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# Net-zero Turkey: Renewable energy potential and implementation challenges

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ABSTRACT

Turkey (*Türkiye*) aims to achieve net-zero emissions by 2053, yet remains heavily reliant on fossil fuel imports, accounting for more than 70% of its total energy use. The energy sector is also the largest contributor to national greenhouse gas emissions, responsible for 71.8% of the total in 2022. Renewables comprised 59.4% of installed capacity by energy source in 2024 and generated 45.5% of the electricity consumed. This research presents an original synthesis of energy data in Turkey through a meta-analysis of renewable energy potential, complemented by a comprehensive assessment of national demand–supply dynamics and literature. The analysis identifies critical gaps between theoretical potential and actual implementation, revealing underutilisation of available resources. Solar potential is estimated at 380 TWh/year, yet only 25 TWh is currently produced. Similarly, only 13 GW of a 48 GW wind potential is installed. Geothermal installed capacity stands at 4.5 $GW_e$, utilising 38.4% of the potential. Reservoir levels in several basins critical to hydropower have declined since 2010, with Gediz experiencing a reduction of 45.5%. These trends, driven by climate variability and overuse, have adversely affected hydropower generation in regions where water availability has become increasingly unreliable. Geographical mismatches in demand and supply exist—demand centres are located in the industrial northwest, whereas optimal generation sites are in remote areas, necessitating significant infrastructure investment. Barriers to scaling renewables deployment include grid and storage limitations, regulatory constraints, and inadequate infrastructure. Meeting the projected 2035 electricity demand of 511 TWh sustainably requires the prioritisation of resource optimisation alongside capacity expansion. The net-zero energy transition requires modernising existing facilities, integrating storage solutions, enhancing grid infrastructure, and developing comprehensive policy frameworks for large-scale and distributed renewable energy.

**Contents**



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## Introduction

The global energy sector is responsible for more than 75% of total greenhouse gas emissions (IEA, 2024b), releasing 37.8 $GtCO_2e$ in 2024 (IEA, 2025). Decarbonising national energy systems is, therefore, critical for mitigating climate change impacts, enhancing energy security and meeting sustainable development goals (IRENA, 2024c). Renewable energy resources offer a crucial pathway to achieving these objectives because of their abundance and low environmental impact (Edenhofer et al., 2011). Their adoption has accelerated due to declining technology costs, policy incentives, and advances in energy storage and grid integration technologies (IEA, 2024a). However, the transition remains uneven across regions, influenced by resource availability, policy frameworks, and infrastructure readiness (IRENA, 2024a).

Turkey (Türkiye) exemplifies the complex interplay of opportunities and challenges associated with the global net zero transition. Strategically positioned at the crossroads of Europe and Asia, Turkey's energy demand is rising due to urbanisation, industrial expansion, and population growth (Yildiz, 2010). This demand has outpaced domestic energy production, leaving the country heavily reliant on imported fossil fuels to meet its needs (MENR, 2023b). This dependence has exposed Turkey to price volatility in global energy markets, increased energy security risks, and a growing economic burden (World Bank, 2022). The energy sector is also the country's largest contributor to GHG emissions, responsible for 71.8% of the national total in 2022 (TURKSTAT, 2023). Consequently, increasing the share of renewable energy has emerged as a strategic priority in Turkey's energy policy, offering a means to reduce the dependency on imports while supporting the country's climate commitments and economic aspirations (Kaya, 2006). The country ratified the Paris Agreement in 2021 (Government of Türkiye, 2021) and aims to achieve net-zero emissions by 2053 (MEUCC, 2023), yet significant barriers remain, including dependence on fossil fuel imports, high energy costs, and policy and regulatory challenges.

Turkey's renewable energy potential is shaped by its diverse geographical and climatic conditions, enabling access to an array of resources, including solar, wind, hydropower, geothermal, and biomass energy. Each resource presents distinct opportunities and challenges, with variation in technical potential, regional distribution, and cost-effectiveness. Solar energy stands out with its significant theoretical potential, particularly in Turkey's southern and central regions, where high solar irradiance levels are observed year-round (Dinçer, 2011). The country's wind energy potential is also significant, especially in western and coastal areas, while hydropower continues to play a dominant role in electricity generation. Geothermal energy benefits from Turkey's location along tectonic fault lines, presenting one of the world's largest reserves for both power generation and direct heat applications (Kaygusuz & Kaygusuz, 2004). Biomass energy offers additional opportunities, particularly in rural areas where agricultural residues and waste are readily available (Toklu, 2017).

Despite its rich resource base, Turkey faces numerous challenges in fully utilising its renewable energy potential. Infrastructure and grid integration barriers, economic and financial constraints, and regulatory and policy hurdles are among the primary obstacles (IEA, 2021a). The intermittency of solar and wind energy, for instance, requires substantial investments in grid modernisation, energy storage, and demand-side management to ensure a stable power supply (IRENA, 2018). Similarly, the geographical mismatch between resource-rich regions and major demand centres necessitates significant development of transmission infrastructure (Brown et al., 2018). Economic factors, such as high initial investment costs and limited financial support mechanisms, further inhibit renewable energy deployment, particularly for emerging technologies like offshore wind and advanced bioenergy systems (Esteban et al., 2011; Festel et al., 2014). Policy and regulatory frameworks, while improved in recent years, still fall short of fostering a comprehensive and inclusive renewable energy transition, particularly for smaller stakeholders, such as residential and community projects (Walker, 2008).

This research critically examines Turkey's renewable energy landscape, focusing on energy demand trends, resource potential, and deployment challenges. It synthesises existing literature, policy frameworks, and statistical data to assess the interplay between energy supply and demand. A meta-analysis of renewable energy potential, coupled with an evaluation of infrastructure development, offers a comprehensive understanding of the factors shaping Turkey's energy transition. Additionally, a comparative analysis of global best practices informs strategic recommendations for overcoming implementation barriers. The findings provide a systems-level perspective on the challenges and opportunities for accelerating Turkey's net-zero energy transition while offering lessons applicable to other nations facing similar challenges.

The rest of the article is structured as follows. Section 'Energy demand and supply' examines the factors driving Turkey's growing energy demand, including its reliance on energy imports and the role of renewables in mitigating these challenges. Section 'Renewable energy potential' assesses Turkey's renewable energy potential, detailing key resources, their capacities, and estimation methodologies. Section 'Renewable energy implementation challenges' explores challenges in renewable energy deployment, focusing on technical, economic, and regulatory barriers and their implications for Turkey's energy security and climate goals. By synthesising these themes, Section 'Conclusion' highlights the need of integrated strategies that optimise resource complementarity, address implementation barriers, and enhance policy frameworks.

## Energy demand and supply

The energy mix for electricity generation in Turkey is diverse, comprising fossil fuels, hydropower, wind, solar, geothermal, and biomass. As the country stands at a pivotal crossroads, balancing the demands of its booming economy and growing population poses a significant challenge, particularly in the context of global climate change imperatives. Turkey achieved universal access to electricity in 2010, a milestone demonstrating its notable progress in extending this essential service across both rural and urban areas (World Bank, 2023). However, this advancement also brings to the forefront the substantial challenges in meeting the rising energy demand, especially in the context of rapid economic and industrial growth. The country's electricity generation capacity stands at 115.4 GW by the end of 2024 (TEİAŞ, 2024). Looking ahead, the Turkish National Energy Plan study projects that by 2035 the electricity consumption will increase by 50% to 510.5 TWh, a significant increase from the 340.8 TWh[1] in 2024 (MENR, 2022a; TEİAŞ, 2024). This projection highlights the significant challenge Turkey faces in scaling up its energy supply to meet future demands. Fig. 1 illustrates the trajectory of Turkey's electricity generation, consumption

[1] Net amount supplied to the grid after accounting for imports and exports

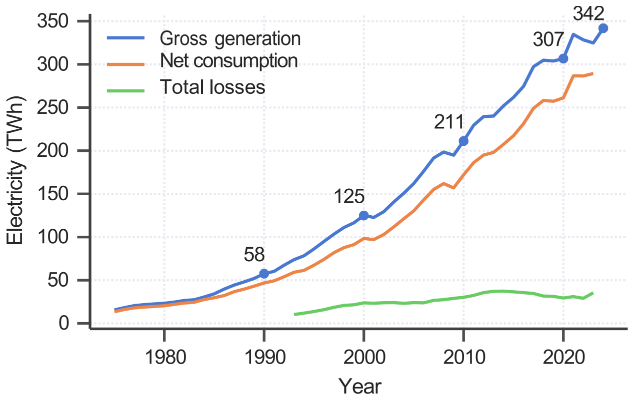


**Fig. 1.** Gross electricity generation in Turkey between 1975 and 2024, along with net consumption and losses from 1993 to 2023.
*Data source:* TEİAŞ (2024), TURKSTAT (2025).

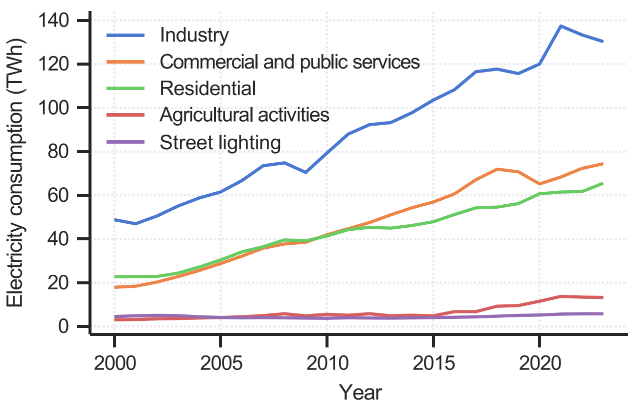


**Fig. 2.** Sector-wise electricity consumption between 1995 and 2022.
*Data source:* TURKSTAT (2025).

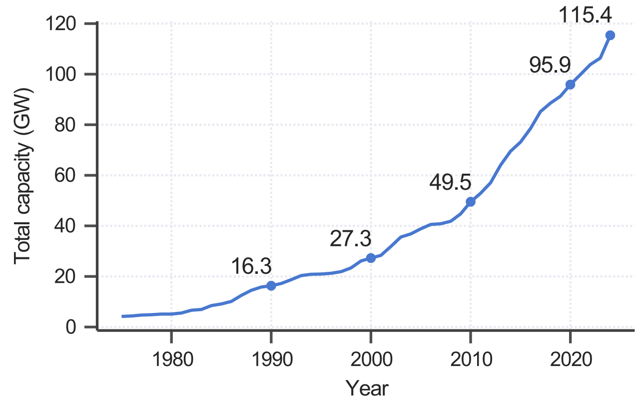


**Fig. 3.** Installed capacity of power plants in Turkey between 1975 and 2024.
*Data source:* TEİAŞ (2024), TURKSTAT (2025).

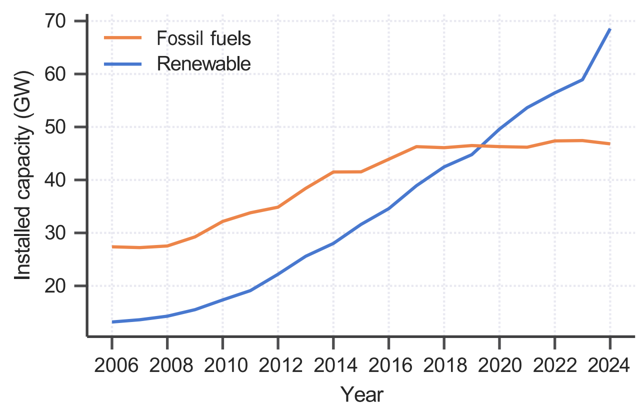


**Fig. 4.** Capacity by energy source between 2006 and 2024.

and losses. Between 1990 and 2024, gross generation expanded nearly sixfold—from 58 TWh to 342 TWh. This growth occurred in distinct phases: increasing from 58 TWh to 125 TWh between 1990 and 2000 (a 117% increase), growing further to 211 TWh by 2010 (a 69% increase), followed by a more moderate growth to 307 TWh by 2020 (a 45% increase). This gradual deceleration in the growth rate across decades suggests a maturing electricity sector and a decoupling of energy consumption from economic growth (Rüstemoğlu, 2024). The persistent gap between gross generation and net consumption, represented by total losses, has remained relatively stable in percentage terms despite the sector's significant expansion.

Fig. 2 further illustrates this growth pattern through sectoral consumption trends, with industry consistently being the dominant consumer, followed by the commercial and public services sector and then the residential sector. The industrial sector's consumption has shown particularly strong growth, especially after 2010, reflecting the country's continued industrial development and economic growth.

Fig. 3 illustrates the significant increase in installed capacity, from 16.3 GW in 1990 to 115.4 GW in 2024, reflecting Turkey's efforts to meet growing demand. The capacity expansion showed steady growth from 16.3 to 27.3 GW between 1990 and 2000, followed by a more rapid increase to 49.5 GW by 2010. The most dramatic growth occurred in the following decade, with capacity nearly doubling to 95.9 GW by 2020. The expansion continued, reaching 115.4 GW by the end of 2024.

