fig. 8 illustrates resource-based growth rates between 2013 and 2023, where renewable energy technologies exhibit significantly higher growth rates compared to conventional energy sources, underscoring the dynamic nature of investment patterns in the energy sector.

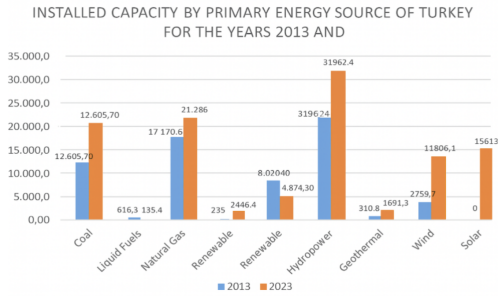

Figure 4 Türkiye's Installed Capacity by Primary Energy Sources for the Years 2013 and 2023

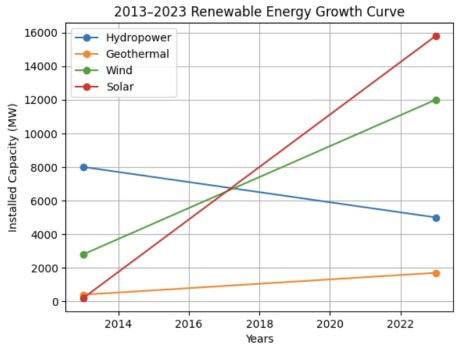

Figure 5 Renewable Energy Growth Curve, 2013–2023

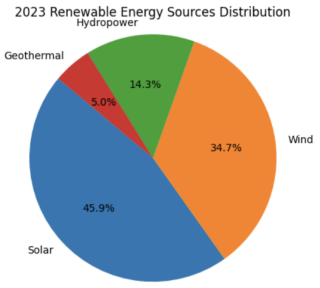

Figure 6 Distribution of Renewable Energy Sources in 2023

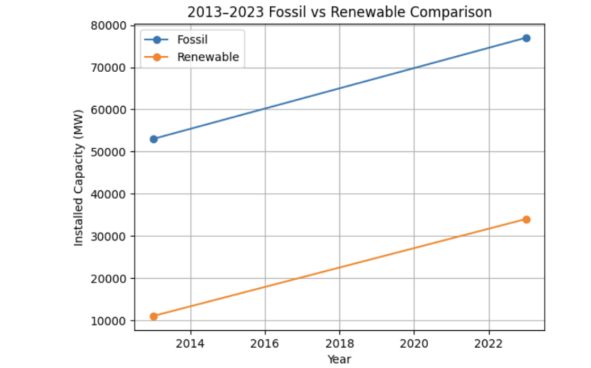

Figure 7 Comparison of Fossil vs. Renewable Energy, 2013–2023

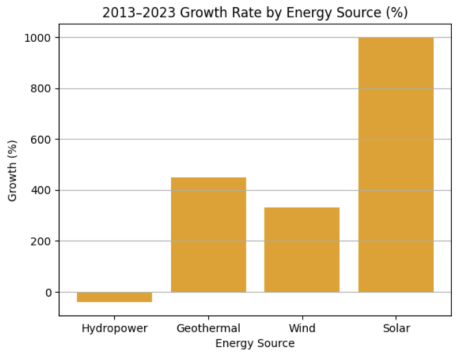

Figure 8 Resource-Based Growth Rate (%) (2013–2023)

CONCLUSION

This mini-data analysis review demonstrates that Türkiye has undergone a significant transformation by nearly doubling its renewable energy capacity over the past decade. The momentum, particularly in solar and wind energy, contributes to the country's carbon reduction targets within the framework of the Paris Agreement. However, to maintain the same level of efficiency in electricity generation as seen in the installed capacity growth, government incentives for grid integration and storage technologies must be increased. It is recommended that future studies quantitatively examine the capacity factors of this expansion on actual electricity generation and the subsequent amounts of emission reductions.

In addition, the structural shift in Türkiye's energy mix, as evidenced by the increasing share of renewable resources and the relative decline of fossil-based capacity, indicates a long-term strategic reorientation toward sustainable energy systems. The heterogeneous growth rates observed across different renewable technologies suggest that investment priorities are increasingly shaped by resource availability, technological maturity, and policy-driven incentives. Nevertheless, the intermittent nature of renewable energy highlights the necessity of enhancing grid flexibility through smart grid applications and battery energy storage systems to ensure system reliability. From this perspective, aligning energy policies with infrastructure development and technological innovation is crucial for translating installed capacity growth into effective electricity generation and measurable environmental benefits.

Ethical standard

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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How to cite this article: Akdoğan, C., Poyraz, M. E., Balcı, B. B., Şen, C. N., and Yılmaz, N. N. Renewable Energy in Türkiye: Principles, Applications and Sustainability Challenges. *Information Technology in Economics and Business*, 3(1), 37-40, 2026.