Fig. 4 reveals the underlying transformation in Turkey's power sector composition: while fossil fuel-based capacity showed steady growth until 2017, reaching approximately 46 GW, it has since plateaued. In contrast, renewable energy capacity grew significantly, particularly after 2016, accelerating from about 40 GW to nearly 70 GW by 2024. This fundamental shift in capacity addition patterns indicates a clear transition in Turkey's electricity infrastructure development strategy, moving away from fossil fuel-based expansion towards renewable energy technologies.

Fig. 5 illustrates the long-term transformation in generation shares—fossil fuel-based generation shows a consistent downward trend, declining from around 80% in 2006 to 54.5% in 2024, albeit with year-to-year fluctuations. Simultaneously, renewable generation demonstrates a steady upward trajectory, increasing from approximately 20% to 45.5% during the same period. This convergence of shares represents not only a fundamental shift in Turkey's electricity generation profile but also signals an accelerating renewable energy transition. By 2024, renewable sources accounted for 59.4% of Turkey's installed electricity generation capacity and 45.5% of total electricity generation. This difference reflects the nature of generation profiles across energy sources and does not necessarily indicate underperformance, as it is largely driven by the intermittent nature of renewables, which are dependent on weather conditions—including hydrological variability for hydropower.

While there are no active nuclear power plants, ongoing projects, such as the one in Akkuyu, Mersin, initiated through a cooperation agreement with Russia, signal the country's efforts to diversify its energy sources further (MENR, 2022c).

*Power supply from fossil fuels*

In Turkey, thermal power plants constitute a major part of the nation's electricity supply. By the end of 2024, the country operated 339 natural gas-fuelled thermal power plants with a combined installed

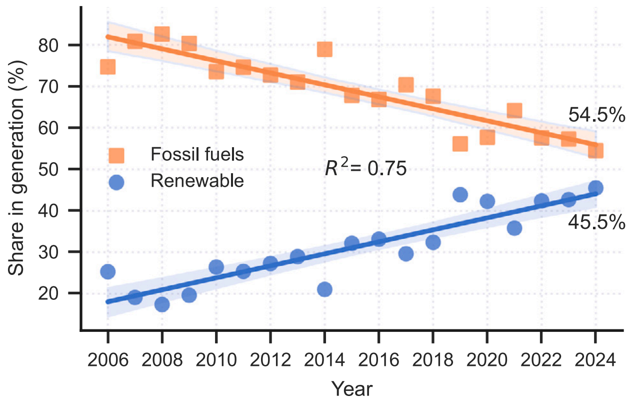


**Fig. 5.** The share of energy sources in electricity generation between 2006 and 2024. $R^2 = 0.75$ applies to both series.

capacity of 24.7 GW. In addition, 81 thermal power plants using various types of coal and petroleum products contributed a collective capacity of 22.1 GW. Furthermore, 460 thermal plants utilising industrial waste heat and biomass added a capacity of 2.4 GW. Although these waste heat and biomass plants operate thermally, their figures are classified under the renewable biomass category in this paper, as they do not rely on fossil fuel-based sources.

Turkey's dependency on imported energy sources is noteworthy. While the country does possess coal mines, its oil resources are extremely limited. According to the country's 2023 energy balance, nearly all (98%) of its natural gas supply is imported (MENR, 2023b). This heavy reliance on imports poses both economic and security challenges for Turkey's energy landscape, as Fig. 6 illustrates the difference between local production and energy imports. The figure reveals that imported energy sources accounted for 71.9% of Turkey's total energy supply in 2023, with natural gas representing the largest share at 33.1% of imports, followed by crude oil (26.2%), coal (19.7%), and petroleum products (20.6%). Domestic production, comprising both fossil fuels (19.3%) and renewable sources (8.8%), contributed only 28.1% to the total energy mix, highlighting the country's significant external energy dependence.

The temporal evolution shown in Fig. 6a demonstrates a steady increase in total energy consumption from approximately 100 Mtoe in 2006 to over 175 Mtoe by 2023. While imports have historically dominated the supply mix, a notable trend emerges after 2017. Despite continuing growth in total energy demand, import levels have relatively stabilised. This stabilisation coincides with accelerated growth in domestic renewable energy production, suggesting that the incremental energy demand in recent years has been increasingly met through domestic renewable sources rather than additional imports. This trend indicates that renewable energy expansion is beginning to influence Turkey's energy trade balance, though the country's fundamental dependence on fossil fuel imports, particularly natural gas (33.1%) and crude oil (26.2%), remains significant. This persistent import dependency exposes Turkey's energy sector to international market volatility and geopolitical risks, reinforcing the strategic rationale for continued renewable energy expansion.

*Power supply from renewables*

Turkey benefits from diverse and regionally distributed renewable energy resources. By the end of 2024, the hydropower sector is particularly robust, with 764 plants and a total power capacity of 32.2 GW, inclusive of both river- and dam-based facilities. The country has 369 wind power plants with a combined installed capacity of 12.6 GW, and solar energy is also on the rise with 31,224 power plants and a total capacity of 19.6 GW. Other renewable sources include 76 industrial waste heat facilities (0.32 GW), 384 biogas, biomass, and other biological plants (2.16 GW), and 66 geothermal plants (1.73 GW).

The temporal evolution of Turkey's renewable electricity generation portfolio exhibits distinct patterns of growth and diversification across different technologies, as illustrated in Fig. 7. Hydropower maintains a dominant position in the renewable generation mix, demonstrating both its established role and characteristic inter-annual variability. In 2024, hydropower generation reached 73.1 TWh, representing the largest share among renewable sources. However, the trajectory of hydropower generation shows notable fluctuations, with significant peaks in 2019 (~90 TWh) and troughs in 2014 (~40 TWh), reflecting its sensitivity to hydrological conditions. Wind power has emerged as the second-largest renewable source, exhibiting consistent year-on-year growth from negligible generation in 2006 to 36.7 TWh in 2024. This growth pattern demonstrates a more stable and predictable expansion compared to hydropower's variable output. Solar power entered Turkey's renewable energy portfolio in 2014 and has demonstrated remarkable growth, reaching 24.9 TWh by 2024. This extraordinary decade of growth — practically from zero to becoming the third-largest renewable source — exemplifies the transformative potential of supportive policy frameworks combined with rapidly declining technology costs. Geothermal and biomass have followed more moderate but steady growth trajectories, reaching 11.1 TWh and 9.8 TWh respectively in 2024. Notably, geothermal power showed early adoption compared to solar, with significant generation beginning around 2010, while biomass development gained momentum post-2014. The concurrent growth of these technologies suggests a favourable policy framework supporting technological diversification in Turkey's renewable energy sector. The overall trends reveal a strategic transition from heavy dependence on hydropower to a more balanced renewable generation portfolio, with wind and solar emerging as significant contributors in the latter half of the observed period. This diversification not only enhances energy security through reduced dependence on hydrological conditions but also reflects Turkey's adaptation to technological advances and cost reductions in various renewable technologies.

Fig. 8 presents a comprehensive view of Turkey's power sector transformation through three complementary visualisations of installed generation capacity: temporal evolution (Fig. 8a), distribution by source in 2024 (Fig. 8b), and fossil fuel subcategories (Fig. 8c). The installed capacity development from 2006 to 2024 reveals a sustained expansion of the power sector, with total capacity more than doubling from approximately 40 to 115 GW. While fossil fuels maintained a relatively stable installed capacity of around 45 GW throughout this period (40.6% of total capacity in 2024), renewable technologies have driven the majority of capacity additions. Hydropower remains the leading renewable technology with 27.9% of total installed capacity in 2024, followed by solar and wind with 17% and 10.9% respectively. Biomass and geothermal contribute smaller but notable shares at 2.1% and 1.5% respectively. This capacity distribution reflects Turkey's concurrent commitment to sustaining its conventional thermal power fleet while significantly scaling up renewable energy capacity, particularly in solar and wind. The simultaneous expansion across multiple renewable technologies indicates a strategic effort to diversify the national electricity generation mix.

The country continues to demonstrate its commitment to energy transition through increasingly ambitious renewable energy targets. While the previous strategic plan for 2019–2023 set relatively modest goals, the new National Energy Plan 2022 (MENR, 2022a) focuses on substantial wind and solar power installations by 2035. According to the plan, Turkey aims to more than quadruple its solar energy capacity to 52.9 GW by 2035, representing one of the most ambitious solar deployment targets in the region. For wind energy, the target of 29.6 GW (including 24.6 GW onshore and 5 GW offshore) demonstrates a significant scaling up from previous goals. The hydropower sector, which has historically been the backbone of Turkey's renewable energy portfolio, is projected to reach 35.1 GW, showing a more measured

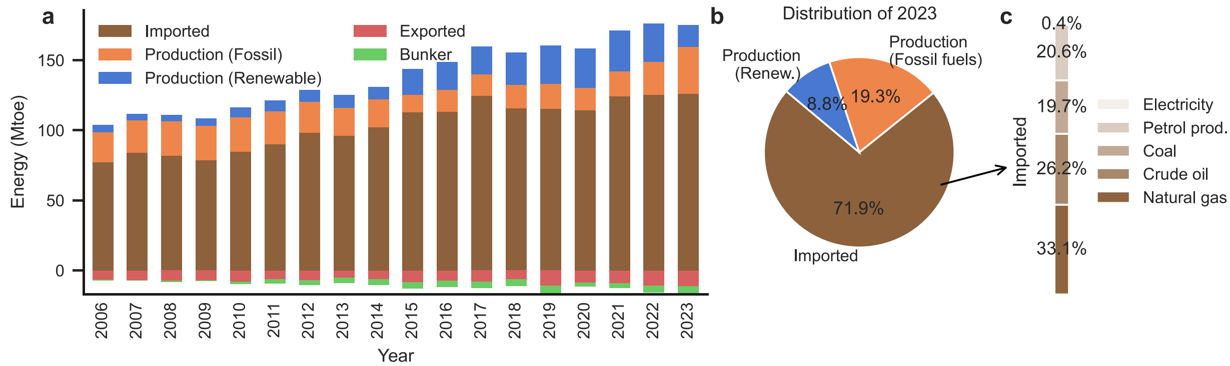


**Fig. 6.** Turkey's primary energy supply by source between 2006 and 2023. (a) Imported energy, national production, exported energy and bunker fuel use. (b) Distribution of total primary energy supply in 2023 (c) Breakdown of imported energy sources in 2023.
*Data source:* MENR (2023b).

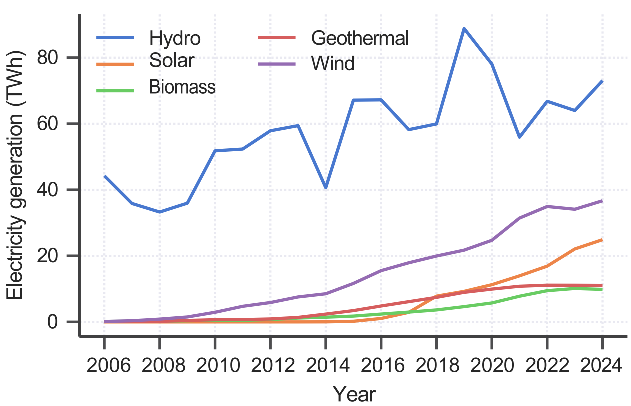


**Fig. 7.** Electricity generation from renewable sources from 2006 to 2024.
*Data source:* MENR (2023b), TEİAŞ (2024).

expansion given the economic, technical and environmental challenges. The combined target for geothermal and biomass power of 5.1 GW indicates continued interest in diversifying the renewable energy mix, though the aggregated presentation of these technologies in the plan makes it difficult to assess specific goals for each source. Notably, the plan also introduces substantial flexibility measures, including 7.5 GW of battery storage and 5.0 GW of electrolyser capacity, acknowledging the integration challenges posed by high renewable penetration. These targets, while ambitious, raise important questions about implementation pathways, grid integration strategies, and the required policy frameworks to support such rapid deployment. The plan's projection that renewable sources will constitute 64.7% of installed capacity by 2035 represents a significant transformation of Turkey's energy system, requiring careful consideration of technical, economic, and social factors. Moreover, Turkey's significant dependence on energy imports adds another layer of complexity, as geopolitical instabilities could impact the nation's ability to secure the necessary technology and components for renewable energy infrastructure. The feasibility of achieving such rapid growth rates must be evaluated within the context of both technological readiness and market dynamics. The plan's success will ultimately depend on comprehensive strategy implementation, cross-sectoral coordination, and the development of robust policy mechanisms to support this ambitious energy transition.

## Renewable energy potential

### *Hydro energy*

Hydropower has been a cornerstone of Turkey's energy landscape since before the republic's establishment in 1923. Turkey's hydropower potential figures have been consistently reported across multiple studies, primarily based on assessments by the State Hydraulic Works (*Devlet Su İşleri*– hereafter DSI). The theoretical maximum hydropower potential is estimated at 433 TWh/year (Bakis & Demirbas, 2004), representing approximately 1.1% of global theoretical potential. The technically feasible potential, accounting for construction and operational limitations, is 216 TWh/year (Kucukali, 2010). However, estimates of economically viable potential show variations, generally ranging between 125–140 TWh/year (Capik et al., 2012; Erdogdu, 2011; Ozturk et al., 2009; Yüksel, 2010; Yuksel, 2012), with 130 TWh/year being the most frequently cited figure (Akpinar et al., 2011; Dursun & Gokcol, 2011). DSI's economic potential calculations expanded over time to include small hydropower installations, contributing an additional 38 TWh/year from smaller water bodies and upper elevations of larger basins (Kaygusuz, 2009). These variations in economic potential assessments reflect both evolving energy market conditions and the inclusion of previously undervalued benefits in hydropower development (Kömürcü & Akpinar, 2010).

However, these historical potential estimates require critical examination in light of climate change impacts. Data from the Turkish State Meteorological Service demonstrates concerning trends: mean annual precipitation has decreased by 8% between 2002 and 2023 (TSMS, 2023b), while average temperatures have risen by 1.2 °C in the last three decades (TSMS, 2023a). The vulnerability of hydropower to climate variability is evident in recent production figures, with hydroelectric generation dropping significantly from 78.1 TWh in 2020 to 55.9 TWh in 2021 despite increased installed capacity (MENR, 2023b). As shown in Fig. 7, while other renewable sources demonstrate steady upward trends in generation, hydropower exhibits notable fluctuations, highlighting its sensitivity to climate variations.

Climate projections suggest challenging conditions ahead, with Turkey potentially facing temperature increases of 0.5–3 °C by 2040, with more pronounced warming of 2–3 °C expected in summer months, while precipitation patterns during this period show significant regional variability, ranging from −40% to +40% depending on the region and season (Demircan et al., 2017). These changes could reduce annual river discharge by 19%–58% in affected regions, particularly in the southeastern region where major hydroelectric facilities on the Euphrates-Tigris system were designed using historical flow assumptions that may no longer be valid under changing climate conditions (Bozkurt et al., 2015).

The economic viability of hydropower in Turkey warrants critical reassessment given mounting evidence of water availability challenges and evolving market conditions. While global levelised cost of electricity for newly-commissioned hydropower projects remains competitive at $0.057/kWh in 2023 (IRENA, 2024b), this figure assumes optimal capacity factors that may be increasingly difficult to achieve in Turkey.

Historical reservoir levels across major basins show concerning trends, as visualised in Fig. 9. The Euphrates-Tigris basin, home to

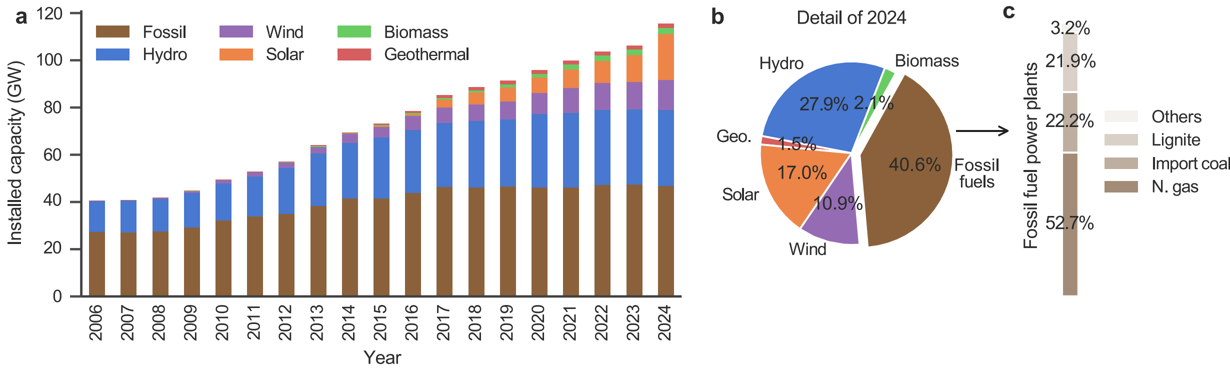


**Fig. 8.** Installed electricity generation capacity by energy source between 2006 and 2024. (a) Development of installed capacity. (b) Share of installed capacity by source in 2024. (c) Breakdown of installed fossil-fuel capacity by source in 2024.
*Data source:* TEİAŞ (2022, 2024).

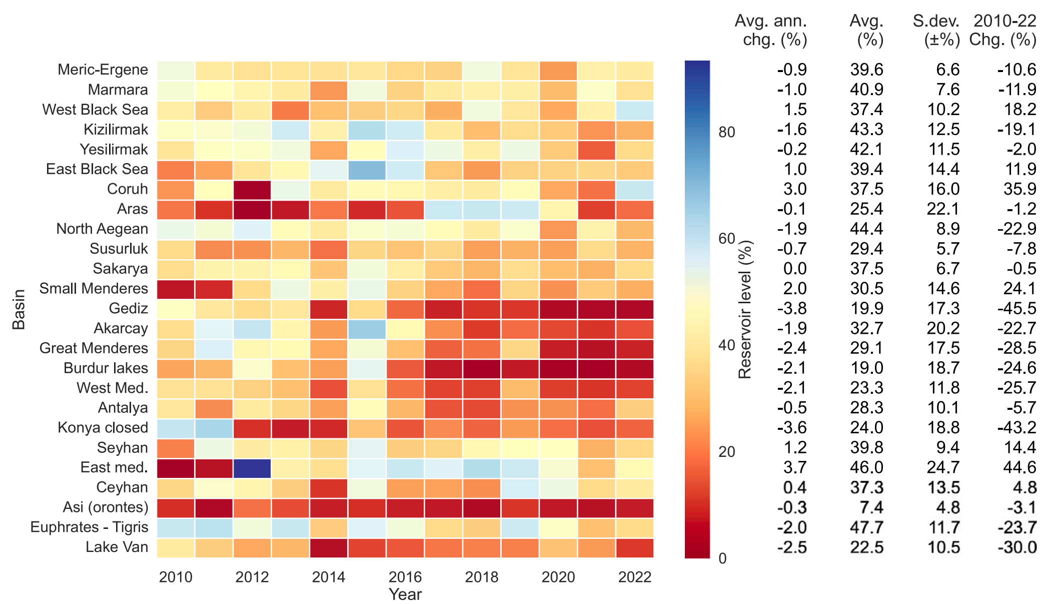


**Fig. 9.** Reservoir levels in Turkish basins 2010–2022.
*Data source:* DSİ (2023).

major hydroelectric facilities, shows a consistent pattern of declining water availability with a 2% average annual reduction (DSİ, 2023). This spatial pattern becomes particularly evident when examining basins regionally, with southwestern regions showing consistently lower reservoir levels in recent years. The data reveals a concerning cluster of severe depletion in southwestern basins, including Gediz with an average annual decrease of −3.8%, followed by Great Menderes (−2.1%), Burdur (−2.1%), West Mediterranean (−2.1%) and Akarçay (−1.9%). Most notably, Gediz and Konya basins experienced the most declines, with −45.5% and −43.2% changes respectively compared to 2010 levels. This contrasts sharply with positive trends in some basins, particularly the East Mediterranean (+44.6%) and Çoruh (+35.9%), highlighting significant regional disparities in water resource trends.

This pattern of decreasing reservoir levels extends across multiple basins, exhibiting even more severe declines. The figure reveals not only declining trends but also increasing variability in reservoir levels, suggesting less reliable water availability for power generation. The variability in reservoir levels, measured by standard deviation, shows marked regional differences. While northern basins like Meriç-Ergene and Marmara show relatively stable patterns (standard deviations of 6.6% and 7.6% respectively), southeastern regions demonstrate much higher volatility, with the East Mediterranean basin showing the highest variability (±24.7%). This north-south disparity in stability adds another layer of complexity to hydropower planning, as facilities in more volatile regions may face greater operational challenges.

Despite these warning signs, Turkey ranked first in European capacity additions with 513 MW of newly installed hydropower capacity in 2021 (IHA, 2022), raising questions about potential stranded asset risks. This aggressive expansion appears to conflict with observed water availability trends and may lead to facilities operating well below designed capacity factors, undermining their economic rationale. While the rising social cost of carbon — from \$9 to \$40 per $tCO_2$ (high discount rate) over the past decade (Tol, 2023) — seemingly justifies shifting investment away from thermal alternatives, the diminishing water availability may erode hydropower's traditional cost advantages, creating a complex risk-reward scenario for energy planners.

While Turkey has focused heavily on large-scale hydropower development, examination of its small hydropower (SHP) sector reveals a different development pattern. Turkey's SHP development, defined as installations less than 10 MW capacity (Punys & Pelikan, 2007), reflects a notable underutilisation compared to its large-scale hydropower. Despite constituting only 1.5% of exploited hydropower potential through run-off river and channel installations (Bakis & Demirbas, 2004), SHP represents a significant untapped opportunity. The economic viability of SHP is particularly compelling when utilising existing infrastructure and natural head drops in Turkey's mountainous regions, requiring

**Table 1**
Wind power potential at different wind speeds in Turkey.

| Annual average wind speed (m/s) | Offshore wind potential (GW) | Total potential (GW) | Source |
|---|---|---|---|
| 7 to 8 | 40.70 | | WBG (2019) |
| >8 | 34.50 | | |
| 6.5–7.0 | 6.93 | 83.91 | İlkiliç (2012) MENR (2022e) |
| 7.0–7.5 | 5.13 | 29.26 | |
| 7.5–8.0 | 3.44 | 12.99 | |
| 8.0–9.0 | 1.74 | 5.40 | |
| >9.0 | 0.14 | 0.20 | |

**Table 2**
Solar radiation and sunlight duration in different regions of Turkey.
*Data source:* MENR (2023a)

| Region | Solar radiation ($kWh/m^2day$) | Sunlight duration (hour/day) |
|---|---|---|
| Southeast Anatolia | 4.0 | 8.2 |
| Mediterranean | 3.8 | 8.1 |
| East Anatolia | 3.7 | 7.3 |
| Central Anatolia | 3.6 | 7.2 |
| Aegean | 3.6 | 7.5 |
| Marmara | 3.2 | 6.6 |
| Black Sea | 3.1 | 5.4 |
| Countrywide average | **4.18** | **7.5** |

simpler infrastructure and lower investment compared to large hydropower installations (Kucukali, 2010). This pattern of development contrasts with many European countries where SHP has played a more substantial role in renewable energy portfolios (Capik et al., 2012).

Turkey's current utilisation rate of less than 50% of identified economic potential appears favourable at first glance, suggesting room for growth. However, this figure deserves careful scrutiny due to several critical factors. Historical potential estimates likely overstate actual generation capacity under changing climate conditions, as evidenced by the declining reservoir levels. Moreover, the widening gap between installed capacity and actual generation (MENR, 2023b) suggests diminishing returns on new investments. European countries which achieved high utilisation rates of their economic potential, such as Austria (79%) and Germany (92%) (IEA, 2021b), operated under different climate and economic conditions, making direct comparisons potentially misleading. Given the clear trends of declining reservoir levels due to climate change (DSİ, 2023), the modernisation of existing facilities through solutions such as pump-storage hydropower (Barbaros et al., 2021) and floating solar-hydro hybrid systems (Ateş, 2022; Kulat et al., 2023) might be a more valuable investment strategy than new construction (Spencer et al., 2019). Overall, Turkey's hydropower sector requires a strategic reset, with a particular focus on updating economic potential assessments to reflect long-term climate projections.

*Wind energy*

The first commercial wind power installation in Turkey was established in Çeşme in 1998 with an 8.7 MW capacity (TSMS, 2022). The Aegean and Mediterranean coastal regions have since become primary locations for wind energy development, driven by their favourable wind conditions. Multiple assessments have produced varying estimates of Turkey's wind energy potential. The Turkish National Committee of World Energy Council's initial evaluation indicated an overall potential of 88 GW, with 10 GW deemed economically viable (Güler, 2009). According to Sahin (2008), Turkey's wind atlas indicated a total potential of 58 GW, comprising 47 GW onshore and 11 GW offshore capacity. The World Bank Group estimates Turkey's offshore wind potential at 75 GW, comprising 12 GW fixed and 63 GW floating platforms (WBG, 2019). The Ministry of Energy and Natural Resources of Turkey (MENR), through the Wind Energy Potential Atlas of Turkey, identifies a viable onshore wind potential of 57.8 GW, based on installing 5.3 MW wind turbines per square kilometre in areas with annual average wind speeds exceeding 6.5 m/s at 100 m above ground level, at elevations between 0 and 3000 m. Additionally, they estimate an offshore wind potential of 20.8 GW, achievable through 8.0 MW turbines in areas with wind speeds exceeding 7.5 m/s at 100 m above sea level, where water depths range from 0 to 200 m (MENR, 2022e).

Table 1 summarises wind power potential estimates at various speed, while Fig. 10 offers a visual representation of Turkey's wind energy potential. While wind energy is abundant in both offshore and inland regions, the potential for offshore energy is distinctly higher.

Based on 2022 data, regional distribution reveals that three provinces in the western region — Izmir, Balikesir, and Canakkale — account for 36.5% of the country's total installed wind capacity (TÜREB, 2022). While this concentration in western regions reflects favourable wind conditions, it also indicates potential underutilisation in other areas. Central Anatolian provinces show limited development—for instance, within these 2022 statistics, Kayseri contributes only 2.4% despite having substantial wind resources (Genç & Gökçek, 2009). Recent studies have identified several regions with significant untapped potential, including the Ağaçören district in Aksaray province which showed considerable wind potential despite being marked as zero-potential in earlier assessments, and the Tatvan region in Eastern Anatolia (Şahin & Türkeş, 2020). The stark contrast between coastal and inland installations, with western coastal provinces accounting for over 70% of the total capacity (TÜREB, 2022), suggests that factors beyond wind resource availability, such as grid infrastructure, land accessibility, and investment patterns, significantly influence development patterns (Demir et al., 2024). While wind power installations have concentrated in Turkey's western regions due to favourable wind conditions (Ilkiliç & Aydin, 2015), recent assessments suggest additional viable wind resources exist across different geographical zones that warrant more comprehensive evaluation for optimal utilisation (Şahin & Türkeş, 2020). This geographical imbalance presents challenges for achieving balanced regional development of wind energy resources and highlights the need for the reassessment of wind potential in inland regions.

*Solar energy*

Turkey's journey with solar energy utilisation spans decades, initially focusing on basic applications such as water heating and crop drying, before evolving towards electricity generation. The country's first significant step into solar power generation occurred relatively recently, with an initial capacity of 40 MW in 2014 (TEİAŞ, 2022), marking a delayed entry into large-scale solar electricity production compared to other Mediterranean nations.

Turkey's geographical positioning between 36° and 42° North latitude provides exceptional solar energy resources. Several cite regional solar potential figures from MENR, with daily solar irradiation and sunshine duration data presented in Table 2 (MENR, 2023a). At the national level, the country receives approximately 2767 annual sunshine hours and maintains an average solar irradiation of $1527\,kWh/(m^2year)$. This geographical advantage manifests differently across regions, creating a diverse landscape of solar potential. The Southeastern Anatolia region leads with the highest potential, receiving $1460\,kWh/(m^2year)$ of solar irradiation and approximately 2993 annual sunshine hours. The Mediterranean, Eastern Anatolia, Central Anatolia, and Aegean regions demonstrate strong potential, receiving 1390, 1365, 1314, and $1304\,kWh/(m^2year)$ of solar irradiation respectively. In contrast, Marmara and the Black Sea region show notably lower potential, with solar irradiation levels of 1168 and $1120\,kWh/(m^2year)$ respectively.

Recent assessments of urban solar potential reveal significant opportunities for distributed generation, particularly in metropolitan areas.

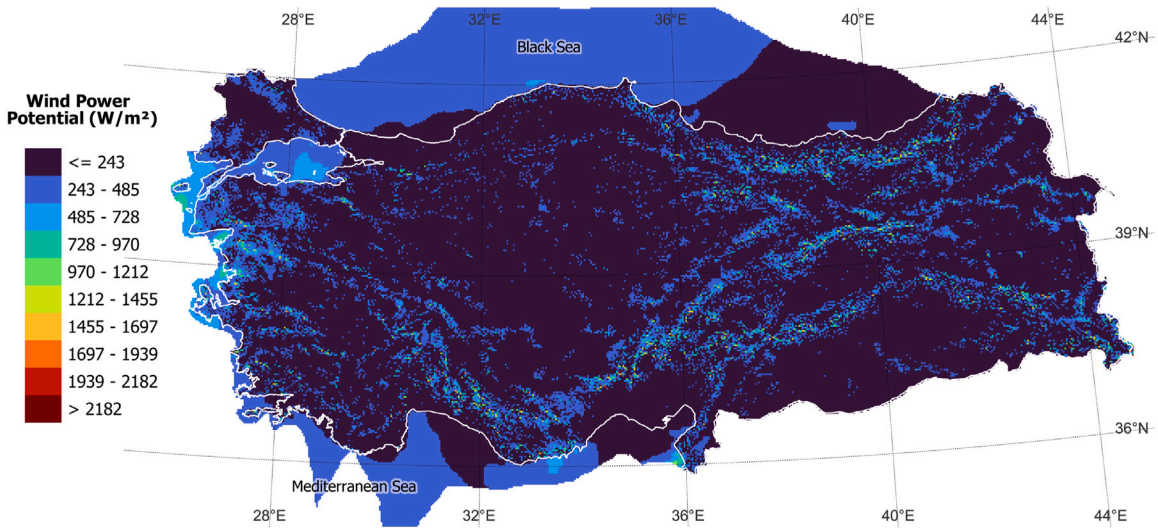


**Fig. 10.** Electricity generation potential from wind power in Turkey.
*Data source:* Davis et al. (2023), DTU (2022).

A comprehensive analysis of Ankara demonstrates a technical PV potential of 1.15 TWh/year for residential buildings, complemented by additional capacity of 55 GWh/year and 26.8 GWh/year for public and commercial buildings respectively (Kutlu et al., 2022). Urban rooftop installations offer particular advantages such as reduced transmission losses and improved grid stability (Or et al., 2024). This approach has proven successful in other Mediterranean countries, where rooftop solar has contributed significantly to meeting urban energy demands (Celik & Özgür, 2020). Integration opportunities between solar and hydropower present another promising avenue for development. Turkey's extensive hydroelectric infrastructure could potentially complement solar generation, with hydro resources providing balancing services during nighttime and low solar radiation (Ateş, 2022; Kulat et al., 2023). Given Turkey's advantageous geographical positioning for solar energy and the high solar radiation potential of its Eastern Mediterranean region (Yıldırım et al., 2018), this synergy between hydropower and floating solar becomes particularly relevant for maximising renewable energy generation.

Turkey's total technical potential suggests the ability to generate 380 TWh/year, of which 305 TWh/year is considered economically viable (Benli, 2016). This technical potential, equivalent to 56 GW of gas-powered station capacity (Topkaya, 2012), represents almost half of Turkey's 2024 total installed capacity of 115.4 GW (TEİAŞ, 2024). Notably, this economic potential nearly matches Turkey's 2024 electricity demand of 340.8 TWh (TEİAŞ, 2024), suggesting that solar energy alone could theoretically meet almost all of the country's electricity needs. Despite this considerable potential, Turkey's utilisation of solar energy remains relatively modest, as evidenced by countries such as Slovenia which achieves significant solar deployment despite receiving lower solar irradiation (only 1241 kWh/($m^2$year) even in its sunniest location compared to Turkey's average of 1527 kWh/($m^2$year)) (Stritih et al., 2013). This disparity becomes particularly striking when compared to Germany, which has emerged as a global leader in solar energy deployment despite receiving only 1000 to 1200 kWh/($m^2$year) of solar irradiation (DWD, 2025)—levels comparable to Turkey's least sunny Black Sea region. Germany's success in harnessing its modest solar resources highlights the untapped potential in Turkey's more favourable conditions.

The geographical distribution of solar resources, as illustrated in Fig. 11, highlights both the opportunity and the challenge facing Turkey. The regions receiving solar irradiation of 1800–2200 kWh/($m^2$year) demonstrate the country's exceptional solar potential, suggesting the need for region-specific approaches that consider local conditions and infrastructure requirements (Wolsink, 2007). The underutilisation becomes especially evident when examining regional disparities. The Southeast Anatolia region, despite having the highest solar potential in the country, has not fully capitalised on this resource (Benli, 2016). The contrast between potential and actual implementation raises questions about Turkey's approach to solar energy development. While technological advancements suggest that even individual households in sun-drenched southern regions could potentially meet their daily electrical needs, achieving this potential requires comprehensive feasibility studies addressing land use, environmental impact, and grid infrastructure challenges (Wolsink, 2007). This multi-faceted approach to development becomes crucial for bridging the gap between Turkey's substantial solar potential and its current utilisation levels.

*Bioenergy*

Turkey's bioenergy landscape reflects the country's extensive agricultural and animal husbandry sectors, generating substantial bio-waste from diverse sources including vegetal biomass, forest products, animal manure, and organic waste from domestic and industrial sources. Historical assessments of Turkey's biomass potential demonstrate notable variations in national estimates. Demirbas (2002) reported Turkey's total annual biomass potential of 32 Mtoe (372.2 TWh), with major contributions from annual crops at 14.9 Mtoe (173.3 TWh) and forest residues at 5.4 Mtoe (62.8 TWh). Additional sources included perennial crops at 4.1 Mtoe (47.7 TWh), agro-industry residues at 3.0 Mtoe (34.9 TWh), wood industry residues at 1.8 Mtoe (20.9 TWh), animal wastes at 1.5 Mtoe (17.4 TWh), and other sources at 1.3 Mtoe (15.1 TWh) (Demirbas, 2002).Yelmen and Çakir (2016) reported biomass potential estimates for Turkey, suggesting a theoretical potential of 135–150 Mtoe/year (1570.1–1744.5 TWh/year), a technical potential of 40 Mtoe/year (465.2 TWh/year), and an economic potential of 25 Mtoe/year (290.8 TWh/year). This substantial gap between theoretical and economically viable potential underscores the complexity of resource utilisation in the bioenergy sector (Hoogwijk et al., 2003).

The geographical distribution of these biomass resources reveals significant regional differences across Turkey. The Central Anatolia region, serving as Turkey's primary agricultural hub, demonstrates considerable potential from agricultural residues with an estimated annual biomass energy potential of 8 TWh (Ayan & Senturk, 2023). The Mediterranean region has a total biomass potential of 8.3 PJ/year (2.3 TWh/year), with Mersin and Adana provinces showing particularly significant plant and animal biomass potential (Bilgili, 2022).

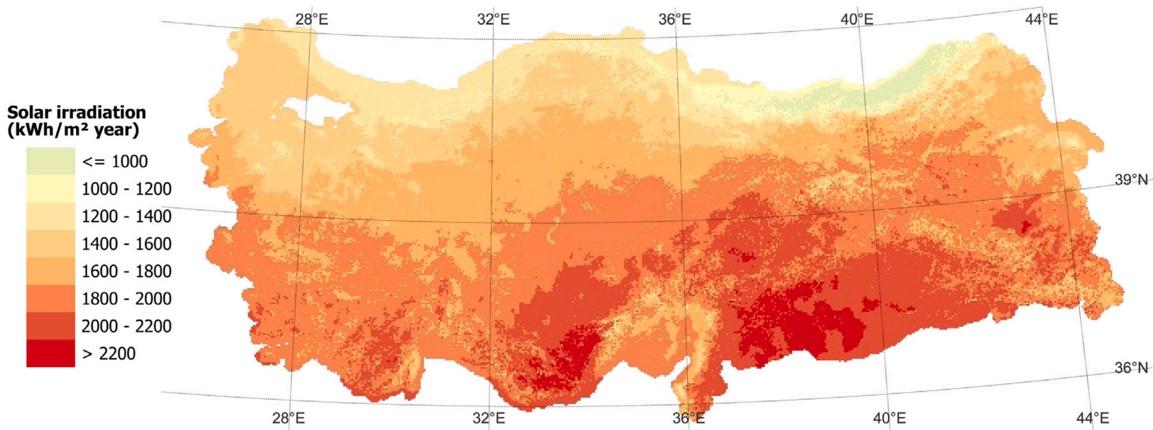


**Fig. 11.** Solar direct normal irradiation around Turkey.
*Data source:* Solargis (2025).

The Marmara Region alone demonstrates substantial potential with agricultural and animal wastes offering 4.65 Mtoe/year (54.1 TWh) of theoretical energy equivalent, which could theoretically meet 58% of the region's electricity consumption (Ocak & Acar, 2021). In contrast, the Eastern Anatolia, East Black Sea, and Southeast Anatolia regions demonstrate lower potential due to topographical characteristics and lower population density (Ayan & Senturk, 2023).

The municipal solid waste (MSW) sector presents another significant avenue for energy generation. Melikoglu (2013) projected potential electricity generation of 8.5 TWh in 2012 through direct MSW combustion, rising to 9.7 TWh by 2023, with an additional 2.9 TWh possible from captured landfill methane. In terms of biofuel production, Eryilmaz et al. (2016) identified potential for producing 1.12 million tons of biodiesel annually from approximately 3.31 million tons of oil seed crops, based on current agricultural land use. The study also noted significant expansion potential, as Turkey has about 4.15 million hectares of fallow land that could be utilised for energy crops. However, transportation costs and feedstock collection logistics remain key factors affecting the economic feasibility of biodiesel production across different regions (Gold & Seuring, 2011). Environmental considerations present another crucial dimension in resource utilisation planning. Though biomass is often considered carbon-neutral, lifecycle assessments reveal varying environmental impacts depending on feedstock source and conversion technology. Agricultural residue collection must be balanced against soil quality maintenance, while forest residue utilisation requires careful management to prevent ecosystem degradation (Lattimore et al., 2009).

MENR's bio-energy potential atlas provides a current perspective, as shown in Table 3, a theoretical biomass potential of approximately 34 Mtoe/year (395.4 TWh), while the economic energy equivalent is around 3.89 Mtoe/year (45.2 TWh) from all kinds of waste (MENR, 2022d). As of 2024, biomass electricity generation of 8.9 TWh represents only one fifth of its economic potential. However, rising fossil fuel prices and Turkey's energy import dependence may improve the economic viability of biomass projects over time. Recent technological advancements, particularly in waste-to-energy and advanced biofuel production, suggest that biomass could play an increasingly important role in Turkey's energy transition, especially at local and regional levels where resource availability and infrastructure support align favourably.

**Table 3**
Biomass potential in Turkey.
*Data source:* MENR (2022d)

| Biomass (Mtoe/year) | Theoretical | Economic |
|---|---|---|
| Animal waste | 4.39 | 1.08 |
| Crop residues | 25.38 | 1.46 |
| Municipal waste | 3.37 | 0.49 |
| Forest waste | 0.86 | 0.86 |
| Total | 34.0 | 3.89 |

### *Geothermal energy*

Turkey possesses diverse geothermal resources, including hot springs and geothermal fields, with its first geothermal electricity generation facility commencing operations in 1975 at 0.5 $MW_e$ (MENR, 2022b). The country's strategic location on an active tectonic belt has endowed it with substantial geothermal potential. As of 2023, Turkey ranked fourth globally in geothermal power capacity with 1.69 $GW_e$, after the United States, Indonesia, and the Philippines (Cariaga, 2024). Total electricity generation from geothermal resources in 2024 reached 11 TWh with an installed capacity of 1.73 $GW_e$ (TEİAŞ, 2024). In terms of direct use applications, geothermal energy provided heating for 170,481 residential dwellings across the country in 2022 (GDMRE, 2025).

The assessment of Turkey's geothermal potential has evolved significantly over time, with many studies drawing upon data from the General Directorate of Mineral Research and Exploration (GDMRE). Initial evaluations by Taşdemiroğlu (1988), based on data collected by GDMRE since 1962, indicated potential for 4.5 $GW_e$ of electricity generation in high-temperature geothermal areas, alongside a direct use potential of 31.1 $GW_t$. A more recent and comprehensive statistical analysis by Korkmaz et al. (2014) examined 135 geothermal fields, estimating power generation potential between 1.67 $GW_e$ and 3.14 $GW_e$, with thermal potential ranging from 38.2 to 68.4 $GW_t$. This approach provided more reliable estimates by incorporating resource assessment uncertainties.

The potential for enhanced geothermal systems (EGS) adds another dimension to Turkey's geothermal prospects. Chamorro et al. (2014) estimated technical potential of 135 $GW_e$, 510 $GW_e$, and 1320 $GW_e$ for EGS at depths of 5, 7, and 10 km respectively, with 6.0 $GW_e$ identified as sustainable between 3 and 10 km. The large variation between theoretical and sustainable potential estimates highlights the need for conducting more comprehensive technical and economic feasibility studies before incorporating EGS resources into Turkey's realistic geothermal development targets, particularly in regions where conventional geothermal resources are limited.

Current official estimates from MENR place Turkey's probable geothermal heat potential at 35.5 $GW_t$, with electricity generation potential of 4.5 $GW_e$ (MENR, 2022b). As shown in Table 4, several studies estimated Turkey's geothermal potential ranging from 1.7 to 4.5 $GW_e$ for electricity generation and from 31.1 to 68.4 $GW_t$ for direct use applications. While official estimates provide a baseline, the variation in potential assessments across different studies suggests that actual

**Table 4**
Geothermal potential estimates for Turkey from different studies and governmental assessments.

| Direct use ($GW_t$) | Electricity generation ($GW_e$) | Source |
|---|---|---|
| 31.1 | 4.5 | Taşdemiroğlu (1988) |
| – | 6 | Chamorro et al. (2014) |
| 35.5 | 4.5 | MENR (2022b) |
| 38.2–68.4 | 1.673–3.140 | Korkmaz et al. (2014) |

geothermal potential might be higher, highlighting how methodological approaches and assessment techniques can substantially influence potential estimations. With the current installed capacity of 1.73 $GW_e$ representing approximately 38.4% of MENR's estimated potential of 4.5 $GW_e$, Turkey has made significant progress in harnessing its geothermal resources for electricity generation, though substantial untapped potential remains. According to detailed mapping by GDMRE, significant geothermal potential exists across various regions, with notably limited potential in the Central Black Sea and Mediterranean regions (GDMRE, 2025). The western regions, particularly the Gediz and Great Menderes grabens, demonstrate exceptional potential with temperatures exceeding 260–287 °C (Aksoy, 2014).

While geothermal energy is often considered environmentally benign, recent studies from Turkey reveal $CO_2$ emissions from geothermal power plants ranging between 900–1150 g/kWh (Aksoy, 2014), primarily due to thermal decomposition of carbonate-rich rock formations. These emissions can exceed those from fossil fuel sources like natural gas and coal. Although geothermal emissions lack particulate pollutants and harmful by-products, given Turkey's carbonate-rich geology (Okay, 2008), their high $CO_2$ output highlights the need for comprehensive environmental impact assessments geothermal projects.

By the end of 2023, geothermal energy in Turkey generated 12.4 TWh total, with electricity generation accounting for 7.7% and heat generation comprising the remaining 92.3% (MENR, 2023b). This substantial heat generation capacity serves various sectors including residential, commercial, and agricultural applications, demonstrating the significant role of geothermal energy in Turkey's heating sector.

*Overall potential*

An assessment of Turkey's renewable energy potential reveals significant opportunities across various resources, though estimation methodologies and reported figures vary considerably across studies (Table 5). These variations reflect not only different assessment approaches but also the evolving understanding of resource availability and technological capabilities.

Hydropower potential estimates demonstrate relatively consistent ranges, with economic potential between 125–140 TWh/year based on assessments from DSI. This represents a substantial portion of Turkey's current electricity demand of 340.8 TWh, though current utilisation stands at 73.1 TWh. Wind energy potential shows the widest variation in estimates, ranging from 10 to 88 GW, reflecting different geographical scope and technical assumptions in various studies. With current installed capacity at 12.6 GW generating 36.7 TWh annually, significant potential remains untapped, particularly in offshore locations. Solar energy demonstrates substantial economic potential of 305 TWh/year, nearly equivalent to Turkey's current annual electricity demand. The current installed capacity of 19.6 GW, generating 24.9 TWh annually, suggests considerable room for expansion. Biomass resources have an estimated economic potential of 45.4 TWh/year according to official estimates, while other sources suggest potential up to 290.8 TWh/year, with current generation at 9.8 TWh from 2.16 GW of installed capacity. Geothermal potential estimates range from 4.5 to 6 GW, compared to current installed capacity of 1.73 GW generating 11.1 TWh annually. The diversity of these renewable resources presents both opportunities and challenges for system integration. While hydropower and

**Table 5**
Overview of Turkey's economically viable renewable energy potential estimates.

| Energy Source | Lowest estimate | Highest estimate | Source |
|---|---|---|---|
| Hydro (TWh) | 125 | 140 | Bakis and Demirbas (2004)<br>Ozturk et al. (2009)<br>Kaygusuz (2009)<br>Yüksel (2010)<br>Akpinar et al. (2011)<br>Dursun and Gokcol (2011)<br>Erdogdu (2011)<br>Kucukali (2010)<br>Yuksel (2012)<br>Capik et al. (2012) |
| Wind (GW) | 10 | 88 | Sahin (2008)<br>Güler (2009)<br>WBG (2019)<br>MENR (2022e) |
| Solar (TWh) | 305 | | Benli (2016) |
| Biomass (TWh) | 45.2 | 290.8 | Yelmen and Çakir (2016)<br>MENR (2022d) |
| Geothermal (GW) | 4.5 | 6 | Taşdemiroğlu (1988)<br>Chamorro et al. (2014)<br>MENR (2022b) |

geothermal resources can provide relatively stable baseload power, solar and wind resources exhibit natural variability in their generation patterns. Biomass resources offer flexible generation potential, though at a smaller scale. This complementarity among different renewable sources becomes particularly relevant when considering Turkey's projected electricity demand of 510.5 TWh by 2035. Notably, the methodology for potential estimation varies significantly across resources, making direct comparisons challenging. Hydropower estimates derive from long-term hydrological data and established assessment methodologies. Wind potential estimates vary based on geographical scope and different technical assumptions. Solar potential calculations depend heavily on assumptions about land availability and system efficiency, while biomass potential estimates reflect various resource types and collection efficiencies. Geothermal potential estimates vary with technological capabilities and depth considerations. The aggregate economic potential across all renewable sources suggests substantial capability to meet Turkey's current and near-term electricity demand, though practical utilisation requires careful consideration of resource characteristics and system integration requirements. This is particularly relevant given Turkey's current renewable energy deployment, where installed capacity of 68.6 GW contributes 45.5% of annual electricity generation, demonstrating the practical implications of resource variability in actual system operation.

## Renewable energy implementation challenges

In Turkey, energy-related challenges are multifaceted, including heavy reliance on imports, finite fossil fuel reserves, rapidly rising energy prices, and significant environmental concerns (Erdem, 2010). A key issue is energy security, worsened by increasing energy demand and growing dependence on foreign energy imports without a corresponding rise in local energy production (Esen, 2016). Turkey's energy dependence is significant, with 76% of its energy needs met through imports, including 90% of oil and 98% of natural gas (MENR, 2023b). While these challenges affect the broader energy sector, this section focuses on the implementation of renewable energy sources.

*Source-specific challenges*

Hydro energy faces significant operational challenges due to the changing climate. The documented decreasing trends in precipitation

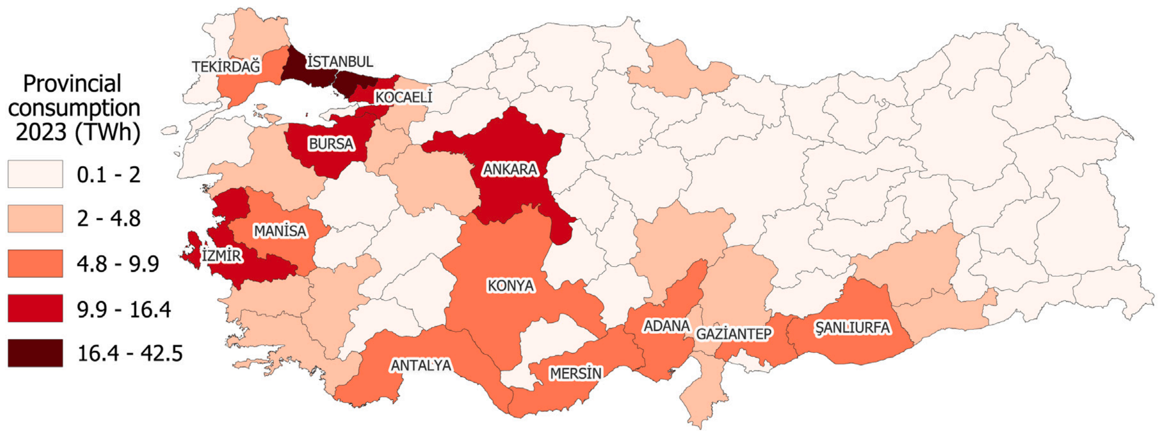


**Fig. 12.** Electricity consumption by province in 2023.
*Data source:* EMRA (2023).

and temperature rise (TSMS, 2023a, 2023b) directly impact facility operations, requiring adaptations in reservoir management and generation planning (Mukheibir, 2013). These climate-driven changes affect hydroelectric facilities' operations, as projected changes in river flow variations and discharge patterns can significantly impact generation capabilities, though the effects vary considerably by region (Berga, 2016). The operational challenges are evident in the increasing variability of generation output (MENR, 2023b), which leads to changes in seasonal generation patterns and affects the ability to maintain consistent power output throughout the year (Koch et al., 2016).

While Turkey has traditionally focused on large-scale hydropower development, its small hydropower sector presents distinct implementation challenges. Despite advantages including simpler infrastructure requirements and lower investment costs compared to large installations (Paish, 2002), small hydropower development faces obstacles including requirements for detailed site assessments and lengthy administrative procedures with licensing periods of 20–40 years in Turkey (Punys & Pelikan, 2007). The underutilisation of small hydropower in Turkey's energy mix contrasts with many European countries where targeted policies and support mechanisms have enabled small hydropower to play a more substantial role in renewable energy portfolios (Capik et al., 2012).

Solar energy implementation often faces geographical mismatches between optimal generation locations and major demand centres, a challenge observed in various countries (Zhang et al., 2015). In Turkey's case, analysis of solar resource distribution and electricity consumption patterns reveals a clear spatial disconnect. While the highest solar potential exists in the southeastern regions (MENR, 2023a), the largest electricity consumption is concentrated in industrial provinces such as Istanbul (42.5 TWh), Izmir (16.4 TWh), and Ankara (14.9 TWh), creating transmission infrastructure challenges, as illustrated in Fig. 12. The implementation of urban solar installations faces additional challenges including grid integration complexities, initial investment barriers, and limited incentive structures for residential installations (Kılıç & Kekezoğlu, 2022), particularly in high-density urban areas where roof space optimisation becomes critical (Byrne et al., 2015).

Wind energy development presents distinct regional implementation challenges. Three western coastal provinces, Izmir, Balikesir, and Canakkale, account for 36.5% of total installed wind capacity (TÜREB, 2022), while other regions with significant wind potential remain underutilised (Şahin & Türkeş, 2020). Offshore wind development, despite its 75 GW potential (WBG, 2019), faces additional barriers including higher installation and maintenance costs, complex grid connection requirements, and the need for specialised infrastructure and expertise (Esteban et al., 2011). The geographical imbalance in development patterns suggests the need for more comprehensive regional planning approaches that consider both resource availability and infrastructure requirements.

Geothermal energy faces economic, geographical and technical constraints, with resources suitable for electricity generation confined to specific regions (GDMRE, 2025). While widespread potential exists for residential heating applications across the majority of the country (barring the Mediterranean and Central Black Sea regions (GDMRE, 2025)), developing geothermal resources generally requires significant initial investment and is subject to inherent geological uncertainties (Tester et al., 2007).

Bioenergy implementation challenges centre around resource collection and logistics. Despite biomass waste being generated throughout Turkey, the dispersed nature of these resources complicates efficient collection and transportation (Ozturk et al., 2017). The Central Anatolia region demonstrates considerable potential from agricultural residues with an estimated annual biomass energy potential of 8 TWh (Ayan & Senturk, 2023), yet developing efficient biomass collection networks requires careful consideration of geographic constraints and biomass availability patterns (Morato et al., 2019). The economic viability of bioenergy projects often depends on optimising transportation costs and feedstock collection logistics (Gold & Seuring, 2011).

*Infrastructure and grid integration*

The integration of renewable energy sources into Turkey's existing grid infrastructure presents significant technical and operational challenges. The intermittent nature of renewable energy, particularly wind and solar, necessitates substantial grid modernisation to maintain stability and reliability. This challenge is particularly relevant for Turkey given its geographically distributed wind resources, with significant offshore wind potential along its coastal regions (Çelik et al., 2022). The implementation of smart grids is essential for effectively managing the integration of renewable energy sources . Traditional grid infrastructure, designed for one-way power flow from centralised generation facilities, requires significant upgrades to accommodate the bidirectional flow characteristics of distributed renewable generation (Ipakchi & Albuyeh, 2009). The transition to smart grids necessitates substantial investment in advanced metering infrastructure, control systems, and communication networks (Gungor et al., 2011). These requirements are particularly critical in regions with high renewable energy potential but limited grid infrastructure. Energy storage solutions play a vital role in addressing intermittency challenges. While Turkey has significant hydropower capacity, it currently lacks operational pumped storage facilities (Haktanir et al., 2021), despite having the highest potential for pumped storage in Europe (Barbaros et al., 2021), leaving its energy storage infrastructure limited relative to its renewable energy growth. Integration opportunities between floating solar and hydropower present promising solutions, with hydro resources potentially providing balancing services during periods of low solar radiation (Ateş, 2022; Kulat et al., 2023). However, the development of large-scale storage solutions requires significant investment and faces both technical and economic barriers.

### *Economic and market challenges*

The cost of capital plays a crucial role in renewable energy deployment (Debnath & Mourshed, 2024), accounting for 12%–37% of the levelised cost of electricity (LCOE) in developed countries and up to 50% in developing countries (Steffen, 2020). In Turkey's industrial sector, companies primarily view energy investments through the lens of cost savings rather than environmental benefits, with 93% allocating less than 10% of their budget to energy efficiency and environmental initiatives (Biresselioglu et al., 2017). Government incentives play a crucial role in fostering renewable energy adoption. Recent amendments highlight Turkey's progressive approach to promoting renewable investments, especially in solar and wind sectors (Government of Türkiye, 2023). However, these incentives primarily target corporations, with limited provisions for domestic customers or individuals. This contrasts sharply with approaches in countries such as the UK, where comprehensive domestic renewable energy incentives have driven adoption. The UK's domestic renewable heat incentive program, which offered a 7-year payment plan for residential installations of biomass boilers, solar water heating, and heat pumps, exemplifies how targeted incentives can accelerate residential renewable energy adoption (BEIS, 2020; Snape et al., 2015). Turkey's missed opportunity in not providing similar incentives for domestic renewable energy use is particularly striking given its favourable solar conditions.

### *Regulatory and policy framework*

Despite significant legal reforms in 2001 (Government of Türkiye, 2023), regulatory challenges continue to impact renewable energy implementation. Bureaucratic processes, particularly for permit approvals, can extend up to a year and pose a significant deterrent to foreign investors (Toklu, 2013). While administrative processes have seen some improvements, the pace of these processes remains a concern for operators. Public approval processes present additional challenges, especially for projects requiring large land areas, particularly when agricultural land conversion is involved (Özgül et al., 2020). Research indicates that public awareness and acceptance of renewable technologies in Turkey shows significant regional disparities, with areas of high renewable potential sometimes experiencing lower technology adoption due to limited public recognition and understanding (Benli, 2016). Beyond awareness issues, local opposition often arises from multiple factors including landscape impacts, procedural justice concerns, and economic considerations regarding property values and tourism (Delicado, 2018). While renewable energy is not entirely free from environmental impacts such as habitat disruption, the government's role primarily focuses on monitoring and ensuring compliance. The environmental benefits of renewable energy, including improvements to public health, often justify these impacts (Gibon et al., 2017), suggesting that effective communication and responsible action by private companies can address public perception issues. The successful implementation of renewable energy in Turkey requires a coordinated approach to addressing these multifaceted challenges. While some barriers require technological solutions or infrastructure investment, others demand policy innovations and improved stakeholder engagement. Expanding incentive programs to include residential installations, streamlining administrative processes, and developing comprehensive grid modernisation strategies are crucial steps towards achieving Turkey's renewable energy potential and meeting its climate commitments.

## Conclusion

This comprehensive assessment of Turkey's renewable energy landscape reveals a complex interplay between substantial theoretical potential and practical implementation challenges. The temporal evolution of Turkey's renewable energy sector shows distinct patterns of growth and transformation, with fossil fuel-based generation steadily declining from 80% to 54.5% between 2006 and 2024, while renewable generation rose from 20% to 45.5%. This illustrates an accelerating energy transition. Renewable sources account for 59.4% of Turkey's total installed capacity while contributing 45.5% to electricity generation. Although the variable nature of renewable resources largely explains this difference, the upward trend suggests promising progress towards a more diversified and resilient energy mix.

The analysis reveals several important findings. First, climate change poses an direct risk to hydropower generation, with southwestern basins showing alarming depletion trends—notably Gediz experiencing a 45.5% decline and Konya a 43.2% decline since 2010. These findings, coupled with decreasing precipitation and rising temperatures, necessitate a reassessment of Turkey's long-term hydropower strategy.

Second, the geographical mismatch between renewable resources and demand centres presents a fundamental structural challenge. While the optimal solar potential exists in southeastern regions and substantial wind resources are available along the coastal areas, major electricity demand is concentrated in northwestern industrial zones—Istanbul (42.5 TWh), Izmir (16.4 TWh), and Ankara (14.9 TWh). This spatial highlights the need for significant transmission infrastructure investments and coordinated planning for decentralised generation.

Third, Turkey's renewable energy potential remains notably underutilised. Wind energy exhibits substantial untapped capacity, with only 12.6 GW installed of 48 GW potential. Solar energy presents an even greater opportunity, with an estimated technical potential of 380 TWh/year—theoretically sufficient to meet Turkey's current electricity demand of 340.8 TWh/year. Similarly, geothermal resources, despite Turkey's position as the world's fourth-largest producer, operate at only 38.4% of its estimated potential of 4.5 $GW_e$.

Looking forward, three strategic priorities emerge. First, modernising and climate-proofing existing facilities, particularly hydropower infrastructure, may offer greater resilience benefits than new construction. Second, developing integrated storage solutions and expanding grid infrastructure and flexibility are essential to managing variability and better align generation with consumption. Third, policy frameworks must evolve to address regulatory, technical, and financial barriers to renewable energy deployment, particularly in supporting distributed generation and smaller-scale installations.

This study provides an original synthesis through meta-analysis of renewable energy potential and national supply–demand dynamics, offering an evidence base for future energy planning. It concludes that while Turkey possesses renewable energy resources more than sufficient to meet its projected energy demands, forecast to reach 510.5 TWh by 2035. However, realising this potential requires a more nuanced and strategic approach. Success will depend not only on increasing installed capacity but also on addressing systemic challenges, adapting to climate change risks, and integrating enabling technologies. As Turkey continues its energy transition, the focus should shift from merely expanding capacity to optimising resource utilisation, ensuring system resilience, and developing integrated solutions that can effectively harness the country's diverse renewable energy potential.

The findings have significant implications for policy and practice. They suggest the need for a comprehensive approach that considers resource distribution, climate resilience, and infrastructure integration. Future research should focus on developing adaptive strategies for hydropower under climate change, innovative solutions for energy storage and grid integration, and policy mechanisms to accelerate the deployment of both large-scale and distributed renewable energy deployment.

## CRediT authorship contribution statement

**Oguzhan Gulaydin:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Monjur Mourshed:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

Akpinar, A., Kömürcü, M. İ., Özölçer, İ. H., & Şenol, A. (2011). Total electricity and hydroelectric energy generation in Turkey: Projection and comparison. *Energy Sources, Part B: Economics, Planning, and Policy*, *6*(3), 252–262. http://dx.doi.org/10.1080/15567240802534219.

Aksoy, N. (2014). Power generation from geothermal resources in Turkey. *Renewable Energy*, *68*, 595–601. http://dx.doi.org/10.1016/j.renene.2014.02.049.

Ateş, A. M. (2022). Unlocking the floating photovoltaic potential of Türkiye's hydroelectric power plants. *Renewable Energy*, *199*, 1495–1509. http://dx.doi.org/10.1016/j.renene.2022.09.096.

Ayan, A., & Senturk, A. E. (2023). Exploring of biomass energy specific to Turkey and on a global scale. *International Journal of Renewable Energy Research*, *13*(3), 1180–1193. http://dx.doi.org/10.20508/ijrer.v13i3.14085.g8790.

Bakis, R., & Demirbas, A. (2004). Sustainable development of small hydropower plants (SHPs). *Energy Sources*, *26*(12), 1105–1118. http://dx.doi.org/10.1080/00908310390265932.

Barbaros, E., Aydin, I., & Celebioglu, K. (2021). Feasibility of pumped storage hydropower with existing pricing policy in Turkey. *Renewable and Sustainable Energy Reviews*, *136*, Article 110449. http://dx.doi.org/10.1016/j.rser.2020.110449.

BEIS (2020). The domestic renewable heat incentive scheme and renewable heat incentive scheme (amendment) regulations 2020, SI 2020/650. Department for Business, Energy and Industrial Strategy, https://www.legislation.gov.uk/uksi/2020/650/pdfs/uksiem_20200650_en.pdf.

Benli, H. (2016). Potential application of solar water heaters for hot water production in Turkey. *Renewable and Sustainable Energy Reviews*, *54*, 99–109. http://dx.doi.org/10.1016/j.rser.2015.09.061.

Berga, L. (2016). The role of hydropower in climate change mitigation and adaptation: A review. *Engineering*, *2*(3), 313–318. http://dx.doi.org/10.1016/J.ENG.2016.03.004.

Bilgili, M. E. (2022). Exploitable potential of biomass energy in electrical energy production in the mediterranean region of Turkey. *Journal of Agricultural Sciences*, *28*(4), 666–676. http://dx.doi.org/10.15832/ankutbd.944680.

Biresselioglu, M. E., Yelkenci, T., Ozyorulmaz, E., & Yumurtaci, I. Ö. (2017). Interpreting turkish industry's perception on energy security: A national survey. *Renewable and Sustainable Energy Reviews*, *67*, 1208–1224. http://dx.doi.org/10.1016/j.rser.2016.09.093.

Bozkurt, D., Sen, O. L., & Hagemann, S. (2015). Projected river discharge in the euphrates-tigris basin from a hydrological discharge model forced with RCM and GCM outputs. *Climate Research*, *62*(2), 131–147. http://dx.doi.org/10.3354/cr01268.

Brown, T., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., & Mathiesen, B. (2018). Response to 'burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. *Renewable and Sustainable Energy Reviews*, *92*, 834–847. http://dx.doi.org/10.1016/j.rser.2018.04.113.

Byrne, J., Taminiau, J., Kurdgelashvili, L., & Kim, K. N. (2015). A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of seoul. *Renewable and Sustainable Energy Reviews*, *41*, 830–844. http://dx.doi.org/10.1016/j.rser.2014.08.023.

Capik, M., Yılmaz, A. O., & Cavusoglu, İ. (2012). Hydropower for sustainable energy development in Turkey: The small hydropower case of the eastern Black Sea Region. *Renewable and Sustainable Energy Reviews*, *16*(8), 6160–6172. http://dx.doi.org/10.1016/j.rser.2012.06.005.

Cariaga, C. (2024). ThinkGeoEnergy's top 10 geothermal countries 2023: Power generation capacity. Online, https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2023-power-generation-capacity/.

Celik, A. N., & Özgür, E. (2020). Review of Turkey's photovoltaic energy status: Legal structure, existing installed power and comparative analysis. *Renewable and Sustainable Energy Reviews*, *134*, Article 110344. http://dx.doi.org/10.1016/j.rser.2020.110344.

Çelik, Ö., Yalman, Y., Tan, A., Bayındır, K. Ç., Çetinkaya, Ü., Akdeniz, M., Chaudhary, S. K., Høyer, M., & Guerrero, J. M. (2022). Grid code requirements – a case study on the assessment for integration of offshore wind power plants in Turkey. *Sustainable Energy Technologies and Assessments*, *52*, Article 102137. http://dx.doi.org/10.1016/j.seta.2022.102137.

Chamorro, C. R., García-Cuesta, J. L., Mondéjar, M. E., & Pérez-Madrazo, A. (2014). Enhanced geothermal systems in europe: An estimation and comparison of the technical and sustainable potentials. *Energy*, *65*, 250–263. http://dx.doi.org/10.1016/j.energy.2013.11.078.

Davis, N. N., Badger, J., Hahmann, A. N., Hansen, B. O., Mortensen, N. G., Kelly, M., Larsén, X. G., Olsen, B. T., Floors, R., Lizcano, G., Casso, P., Lacave, O., Bosch, A., Bauwens, I., Knight, O. J., van Loon, A. P., Fox, R., Parvanyan, T., Hansen, S. B. K., .... Drummond, R. (2023). "The global wind atlas: A high-resolution dataset of climatologies and associated web-based application. *Bulletin of the American Meteorological Society*, *104*(8), E1507 – E1525. http://dx.doi.org/10.1175/BAMS-D-21-0075.1.

Debnath, K. B., & Mourshed, M. (2024). Although feasible, falling renewables costs might not benefit Bangladesh's energy sector's decarbonisation: Is this another 'debt-fossil fuel production trap'? *Energy for Sustainable Development*, *79*, Article 101416. http://dx.doi.org/10.1016/j.esd.2024.101416.

Delicado, A. (2018). Local responses to renewable energy development. In *Oxford handbook of energy and society* (pp. 1–22). Oxford University Press.

Demir, A., Dinçer, A. E., Çiftçi, C., Gülçimen, S., Uzal, N., & Yılmaz, K. (2024). Wind farm site selection using GIS-based multicriteria analysis with life cycle assessment integration. *Earth Science Informatics*, *17*(2), 1591–1608. http://dx.doi.org/10.1007/s12145-024-01227-4.

Demirbas, A. (2002). Electricity from biomass and hydroelectric development projects in Turkey. *Energy Exploration & Exploitation*, *20*(4), 325–335. http://dx.doi.org/10.1260/014459802762231123.

Demircan, M., Gürkan, H., Eskio˘ glu, O., Arabacı, H., & Coşkun, M. (2017). Climate change projections for Turkey: Three models and two scenarios. *Turkish Journal of Water Science and Management*, *1*(1), 22–43. http://dx.doi.org/10.31807/tjwsm.297183.

Dinçer, F. (2011). Overview of the photovoltaic technology status and perspective in Turkey. *Renewable and Sustainable Energy Reviews*, *15*(8), 3768–3779. http://dx.doi.org/10.1016/j.rser.2011.06.005.

DSİ (2023). Havza bazında baraj doluluk oranları, 2010–2022. Devlet Su İşleri (DSİ), https://www.dsi.gov.tr/Sayfa/Detay/1847.

DTU (2022). The global wind atlas 3.0. Technical University of Denmark (DTU), https://globalwindatlas.info.

Dursun, B., & Gokcol, C. (2011). The role of hydroelectric power and contribution of small hydropower plants for sustainable development in Turkey. *Renewable Energy*, *36*(4), 1227–1235. http://dx.doi.org/10.1016/j.renene.2010.10.001.

DWD (2025). Global radiation (mean 30-year monthly and annual sums). Deutscher Wetterdienst (DWD), https://www.dwd.de/EN/ourservices/solarenergy/maps_globalradiation_mvs.html.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., et al. (2011). *IPCC special report on renewable energy sources and climate change mitigation*: *Technical report*, Cambridge, United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press.

EMRA (2023). *Electricity market sector report 2023*: *Technical report*, Ankara, Turkey: Republic of Turkiye Energy Market Regulatory Authority (EMRA), https://www.epdk.gov.tr/Detay/Icerik/3-0-24-3/elektrikyillik-sektor-raporu.

Erdem, Z. B. (2010). The contribution of renewable resources in meeting Turkey's energy-related challenges. *Renewable and Sustainable Energy Reviews*, *14*(9), 2710–2722. http://dx.doi.org/10.1016/j.rser.2010.07.003.

Erdogdu, E. (2011). An analysis of Turkish hydropower policy. *Renewable and Sustainable Energy Reviews*, *15*(1), 689–696. http://dx.doi.org/10.1016/j.rser.2010.09.019.

Eryilmaz, T., Yesilyurt, M. K., Cesur, C., & Gokdogan, O. (2016). Biodiesel production potential from oil seeds in Turkey. *Renewable and Sustainable Energy Reviews*, *58*, 842–851. http://dx.doi.org/10.1016/j.rser.2015.12.172.

Esen, Ö. (2016). Security of the energy supply in Turkey: Prospects, challenges and opportunities. *International Journal of Energy Economics and Policy*, *6*(2), 281–289.

Esteban, M. D., Diez, J. J., López, J. S., & Negro, V. (2011). Why offshore wind energy? *Renewable Energy*, *36*(2), 444–450. http://dx.doi.org/10.1016/j.renene.2010.07.009.

Festel, G., Würmseher, M., Rammer, C., Boles, E., & Bellof, M. (2014). Modelling production cost scenarios for biofuels and fossil fuels in europe. *Journal of Cleaner Production*, *66*, 242–253. http://dx.doi.org/10.1016/j.jclepro.2013.10.038.

GDMRE (2025). Türkiye jeotermal enerji potansiyeli ve arama çalışmaları. General Directorate of Mineral Research and Exploration (GDMRE), https://www.mta.gov.tr/v3.0/arastirmalar/jeotermal-enerji-arastirmalari.

Genç, M. S., & Gökçek, M. (2009). Evaluation of wind characteristics and energy potential in kayseri, Turkey. *Journal of Energy Engineering*, *135*(2), 33–43. http://dx.doi.org/10.1061/(ASCE)0733-9402(2009)135:2(33).

Gibon, T., Hertwich, E. G., Arvesen, A., Singh, B., & Verones, F. (2017). Health benefits, ecological threats of low-carbon electricity. *Environmental Research Letters*, *12*(3), Article 034023. http://dx.doi.org/10.1088/1748-9326/aa6047.

Gold, S., & Seuring, S. (2011). Supply chain and logistics issues of bio-energy production. *Journal of Cleaner Production*, *19*(1), 32–42. http://dx.doi.org/10.1016/j.jclepro.2010.08.009.

Government of Türkiye (2021). Paris anlaşmasının ilişik beyanla birlikte onaylanması hakkında karar. Official Gazette of the Republic of Türkiye, October 7, 2021. Gazette no: 31621, Decision no: 4618, https://www.resmigazete.gov.tr/eskiler/2021/10/20211007M1-1.pdf. (in Turkish).

Government of Türkiye (2023). Official gazette. Official Gazette of the Republic of Türkiye, November 28, 2023. Gazette no: 32383, https://www.resmigazete.gov.tr/eskiler/2023/11/20231128-8.htm.

Güler, Ö. (2009). Wind energy status in electrical energy production of Turkey. *Renewable and Sustainable Energy Reviews*, *13*(2), 473–478. http://dx.doi.org/10.1016/j.rser.2007.03.015.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P. (2011). Smart grid technologies: Communication technologies and standards. *IEEE Transactions on Industrial Informatics*, *7*(4), 529–539. http://dx.doi.org/10.1109/TII.2011.2166794.

Haktanir, T., Aydemir, A., & Acanal, N. (2021). A study on three different hydropower operation rules by monthly and daily time steps. *Proceedings of the Institution of Civil Engineers - Energy*, *174*(1), 24–34. http://dx.doi.org/10.1680/jener.19.00066.

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., & Turkenburg, W. (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, *25*(2), 119–133. http://dx.doi.org/10.1016/S0961-9534(02)00191-5.

IEA (2021a). *Turkey 2021*: *Technical report*, International Energy Agency (IEA), https://www.iea.org/reports/turkey-2021.

IEA (2021b). Hydropower data explorer. International Energy Agency (IEA), https://www.iea.org/data-and-statistics/data-tools/hydropower-data-explorer.

IEA (2024a). *Renewables 2024*: *Technical report*, Paris, France: International Energy Agency (IEA), https://www.iea.org/reports/renewables-2024.

IEA (2024b). Greenhouse gas emissions from energy data explorer. International Energy Agency (IEA), https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer.

IEA (2025). *Global energy review 2025*: *Technical report*, Paris, France: International Energy Agency (IEA), https://www.iea.org/reports/global-energy-review-2025.

IHA (2022). *2022 Hydropower status report: sector trends and insights*: *Technical report*, London, United Kingdom: International Hydropower Association (IHA), https://www.hydropower.org/publications/2022-hydropower-status-report.

İlkiliç, C. (2012). Wind energy and assessment of wind energy potential in Turkey. *Renewable and Sustainable Energy Reviews*, *16*(2), 1165–1173. http://dx.doi.org/10.1016/j.rser.2011.11.021.

Ilkiliç, C., & Aydin, H. (2015). Wind power potential and usage in the coastal regions of Turkey. *Renewable and Sustainable Energy Reviews*, *44*, 78–86. http://dx.doi.org/10.1016/j.rser.2014.12.010.

Ipakchi, A., & Albuyeh, F. (2009). Grid of the future. *IEEE Power and Energy Magazine*, *7*(2), 52–62. http://dx.doi.org/10.1109/MPE.2008.931384.

IRENA (2018). *Power system flexibility for the energy transition, part 1: Overview for policy makers*: *Technical report*, Abu Dhabi, UAE: International Renewable Energy Agency (IRENA), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf.

IRENA (2024a). *Renewable energy and jobs: annual review 2024*: *Technical report*, Abu Dhabi, UAE: International Renewable Energy Agency (IRENA), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Oct/IRENA_Renewable_energy_and_jobs_2024.pdf.

IRENA (2024b). *Renewable power generation costs in 2023*: *Technical report*, Abu Dhabi, UAE: International Renewable Energy Agency (IRENA), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf.

IRENA (2024c). *World energy transitions outlook 2024: 1.5°c pathway*: *Technical report*, Abu Dhabi, UAE: International Renewable Energy Agency (IRENA), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Nov/IRENA_World_energy_transitions_outlook_2024.pdf.

Kaya, D. (2006). Renewable energy policies in Turkey. *Renewable and Sustainable Energy Reviews*, *10*(2), 152–163. http://dx.doi.org/10.1016/j.rser.2004.08.001.

Kaygusuz, K. (2009). Hydropower in Turkey: The sustainable energy future. *Energy Sources, Part B: Economics, Planning, and Policy*, *4*(1), 34–47. http://dx.doi.org/10.1080/15567240701423928.

Kaygusuz, K., & Kaygusuz, A. (2004). Geothermal energy in Turkey: the sustainable future. *Renewable and Sustainable Energy Reviews*, *8*(6), 545–563. http://dx.doi.org/10.1016/j.rser.2004.01.001.

Kılıç, U., & Kekezoğlu, B. (2022). A review of solar photovoltaic incentives and policy: Selected countries and Turkey. *Ain Shams Engineering Journal*, *13*(5), Article 101669. http://dx.doi.org/10.1016/j.asej.2021.101669.

Koch, F., Reiter, A., & Bach, H. (2016). Effects of climate change on hydropower generation and reservoir management. In W. Mauser, & M. Prasch (Eds.), *Regional assessment of global change impacts: the project GLOWA-danube* (pp. 593–599). Cham, Switzerland: Springer International Publishing, http://dx.doi.org/10.1007/978-3-319-16751-0_68.

Kömürcü, M. İ., & Akpinar, A. (2010). Hydropower energy versus other energy sources in Turkey. *Energy Sources, Part B: Economics, Planning, and Policy*, *5*(2), 185–198. http://dx.doi.org/10.1080/15567240802532627.

Korkmaz, E., Serpen, U., & Satman, A. (2014). Geothermal boom in Turkey: Growth in identified capacities and potentials. *Renewable Energy*, *68*, 314–325. http://dx.doi.org/10.1016/j.renene.2014.01.044.

Kucukali, S. (2010). Municipal water supply dams as a source of small hydropower in Turkey. *Renewable Energy*, *35*(9), 2001–2007. http://dx.doi.org/10.1016/j.renene.2010.01.032.

Kulat, M. I., Tosun, K., Karaveli, A. B., Yucel, I., & Akinoglu, B. G. (2023). A sound potential against energy dependency and climate change challenges: Floating photovoltaics on water reservoirs of Turkey. *Renewable Energy*, *206*, 694–709. http://dx.doi.org/10.1016/j.renene.2022.12.058.

Kutlu, E. C., Durusoy, B., Ozden, T., & Akinoglu, B. G. (2022). Technical potential of rooftop solar photovoltaic for Ankara. *Renewable Energy*, *185*, 779–789. http://dx.doi.org/10.1016/j.renene.2021.12.079.

Lattimore, B., Smith, C., Titus, B., Stupak, I., & Egnell, G. (2009). Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices. *Biomass and Bioenergy*, *33*(10), 1321–1342. http://dx.doi.org/10.1016/j.biombioe.2009.06.005.

Melikoglu, M. (2013). Vision 2023: Assessing the feasibility of electricity and biogas production from municipal solid waste in Turkey. *Renewable and Sustainable Energy Reviews*, *19*, 52–63. http://dx.doi.org/10.1016/j.rser.2012.11.017.

MENR (2022a). *Türkiye national energy plan*: *Technical report*, Ankara, Turkey: Republic of Türkiye Ministry of Energy and Natural Resources (MENR), https://enerji.gov.tr/Media/Dizin/EIGM/tr/Raporlar/TUEP/Türkiye_National_Energy_Plan.pdf.

MENR (2022b). Geothermal energy information. Republic of Türkiye Ministry of Energy and Natural Resources (MENR), https://enerji.gov.tr/bilgi-merkezi-enerji-jeotermal.

MENR (2022c). Nuclear energy information. Republic of Türkiye Ministry of Energy and Natural Resources (MENR), https://enerji.gov.tr/bilgi-merkezi-enerji-nukleer-enerji.

MENR (2022d). Turkey biomass energy potential atlas. Republic of Türkiye Ministry of Energy and Natural Resources (MENR), https://bepa.enerji.gov.tr/.

MENR (2022e). Wind energy information. Republic of Türkiye Ministry of Energy and Natural Resources (MENR), https://enerji.gov.tr/bilgi-merkezi-enerji-ruzgar.

MENR (2023a). Solar. Republic of Türkiye Ministry of Energy and Natural Resources (MENR), https://enerji.gov.tr/bilgi-merkezi-enerji-gunes-en.

MENR (2023b). Ulusal enerji denge tabloları. Republic of Türkiye Ministry of Energy and Natural Resources (MENR), https://enerji.gov.tr/eigm-raporlari.

MEUCC (2023). "2053 yılı itibarıyla net sıfır emisyon hedefini gerçekleştirmeyi öngörüyoruz". Republic of Türkiye Ministry of Environment, Urbanisation and Climate Change (MEUCC), https://iklim.gov.tr/2053-yili-itibariyla-net-sifir-emisyon-hedefini-gerceklestirmeyi-ongoruyoruz-haber-4173. (in Turkish).

Morato, T., Vaezi, M., & Kumar, A. (2019). Developing a framework to optimally locate biomass collection points to improve the biomass-based energy facilities locating procedure – a case study for bolivia. *Renewable and Sustainable Energy Reviews*, *107*, 183–199. http://dx.doi.org/10.1016/j.rser.2019.03.004.

Mukheibir, P. (2013). Potential consequences of projected climate change impacts on hydroelectricity generation. *Climatic Change*, *121*(1), 67–78. http://dx.doi.org/10.1007/s10584-013-0890-5.

Ocak, S., & Acar, S. (2021). Biofuels from wastes in marmara region, Turkey: potentials and constraints. *Environmental Science and Pollution Research*, *28*(46), 66026–66042. http://dx.doi.org/10.1007/s11356-021-15464-3.

Okay, A. I. (2008). Geology of Turkey: a synopsis. *Anschnitt*, *21*, 19–42.

Or, B., Bilgin, G., Akcay, E. C., Dikmen, I., & Birgonul, M. T. (2024). Real options valuation of photovoltaic investments: A case from Turkey. *Renewable and Sustainable Energy Reviews*, *192*, Article 114200. http://dx.doi.org/10.1016/j.rser.2023.114200.

Özgül, S., Koçar, G., & Eryaşar, A. (2020). The progress, challenges, and opportunities of renewable energy cooperatives in Turkey. *Energy for Sustainable Development*, *59*, 107–119. http://dx.doi.org/10.1016/j.esd.2020.09.005.

Ozturk, M., Bezir, N. C., & Ozek, N. (2009). Hydropower–water and renewable energy in Turkey: Sources and policy. *Renewable and Sustainable Energy Reviews*, *13*(3), 605–615. http://dx.doi.org/10.1016/j.rser.2007.11.008.

Ozturk, M., Saba, N., Altay, V., Iqbal, R., Hakeem, K. R., Jawaid, M., & Ibrahim, F. H. (2017). Biomass and bioenergy: An overview of the development potential in Turkey and Malaysia. *Renewable and Sustainable Energy Reviews*, *79*, 1285–1302. http://dx.doi.org/10.1016/j.rser.2017.05.111.

Paish, O. (2002). Small hydro power: technology and current status. *Renewable and Sustainable Energy Reviews*, *6*(6), 537–556. http://dx.doi.org/10.1016/S1364-0321(02)00006-0.

Punys, P., & Pelikan, B. (2007). Review of small hydropower in the new member states and candidate countries in the context of the enlarged European union. *Renewable and Sustainable Energy Reviews*, *11*(7), 1321–1360. http://dx.doi.org/10.1016/j.rser.2005.12.008.

Rüstemoğlu, H. (2024). Dynamics of total and industrial energy use in turkiye from 1991 to 2019: a case study. *Environment, Development and Sustainability*, http://dx.doi.org/10.1007/s10668-024-05135-x.

Sahin, A. D. (2008). A review of research and development of wind energy in Turkey. *CLEAN – Soil, Air, Water*, *36*(9), 734–742. http://dx.doi.org/10.1002/clen.200700143.

Şahin, S., & Türkeş, M. (2020). Assessing wind energy potential of Turkey via vectoral map of prevailing wind and mean wind of Turkey. *Theoretical and Applied Climatology*, *141*(3–4), 1351–1366. http://dx.doi.org/10.1007/s00704-020-03276-3.

Snape, J., Boait, P., & Rylatt, R. (2015). Will domestic consumers take up the renewable heat incentive? An analysis of the barriers to heat pump adoption using agent-based modelling. *Energy Policy*, *85*, 32–38. http://dx.doi.org/10.1016/j.enpol.2015.05.008.

Solargis (2025). Solar resource map. https://solargis.com/maps-and-gis-data/download/turkey.

Spencer, R. S., Macknick, J., Aznar, A., Warren, A., & Reese, M. O. (2019). Floating photovoltaic systems: Assessing the technical potential of photovoltaic systems on man-made water bodies in the continental united states. *Environmental Science and Technology*, *53*(3), 1680–1689. http://dx.doi.org/10.1021/acs.est.8b04735.

Steffen, B. (2020). Estimating the cost of capital for renewable energy projects. *Energy Economics*, *88*, Article 104783. http://dx.doi.org/10.1016/j.eneco.2020.104783.

Stritih, U., Osterman, E., Evliya, H., Butala, V., & Paksoy, H. (2013). Exploiting solar energy potential through thermal energy storage in Slovenia and Turkey. *Renewable and Sustainable Energy Reviews*, *25*, 442–461. http://dx.doi.org/10.1016/j.rser.2013.04.020.

Taşdemiroğlu, E. (1988). Geothermal energy potential and utilization in Turkey. *Energy*, *13*(3), 245–251. http://dx.doi.org/10.1016/0360-5442(88)90018-7.

TEİAŞ (2022). Türkiye elektrik üretim-iletim istatistikleri. Türkiye Elektrik İletim A.Ş. (TEİAŞ), https://www.teias.gov.tr/turkiye-elektrik-uretim-iletim-istatistikleri.

TEİAŞ (2024). Yük tevzi bilgi sistemi. Türkiye Elektrik İletim A.Ş. (TEİAŞ), https://ytbs.teias.gov.tr/. Geo-restricted.

Tester, J. W., Anderson, B. J., Batchelor, A. S., Blackwell, D. D., DiPippo, R., Drake, E. M., Garnish, J., Livesay, B., Moore, M. C., Nichols, K., Petty, S., Nafi Toksoz, M., Veatch, R. W., Baria, R., Augustine, C., Murphy, E., Negraru, P., & Richards, M. (2007). Impact of enhanced geothermal systems on US energy supply in the twenty-first century. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1853), 1057–1094. http://dx.doi.org/10.1098/rsta.2006.1964.

Toklu, E. (2013). Overview of potential and utilization of renewable energy sources in Turkey. *Renewable Energy*, *50*, 456–463. http://dx.doi.org/10.1016/j.renene.2012.06.035.

Toklu, E. (2017). Biomass energy potential and utilization in Turkey. *Renewable Energy*, *107*, 235–244. http://dx.doi.org/10.1016/j.renene.2017.02.008.

Tol, R. S. J. (2023). Social cost of carbon estimates have increased over time. *Nature Climate Change*, *13*(6), 532–536. http://dx.doi.org/10.1038/s41558-023-01680-x.

Topkaya, S. O. (2012). A discussion on recent developments in Turkey's emerging solar power market. *Renewable and Sustainable Energy Reviews*, *16*(6), 3754–3765. http://dx.doi.org/10.1016/j.rser.2012.03.019.

TSMS (2022). Türkiye rüzgar atlası(*Turkey Wind Atlas*). Turkish State Meteorological Service (TSMS), https://www.mgm.gov.tr/genel/ruzgar-atlasi.aspx. (in Turkish).

TSMS (2023a). Türkiye ortalama sıcaklık 2023 (*Turkey Average Temperature 2023*). Turkish State Meteorological Service (TSMS), https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=parametrelerinTurkiyeAnalizi. (in Turkish).

TSMS (2023b). Türkiye yağış 2023 (*Turkey Rainfall 2023*). Turkish State Meteorological Service (TSMS), https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=parametrelerinTurkiyeAnalizi. (in Turkish).

TÜREB (2022). *Türkiye Rüzgar Enerjisi İstatistik Raporu - Temmuz 2022 (Turkey Wind Energy Statistical Report - July 2022)*: *Technical Report.*, Ankara, Turkey: Türkiye Rüzgar Enerjisi Birliği (TÜREB), https://tureb.com.tr//yayin/turkiye-ruzgar-enerjisi-istatistik-raporu-temmuz-2022/149. (in Turkish).

TURKSTAT (2023). Greenhouse gas emissions statistics, 1990–2022. Turkish Statistical Institute (TURKSTAT), https://data.tuik.gov.tr/Bulten/Index?p=Greenhouse-Gas-Emissions-Statistics-1990-2022-53701. (in Turkish).

TURKSTAT (2025). Energy statistics. Turkish Statistical Institute (TURKSTAT), https://biruni.tuik.gov.tr/medas/.

Walker, G. (2008). What are the barriers and incentives for community-owned means of energy production and use? *Energy Policy*, *36*(12), 4401–4405. http://dx.doi.org/10.1016/j.enpol.2008.09.032, Foresight Sustainable Energy Management and the Built Environment Project.

WBG (2019). Offshore wind technical potential in WBG client countries. World Bank Group (WBG), https://datacatalog.worldbank.org/search/dataset/0037794/Offshore-Wind-Technical-Potential-in-WBG-Client-Countries.

Wolsink, M. (2007). Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives'. *Renewable and Sustainable Energy Reviews*, *11*(6), 1188–1207. http://dx.doi.org/10.1016/j.rser.2005.10.005.

World Bank (2022). *Turkey economic monitor, February 2022: Sailing against the tide*: *Technical report*, Washington, DC, USA: International Bank for Reconstruction and Development / The World Bank, https://www.worldbank.org/en/country/turkey/publication/economic-monitor.

World Bank (2023). Access to electricity (% of population) - türkiye. World Development Indicators Database, https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=TR.

Yelmen, B., & Çakir, M. T. (2016). Biomass potential of Turkey and energy production applications. *Energy Sources, Part B: Economics, Planning, and Policy*, *11*(5), 428–435. http://dx.doi.org/10.1080/15567249.2011.613443.

Yıldırım, H. B., Teke, A., & Antonanzas-Torres, F. (2018). Evaluation of classical parametric models for estimating solar radiation in the Eastern Mediterranean Region of Turkey. *Renewable and Sustainable Energy Reviews*, *82*, 2053–2065. http://dx.doi.org/10.1016/j.rser.2017.08.033.

Yildiz, T. (2010). Turkey's energy policy, regional role and future energy vision. *Insight Turkey*, *12*(3), 33–38, http://www.jstor.org/stable/26334102.

Yüksel, I. (2010). Hydropower for sustainable water and energy development. *Renewable and Sustainable Energy Reviews*, *14*(1), 462–469. http://dx.doi.org/10.1016/j.rser.2009.07.025.

Yuksel, I. (2012). Global warming and environmental benefits of hydroelectric for sustainable energy in Turkey. *Renewable and Sustainable Energy Reviews*, *16*(6), 3816–3825. http://dx.doi.org/10.1016/j.rser.2012.03.028.

Zhang, F., Deng, H., Margolis, R., & Su, J. (2015). Analysis of distributed-generation photovoltaic deployment, installation time and cost, market barriers, and policies in China. *Energy Policy*, *81*, 43–55. http://dx.doi.org/10.1016/j.enpol.2015.02.010.